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Improving the dynamics of five-axis machining through optimization of workpiece setup and tool orientations

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ABSTRACT

Existing works in optimization of five-axis machining mainly focus on the machining efficiency and precision, while the dynamic performance of the machine tools has not been fully addressed, especially in high-speed machining, in which the rotary actuators have limited dynamic ability. In this paper, a study is reported on how to generate a tool path so that the maximal angular accelerations of the rotary axes of the five-axis machine can be reduced. Two independent methods are proposed for this task: (1) by optimizing the setup of the workpiece on the machine's table, and (2) by finding better tilt and yaw angles for the tool orientations. In this paper, the setup parameters of the workpiece are incorporated into the inverse kinematic equations, and angular acceleration functions are established according to the numerical solutions of those equations. While varying the tool orientations unquestionably would affect the surface quality of the machining, we introduce the so called Domain of Geometric Constraints that will restrict the allowable tilt and yaw angle of the tool at the cutter contact points on the part surface, so to ensure the satisfaction of the requirement of both local-gouging-free and cusp-height. For the first method – finding the optimal workpiece setup – a heuristic-based approach, i.e., the Genetic Algorithm (GA), is adopted, whereas for the second method – the constrained optimization of tool orientations – we present an elaborate algorithm based on the results from the analysis conducted by the authors. At the end of the paper, computer simulation experiments are reported that demonstrate the effectiveness of our proposed methods and algorithms.

1. Introduction

Five-axis Numerical Controlled (NC) machining has been widely used in industry for processing sculptured surfaces, such as ship impellers, turbine blades and propellers, high-precision lenses, etc. Five-axis NC machining is much more complex as compared to traditional three-axis machining because of the two additional rotary axes. Although the research in five-axis NC machining has been extensive, with its focus spreading over a variety of topics, such as the tool trajectory generation [1–5], the tool orientation optimization [6–10], the kinematics error reduction [11,12], the tool path interpolation [13], the singular configuration avoidance [14,15] and so on, there are still many pending problems, and one of them is the dynamic performance of the machine tool's rotary axes. Specifically, a tool path that is deemed good or even optimal according to some existing criteria might demand too high angular acceleration of the rotary axes and thus exert too severe – often infeasible – dynamic loading on the machine tool. This is especially of great concern in the case of high-speed machining, where actuation of the rotary axes is always the bottleneck for improving the machining efficiency.

Our objective is thus to conduct an in-depth study of this dynamic loading problem and provide practical and efficient solutions to it. In the following, we first review some background and past works on the general subject of tool path generation in five-axis NC machining, starting with the inverse kinematics of five-axis machining.

1.1. Inverse kinematics of the five-axis machining

The existing research on inverse kinematics related to five-axis machining has mainly focused on the kinematic model, the kinematic errors and singularity configurations. Bohez et al. [16] gave a systematic introduction of different types of five-axis milling machines, and analyzed their respective disadvantages and advantages. In a further work [17], they summarized the related errors and built an error model in five-axis machining. Lee and She [18] established an inverse kinematic model of the three most popular types of five-axis milling machines, but no analysis of kinematic errors was given. Sorby [14] extended the

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work of [18] by establishing a mathematical model of a five-axis machine tool with non-orthogonal rotary axes, and proposed a solution dealing with the singularities in inverse kinematics. However, the robustness of his solution to singularities is achieved at the cost of requiring very small tool orientation changes, which inevitably is at risk of causing larger accumulated numerical errors. Affouard et al. [15] introduced an interesting concept, called singular cone, to represent a singular point at which the tool path is deformed according to the singular cone and interpolated with *B*-spline curves to avoid the cone area. In the research of reducing inverse kinematics errors, Munlin et al. [12] minimized the kinematics errors near a stationary point of the machined surface by formulating the problem as a shortest path searching problem with the constraint region of a combination of the angles of *A* and *B* axis, and the optimization process is carried out by a greedy discrete method—the Dijkstra's algorithm. Later, Anotaipaiboon et al. [11] minimized the kinematics errors by choosing an appropriate workpiece setup in five-axis machining, which includes no more than 6 parameters, i.e., the position and orientation of the workpiece with respect to the machine coordinate system and the machine's configuration, and the optimization process is carried out by the least squares method.

1.2. Optimization of five-axis machining

Over the last 15 years or so, there has been a surge of research interest in various kinds of optimization in five-axis machining. Those optimizations, however, mainly aim at improving machining efficiency and/or machining precision from the point of view of part coordinate system.

In the planning of the tool trajectory (also referred to as the cutter contact curves), Suresh and Yang [19] proposed the concept of iso-scallop that aims at maintaining equal scallop height in a tool path. Lo [20] extended the idea further by adaptively selecting the cutter-inclination for a flat-end cutter, while at the same time trying to minimize the total length of the tool path. Agrawal et al. [21] minimized the length of the tool path by choosing proper primary path direction using the Genetic Algorithm (GA). Wang and Tang [22] presented a tool path generation algorithm based on the so called iso-conic concept in which a special direction on the cone is found in the part surface to generate the cutter contact curves, reducing the angular velocity and angular acceleration of the *A*-axis into zero. Unfortunately, their algorithm only applies to the specific five-axis machine with two rotary axes on the spindle.

Whereas in the planning of tool orientations in a tool path, most existing methods opt to the fixed-orientation practice, i.e., the tool orientation is fixed relative to the surface normal vector at the Cutter Contact (CC) point [23]. This inflexibility suffers from the serious drawback that, for a part surface with high curvature, the tool orientation often has to undergo drastic change that in turn causes large angular velocity and acceleration on the rotary axes of the machine. Morishige et al. [24] relied on the powerful algebraic tool of *C*-space to determine the tool orientation, wherein the thus obtained tool orientations are further smoothed with the collision-free condition upheld; however, some important local geometric properties, such as local gouging, is not taken into consideration in their algorithm. Jun et al. [8] improved this by adding the local-gouging-free constraint into the *C*-space; in addition, to address the issue of dramatic change in tool orientation, they proposed to smooth the tool orientation in the *C*-space. In their recent work, Wang and Tang [9] went one step further by also taking into account the limit on the maximum angular velocity of the tool and presented an elaborate tool path generation algorithm that entails a systematic framework knitting together all the necessary considerations such as collision avoidance, local gouging, and the angular velocity of the tool. Nevertheless, all the works in [24,8,9] are done with respect to the Part Coordinate System (PCS), independent of the specific machines, and therefore are susceptible to causing heavy dynamic loading on the machine's rotary axes—it is well known that a tool path smooth in tool orientation (but only measured in PCS) may deceivingly impose severe angular acceleration on the *A*, *B*, or *C* axis of a specific five-axis machine.

Aside from the abovementioned, there are also many attempts at optimizing tool orientations, with different objectives and different techniques. Lavernhe et al. [6] optimized the tool orientation of every CC point, aiming at finding the best kinematic parameters, thus reducing the difference between the programmed and the actual feed rate in high-speed machining. Ye and Xiong [25] improved the machining accuracy by optimizing the geometric machining parameters such as the tool orientation, the cutter shape, and the setup of workpiece. Ho et al. [7] used the quaternion interpolation scheme to smooth the tool orientation, aiming at reducing the cutting error, though only in the PCS. Fleisig and Spence [13] used continuous splines to approximate tool position and orientation, which yields near constant feed speed and reduces angular acceleration; unfortunately again, the interpolation is carried out in the PCS. Chiou and Lee [26] searched for better tool orientations based on the swept envelope approach, considering both the local gouging and global collision. Kim and Sarma [27] modeled a tool path as the streamlines of a vector field, which is constructed by selecting the best directions of CC points subject to the constraints of the machine's rotary motor speed limits and the cusp-height limit, and the best directions for performance envelope are found by a greedy approximation method; however, this very complicated system is not implemented and no specific machine-dependent solution is offered. Chiou [28] introduced the concepts of floor, wall and ceiling, for the determination of optimal local-gouge-free tool orientations, albeit in PCS. Recently, Castagnetti et al. [29] introduced an interesting concept of Domain of Admissible Orientation (DAO) which delineates the allowable tool orientations at each CC point. The DAO is originally defined in PCS as a rectangle, which then is transformed into an irregular area in the specific Machine Coordinate System (MCS) and is subsequently approximated by a quadrilateral. Every point in the quadrilateral represents a valid tool orientation for the associated CC point. Optimizations can then be performed directly in these quadrilaterals to find the best tool orientations for the desired objective. Debout et al. [30] utilized the concept of DAO in the smoothing of tool orientations for a particular manufacturing process – the automated fiber placement – which though cannot be extended to general five-axis machining.

In summary, existing five-axis tool path generation or optimization algorithms are not able to address the following fundamental question: given a free-form part surface, a specific type of five-axis machine, and a required limit of cusp-height, how to generate a tool path that will cut the surface with the cusp-height requirement upheld while at the same time minimize the dynamic loading on the rotary axes of the machine? While the dynamics of a five-axis machine could be measured in various different ways, in this paper we focus on the angular accelerations of the rotary axes (the *A*, *B*, or *C* axis) of the machine, i.e., how to minimize the maximal magnitudes of angular accelerations, individual or combined.

1.3. Contribution of the paper

In this paper, we present two optimization methods for the prescribed problem of minimizing the maximal (magnitude of the) angular acceleration of either an individual rotary axis, e.g., the *A*-axis, or the quadratic sum of two axes, e.g., the *A* and *B* axis. In the first method, we take as input an already computed tool