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Improving machined surface textures in avoiding five-axis singularities considering tool orientation angle changes

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ABSTRACT

This paper looks into the irregular machined surface textures appearing in the process of avoiding five-axis singularities using the C-space based tool orientation translation method. At first, the mechanism for the appearances of the irregular surface textures is analyzed. A cutting simulation in VERICUT reveals that irregular surface textures are actually caused by lacking control of the tool orientation angles in the orientation modification process. Realizing that, a modified particle swarm optimization (PSO) is intergraded into the previous tool orientation translation method. In the PSO, the particle evolving equations are redefined and a mutation operation is added. The objective of the PSO is to find an optimal translating vector in the C-space so that the changed tool orientation angles can reach minimum values. In this way, the surface textures can be controlled. Three comparative cutting experiments with fillet endmills are carried out to verify the effect of the proposed method. The experimental results show that: (1) with the tool orientation translation method, the five-axis singular problem can be well avoided; and (2) with the optimal translating vector found by the PSO, the machined surface textures can be greatly improved.

1. Introduction

Five-axis machine tools possess the characteristics of high efficiency and high precision thanks to the additional rotary axes. However, even with today's CAM/CNC technologies, five-axis machine tools are still hard to use. Problems such as collisions and singularities still exit in practical five-axis applications. During the last two decades, the collision problem has been heavily studied. Approaches like the rolling-ball method [1], visibility map method [2], sweep plane method [3] and admissible area morphing method [4] have been developed. For the singular problem, however, it has attracted relatively fewer research attentions.

The singular problem hides in all types of five-axis machine tools, no matter what the configurations are. It only appears when the rotary axes traverse the singular point. At the vicinity of this point, instantaneous but dramatical motions of the machine axes might be observed. More specifically, for an AC-type machine tool, the singularity happens when the tool axis is nearly parallel to the *Z* axis of the machine tool. In this case, even very slight changes of the tool orientation in the P-system may stimulate a great rotation for the *C* axis, which often involves great correction displacements of the translation axes and an important reduction of the feedrate. This phenomenon is very similar to the case when a man stands at the North Pole (singular point) of the earth, even his small step could have meant half the earth from the perspective of longitude (*C* axis rotation). Obviously, the singular problem is harmful to the five-axis machining process and must be avoided.

Affouard et al. [5] blamed the singular problem to the positioning uncertainties of the five-axis machine tools. They took the advantages of the tool path in double B-spline format and proposed a local deformation method to prevent the tool axis traversing the singular cone. Castagnetti et al. [6] proposed a minimal movement optimization for the tool path based on the Domain of Admissible Orientation (DAO) concept. In their work, the singularity is detected if the DAO contains the vertical axis (0,0,1) for the AC-type machine tools. Sørby [7] presented a post-processing algorithm to avoid the singular problem. His algorithm modifies the exact inverse kinematics in order to give robustness to singularities at the expense of a small tool orientation deviation. Singularities are finally eliminated by a linearization procedure which interpolates a number of new cutter locations (CLs) along the ideal tool path. She and Huang [8] developed a postprocessor for a machine tool with nutating head and table configuration, in which the linearization algorithm is also used to ensure the machining accuracy. Munlin et al. [9] tried to alleviate the influence of

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0890-6955/

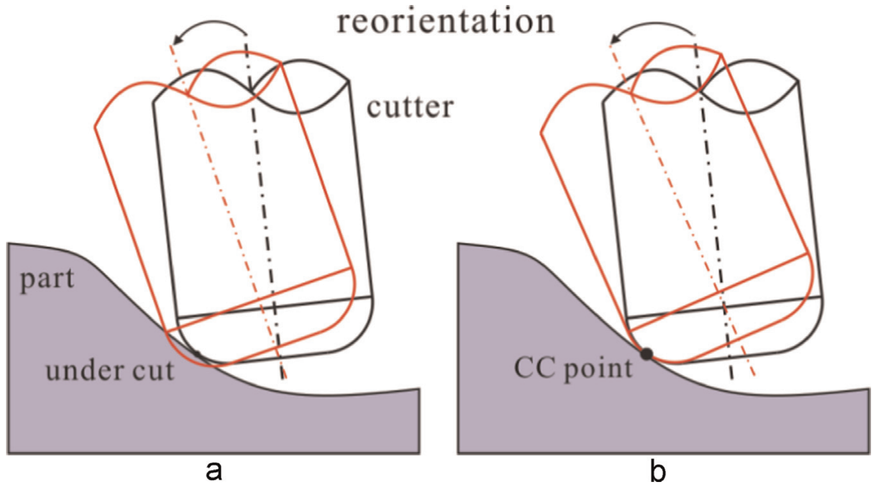

Fig. 1. Tool orientation adjustments; (a) arbitrary tool reorientation, causing uncontrollable cutting error; (b) tool reorientation with respect to the CC point.

