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Optimized tool path planning for five-axis flank milling of ruled surfaces using geometric decomposition strategy and multi-population harmony search algorithm

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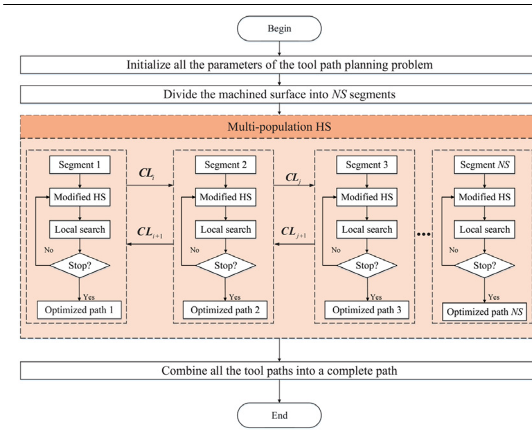
HIGHLIGHTS

- A new tool path planning method for 5-axis flank milling is proposed.
- It geometrically divides the surface into a number of segments.
- The multi-population harmony search is proposed to optimize tool path on each sub-surface independently.
- The effectiveness of the proposed approach is demonstrated on eight representative surfaces with different characteristics.

GRAPHICAL ABSTRACT



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ABSTRACT

Tool path planning is a key to ensure high machining quality and productivity in 5-axis flank milling of ruled surfaces. Previous studies have shown that optimization-driven tool path planning can effectively reduce the geometrical errors on the finished surface. However, to solve the corresponding optimization problem is a challenging task involving a large number of decision variables. This paper proposes a novel approach to generating optimized tool path for 5-axis flank finishing cut based on a geometric decomposition strategy and multi-population harmony search algorithm. The proposed approach geometrically divides the surface to be machined into a number of segments. The tool paths on those sub-surfaces are independently optimized by the multi-population harmony search algorithm. Individual tool paths are then combined together to form a complete one. The test results of representative surfaces show that the proposed approach produces higher machining precision with less computational time than compared previous methods. And the computational time is further reduced by Message passing interface based parallel computing techniques. A detailed analysis is conducted to characterize how the number of divisions affects the optimization results. And the proposed approach also shows good scalability with the increasing number of cutter locations.

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1. Introduction

Five-axis CNC machining is widely used in manufacturing industry nowadays. This machining operation provides better shaping capability for complex parts containing free form surfaces, such as impeller of the aircraft engine, propeller of the ship, and steam turbine. There are two kinds of milling operations in 5-axis CNC machining: end milling and flank milling. The end milling operation is usually applied to create free form surfaces. Its machining time can be quite lengthy for high machining quality. In contrast, the flank milling operation is more effective for machining ruled surfaces with higher material removal rate and machining productivity. Flank milling can also provide superior surface quality with proper tool path planning. In practice, the machined surface quality is considered acceptable as long as the amount of the machining error can be limited within a given tolerance [1]. The geometrical errors on the surface finished by 5-axis flank milling can be significantly reduced by adjusting cutter locations comprising a tool path. Previous studies have proposed different approaches to realizing this idea.

Tsay and Her [2] studied the relationship between the machining error and different combinations of the rotation angle of the cutter, length of ruling line, distance to the machined surface, and the cutter radius. A look-up table was used to position the cutter to reduce the errors. Lartigue et al. [3] approximated the volume generated by tool motion using the envelop surface. The machining errors were estimated by the deviation between the surface to be machined and the envelop surface. The error amount was reduced by constantly adjusting the tool orientation to match the two surfaces as much as possible. Wu et al. [4] transformed the tool path planning problem into a 2D curve matching problem. Discrete dynamic programming techniques were applied to reduce the machining errors. Ding et al. [5] proposed a two-step approach to planning cylindrical cutter location for flank milling of ruled surfaces. In the first step, a sequence of initial cutter locations (CLs) was determined by offsetting the grid sampled points based on semi-definite programming (SDP). In the second step, the tool axis was re-positioned by adjusting the offset value of each sampled point on the designed surface according to the predicted cutting errors. In their subsequent research [6], the tool path planning problem was addressed from a global perspective. They developed the complete principle, model and algorithm or global tool path optimization for five-axis flank milling with a conical cutter. Some meta-heuristic algorithms have been developed for global (or nearly global) optimization of tool path planning by adjusting all cutter locations simultaneously. Chu et al. [7] applied the ant colony systems (ACS) algorithm to obtain an optimal tool path with the accumulated errors on the machined surface to be minimized. The limit of this method is that the cutter can only contact the surface at predefined discrete points on its boundary curves. In their subsequent work [8], this constraint was relaxed by allowing the cutter freely contact the surface. The particle swarm optimization (PSO) algorithm combined with GPU parallel computing techniques was applied to search for optimal solutions. Although the search process was largely accelerated using GPU, this method cannot guarantee satisfactory solution quality. To overcome this drawback, Hsieh and Chu [9] added extra freedom to CLs by allowing the cutter to deviate from the surface along the normal, tangent, and bi-normal directions at the contact points on the machined surface. This method yielded better solutions than those of previous studies. However, adding extra freedoms in the tool motion increases the dimensionality of the search space (from $2n$ to $8n$, n represents the number of CLs). The solution quality obtained by searching in such a high-dimensional space is not always satisfactory. In their later studies [10–12], several more efficient methods such as advanced PSO (APSO), fully informed PSO (FIPSO), Electromagnetism-like (EM) algorithm and methods integrating sampling techniques were developed for yielding better results. Those methods indeed continue to improve the solution quality than previous ones, but some of them may require a long computational time to complete the search process [11].

This paper proposes a novel approach based on geometric decomposition strategy and the multi-population harmony search algorithm (abbreviated as GD-MPHS) to further improve the solution quality and shorten the computational time in the optimization problem. The idea of GD-MPHS is inspired from the "divide and conquer" strategy. In the first step, the surface to be machined is geometrically divided into several segments. A multi-population harmony search algorithm is then employed to obtain the optimal tool path for each segment. Finally, those tool paths are combined together to form a complete path covering the entire surface. The motivation behind the geometric decomposition strategy is based on the observation that interactions on controlling the machining errors only exist among cutter locations not far from each other in a tool path (Section 3 will elaborate this part). As a result, the tool paths for different segments can be independently optimized without sacrificing too much on the quality of the optimal solution. The proposed approach would be a compromise between global optima and greedy solutions, thus providing several advantages. First, the original high-dimensional optimization problem is decomposed into several lower dimensional problems, which optima may be easier to attain. Second, the search algorithms designed to find optimal solutions in a low-dimensional solution space may work more efficiently with fewer iterations. Third, applying geometric decomposition makes the problem to be suitable for implementation using parallel computing techniques, which can further accelerate the optimization process (This part will be discussed in Section 5.1). The performance of GD-MPHS is tested on several representative surfaces and compared against previous methods. The test results show that the GD-MPHS method outperforms all the compared previous methods in the solution quality with fewer computations in the search process. Simulation results generated by a commercial software tool validate the effectiveness of the proposed method. Results also show that GD-MPHS is scalable in performance with the increasing number of CLs.

The rest of the paper is organized as follows. In Section 2, the background of optimization-driven tool path planning for 5-axis flank milling is presented. The procedure of the GD-MPHS method is explained in Section 3. In Section 4, a set of experiments are conducted to validate the performance of the proposed method. Section 5 presents the discussions on speed acceleration by parallel computing techniques of GD-MPHS and its scalability with the increasing number of CLs. And the concluding remarks are provided in Section 6.

2. Tool path planning in 5-axis flank milling

2.1. Representation of ruled surface

This study is focused on the flank finishing cut of ruled surfaces. To represent a ruled surface, we need to specify two curves in 3D space (the lower and upper boundaries). Here we use cubic Bezier curves as an example. Fig. 1 shows the representation of a ruled surface. By introducing two parameters u and v (u and v are normalized scalars along vectors $\boldsymbol{u}$ and $\boldsymbol{v}$, and both of them are in the range of [0, 1]), the coordinate of an arbitrary point $\boldsymbol{p}$ on the surface is represented by the following equation:

$$\boldsymbol{p}(u, v) = \boldsymbol{A}(u) + v(\boldsymbol{B}(u) - \boldsymbol{A}(u)) = (1 - v)\boldsymbol{A}(u) + v\boldsymbol{B}(u) \quad (1)$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ are the upper and lower boundary curves, respectively.