



# Optimized tool path generation based on dynamic programming for five-axis flank milling of ruled surface

Ping-Han Wu, Yu-Wei Li, Chih-Hsing Chu\*

Department of Industrial Engineering and Engineering Management, National Tsing Hua University, 101 Kuang Fu Road, Hsinchu 300, Taiwan

## ARTICLE INFO

### Article history:

Received 19 October 2007

Received in revised form

13 March 2008

Accepted 18 March 2008

Available online 27 March 2008

### Keywords:

Five-axis machining

Flank milling

Ruled surface

Dynamic programming

Optimization

## ABSTRACT

This paper presents a computation scheme that generates optimized tool path for five-axis flank milling of ruled surface. Tool path planning is transformed into a matching problem between two point sets in 3D space, sampled from the boundary curves of the machined surface. Each connection in the matching corresponds to a possible tool position. Dynamic programming techniques are applied to obtain the optimal combination of tool positions with the objective function as machining error. The error estimation considers both the deviation induced by the cutter at discrete positions and the one between them. The path planning problem is thus solved in a systematic manner by formulating it as a mathematical programming task. In addition, the scheme incorporates several optimization parameters that allow generating new patterns of tool motion. Implementation results obtained from simulation and experiment indicate that our method produces better machining quality. This work provides a concise but effective approach for machining error control in five-axis flank milling.

© 2008 Elsevier Ltd. All rights reserved.

## 1. Introduction

Five-axis CNC machining has become popular in industry since the early 1990s, finding applications in manufacture of aerospace, automobile, air-conditioning, and mold parts. With two additional degrees of freedom, it provides advantages [1,2] over three-axis machining like higher productivity and better quality. Machining preparatory work such as change of jigs and fixtures is reduced and thus the total manufacturing time is shortened. In addition, the tool-cutting end can be a good match with the shape of the machined surface. There are two different milling methods in five-axis machining. In point milling (or end milling), the cutting edges near the end of a tool performs the action of material removal [3]. On the contrary, the cylindrical part of a tool does the main cutting in flank milling [4].

Tool path planning is a critical issue in any machining operation. To generate the tool path that achieves the specified surface roughness is a major concern in point milling. Elimination of tool interference is another challenge in use of five-axis machining. The tool must be properly posed in 3D space using the two rotational degrees of freedom so as not to cause any unexpected collisions in the machining environment [5,6]. The situation in flank milling is more complicated. To completely avoid tool interference is difficult, if not impossible, in most cases

except for machining of simple shapes such as cylindrical, conical, and developable surfaces [7]. In practice, the surface quality after machining is considered acceptable on condition that the amount of tool interference can be limited within a given tolerance. The following literature survey only reviews the studies related to five-axis flank milling, as the focus of this research is on the tool path generation of that milling method.

Liu [8] proposed a heuristic algorithm that offsets the points corresponding to the parameter values 0.25 and 0.75 of a ruling with a distance of the tool radius. The line connected by the offset points determines the tool orientation. The tool path generated in this manner produces serious tool interferences near the middle of the machined surface. Bohez et al. [9] determined the tool orientation by offsetting the end points of surface rulings. The offset direction is chosen as the average of the surface normal at these points. They claim that this approach can significantly reduce the amount of tool interference. Lartigue et al. [10] modeled the tool swept volume using the envelope surface. The machined geometry is thus estimated. They also proposed an evaluation method of the machining error that can be applied to compare the quality of different tool paths. Tsay et al. [11,12] studied the influence of the yaw and tilt angles on the amount of tool interference in five-axis flank milling from the machining error estimation of various examples. The result works as look-up tables integrated in a tool path generation algorithm for B-spline ruled surface. Bedi et al. [13] studied the relationship between the tool orientation at a cutter location and the amount of undercut/overcut in flank milling of a ruled surface. They assumed that a

\* Corresponding author.

E-mail address: [chchu@ie.nthu.edu.tw](mailto:chchu@ie.nthu.edu.tw) (C.-H. Chu).

cylindrical cutter initially makes a contact with a boundary curve of the surface with the tool orientation as the surface ruling at the contact point. Based on this work, they [14] proposed a nonlinear optimization scheme for minimizing the tool interference at discrete positions by locally adjusting the tool position and orientation around the contact ruling. Chu and Chen [7] proposed approximation of a ruled surface using consecutive developable surfaces. The tool path free of local interference is generated by guiding the tool along the rulings of the developable surfaces. However, the machining error cannot be precisely controlled in their method.

The above literature review shows several limitations in previous studies. First, optimization methods have been applied to locally adjust the tool orientation at discrete locations, but they are all based on a greedy approach. An implicit assumption is thus made: the global optimum equals to the sum of local optimums. Unfortunately, this statement is generally not true. In addition, the previous methods neglect the possibility of skipping some rulings (or contact points along the boundary curves) in the tool path. The path computed in this manner is not guaranteed to produce better result in terms of the machining error. To overcome these problems, we propose a novel idea for tool path generation in five-axis flank milling of ruled surface. A geometric problem (tool path generation) is converted into a mathematical programming task. Specifically, determination of the tool motion transforms into a global matching problem between two curves. The machining error becomes the objective function to be minimized in a global optimization process. Moreover, the boundary curves of the ruled surface are extended in different degrees for generating the tool contact points. The solution space of tool path is enlarged, thus producing a better result than that without the extension. A series of machining tests are conducted to validate our idea. The measure result demonstrates that the tool path generated by the proposed method gives a minimal machining error. This work provides a concise but effective approach to improving machining error control in five-axis flank milling.