singularity by means of the shortest path scheme based on minimization of the kinematics error. Their algorithm can optimally select the axis rotating angles from the multiple solutions of the inverse kinematics equations. Ivanenko et al. [10] and Makhanov et al. [11] presented similar methods in their research studies, respectively. Some interesting work has also been done to avoid singularity or improve machining efficiency at the machining stage by optimal workpiece setup on the working table [12–14].

As pointed by Castagnetti et al. [6], the drawback of avoiding singularities on the already obtained tool path is the lack of error control. The fact is, if the geometry errors of the original path are to be respected, the original CC points should be used as the pivot points during the tool reorientation process, as shown in Fig. 1. Unfortunately, common five-axis tool path contains only the information of the tool reference points (usually the tool tip or tool center) and the tool orientation unit vectors. Such information is not sufficient enough for the mathematical deduction of the original cutter contact (CC) points.

Realizing that, in our previous work [15], a C-space based tool orientation translation method is developed to avoid the singularities at the time just after the initial cutter locations have been calculated. The benefit of avoiding singularities at the tool path planning stage is that the original CC points can be respected during the tool reorientation process. However, as it has been discussed in that work, one side effect of the above method is that irregular surface textures might be generated, as shown in Fig. 2. These textures are due to the arbitrary adjustments of the tool orientations in the local P-system and are also related to the machining errors.

In this work, we focus especially on the machining texture issue caused by modifications of the tool orientations. In our previous work, in order to solve the singular problem, the tool orientation polyline is translated by a shortest distance to avoid the singularity, ignoring the tool orientation changes. In this work, while translating the orientation polyline, the orientation angles in the local P-system are also taken in to consideration. The objective of this study is to find an optimal translating vector in the C-space so that the singular problem can be avoided and the machined surface textures can be controlled.

The study presented in this paper is an extension of our previous work. The rest of the paper is organized as follows. In the following section, the tool orientation translation method is briefly introduced. After that, in Section 3, the mechanism for the appearance of the irregular surface is analyzed. Based on that, in Section 4, an intelligent optimization method is applied for the purpose of improving machined surface textures. Section 5 gives experimental verifications and the last section closes this paper.

2. Tool orientation translation method

Fig. 3 illustrates an overview of the tool orientation translation method, the input of which is a set of cutter locations representing a tool path. Each cutter location is an instance of the following data structure

struct *Detailed_cutter_location*
{
point C, *M*;
vector **f**, **b**, **n**, **T**; // unit vectors
};

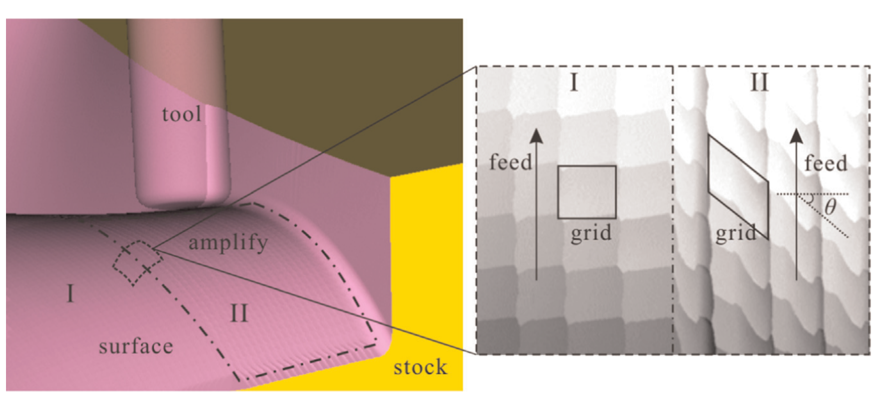

Fig. 2. The finished surface texture caused by uncontrolled tool orientation modifications.