## 2. Introduction of the proposed algorithm

The simplest way of tool path generation in five-axis flank milling of ruled surface is to let the tool follow the surface rulings. This method is often used in industry even though it does not necessarily produce optimal result in terms of machining quality or efficiency. The study proposes an optimization scheme based on discrete dynamic programming to improve such machining practice. In addition, this scheme incorporates four kinds of parameters for users to generate different patterns of tool motion. These are the number of discrete points (NDP), the number of discrete points to skip (PS), the extension ratio (ER), and the scanning step (CS). The following sections will explain each parameter in details.

### 2.1. Number of discrete points (NDP)

A ruled surface  $S(u, v)$  is generated by connecting a set of straight lines from two boundary curves and formulated as

$$S(u, v) = (1 - v)C_0(u) + vC_1(u), \quad \text{with } (u, v) \in [0, 1] \quad (1)$$

where  $C_0(u)$  and  $C_1(u)$  are the boundary curves.

Despite of the continuous equation, the surface representation usually needs to be transformed into a discrete one for tool path generation. The transformation is achieved by sampling the two curves into discrete points. The sampling can be done by either equal parameter or arc length. The NDP value determines the number of the discrete points. Each discrete point is denoted by

two letters:  $m$  identifies the boundary curve to which the discrete point belongs and  $n$  represents the index of a discrete point on the curve.

### 2.2. Number of discrete points to skip (PS)

The PS value represents the maximal number of the discrete points which can be skipped in the calculation process. In practice, the tool removes stock material along the surface rulings and covers every discrete point on the boundary curves. In contrary, the proposed scheme allows skipping points in the tool motion, which may give a better result (this is also what we are going to explore in this work). One can define a range from zero to PS, and the number of skipped points can be any value within the range. As indicated in Fig. 1(a), none of the discrete points on the boundary curves is left out because the PS values on both the curves are 0. Fig. 1(b) is an example with both the values as 2. Such tool path should be adopted when the machining error induced by skipping the two ruling lines (the tool goes directly from  $P_{1,4}$  and  $P_{2,4}$  to  $P_{1,7}$  and  $P_{2,7}$ ) is smaller than the one not skipping.

### 2.3. Extension ratio (ER)

Most previous studies calculate the tool motion in five-axis flank milling by having the cutter move along the bounding curves (or refer to the contact curves). Solution space of possible tool path is therefore limited to the one defined by these curves. Our study, on the other hand, proposes to enlarge the solution space by extending the boundary curves. It is expected that doing so helps attain better tool path by exploring a larger solution space. The term ER represents the extension ratio of the control points. Both boundary curves may have different ratios. Given the ER values, new control point positions are calculated based on the following equations (see Fig. 2):

$$\left. \begin{aligned} CP_{1,i} &= P_{1,i} + (P_{1,i} - P_{2,i}) \times ER_1 \\ CP_{2,i} &= P_{2,i} + (P_{2,i} - P_{1,i}) \times ER_2 \end{aligned} \right\}, \quad i = 1, 2, 3, 4 \quad (2)$$

### 2.4. Scanning step (CS)

The CS value is used to determine a range which restricts the connected points on the boundary curves, as the length of the cutting edge is limited. If one wants to establish a line which connects  $FDP_{1,i}$  with a discrete point on the other curve (see Fig. 3), only the discrete points covered in certain range can be selected. Each point within the range is eligible to form a tool location with  $FDP_{1,i}$ . Adding the CS value to  $i$  leads to the upper bound and subtracting the CS value from  $i$  yields the lower bound, i.e., from  $DP_{2,(i-CS)}$  to  $DP_{2,(i+CS)}$ .

To sum up, our algorithm incorporates seven parameters into the optimization scheme. They are represented as  $NDP_1, NDP_2, PS_1,$

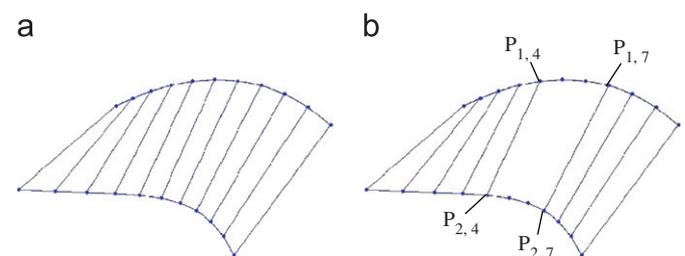


Fig. 1. Number of discrete points to skip. Both the PS values are (a) 0 and (b) 2.

متن کامل مقاله

دریافت فوری ←

**ISI**Articles

مرجع مقالات تخصصی ایران

- ✓ امکان دانلود نسخه تمام متن مقالات انگلیسی
- ✓ امکان دانلود نسخه ترجمه شده مقالات
- ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
- ✓ امکان دانلود رایگان ۲ صفحه اول هر مقاله
- ✓ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
- ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات