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Milling plan optimization with an emergent problem solving approach

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ABSTRACT

With elaboration of products having the more complex design and good quality, minimize machining time becomes very important. The machining time is assumed, by hypothesis, to be proportional to the paths length crossed by the tool on the surface. The path length depends on the feed direction and the surface topology. To get an optimal feed direction at all points of surface, this study concerns machining with zones of the free-form surfaces on a 3-axis machine tool. In each zone, the variation of the steepest slope direction is lower, total path length is minimized and the feed direction is near the optimal feed direction. To resolve this problem, the Adaptive Multi-Agent System approach is used. Furthermore, a penalty reflecting the displacement of the tool from a zone to another one is taken into account. After several simulations and comparisons with the machining in one zone (what is being done at present), the results obtained present a significant saving about 22%.

1. Introduction

In various fields of activity, such as aeronautic, automotive industry or capital goods, the competition leads to the elaboration of products having a design more and more complex and increasing quality. These complex surfaces are named free-form surfaces and require a high quality level and reduced shape defects. The machining of the free-form surfaces, manufacturing moulds or matrix used to make the models is time consuming, not optimized and costly. The main factor influencing the global cost of the free-form surfaces production is the machining time. The free-form surfaces are modeled using computer-assisted design software. The associated mathematical models are parametric surfaces with poles, as NURBS, B-Spline, Bézier curves…(Faux & Pratt, 1985).

Their machining is done by material removal using Numerically Controlled Machine Tools, with hemispherical or toric end mills (Marciniak, 1992). It has been demonstrated (Senatore, Segonds, Rubio, & Dessein, 2012) that using the toric end mill cutter allows to decrease the machining time if cutting feed direction is well chosen. It is the type of tool that will be used in the present study.

There are several machining strategies: parallel planes milling (Huang & Oliver, 1994), guide surfaces (Kim & Choi, 2000), and iso-parametric milling (Loney & Ozsoy, 1987). These strategies are obtained directly from 3-axis machining researches. The one that's used in this study is the parallel planes milling, it's the most used and mastered in the industry. It consists in determining the tool paths using the intersection between the work piece and the parallel planes oriented along one machining direction. Advantages of parallel planes milling strategy are:

- Do not generate an overlapping tool path, allowing a considerable time saving.
- To avoid the appearance of non-machined areas.

The parallel planes milling strategy is not optimal. Indeed, during the machining of the surfaces with a large variation of the normal direction, the successive paths become nearer to respect scallop height criteria, thus increasing manufacturing time. When a tool moves on the surface, it sweeps a volume by leaving an imprint on this surface, it's a swept surface (Steiner, Peternell, Pottman, & Zhao, 2005). Between two adjacent paths, the intersection of the swept surface produces a scallop. Usually, a maximum given scallop height criteria must be respected.

The main object of this study is to minimize the machining time of free-form surfaces while respecting the quality imposed by the engineering consulting firm, by 3-axis machining with toric end mill cutter. A considerable number of works have been devoted

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to reduce machining time (Chen, Vickers, & Dong, 2003; Maeng, Ly, & Vickers, 1996). Indeed, the first path is calculated according to the optimal feed rate direction, then secondary paths are calculated, respecting a fixed step-over distance that guaranties a maximal scallop height, inferior to the imposed scallop height criteria. The problem is that secondary path deviate rapidly and may not be in optimal direction engendering time loss.

Due to the complexity of the machining of free form surfaces respecting a scallop height criterion in a minimal tool path length, and since the choice of a unique machining direction for the whole surface could not be efficient, a new approach is detailed in the following paper. The main innovation consists in using the best local advantages of both toric end mill use and parallel planes strategy by extending it to a whole surface by zoning it in several zones. The zones will be machined using a specific optimal feed rate direction. Furthermore, a penalty reflecting the displacement of the tool from a zone to another one is taken into account. The problem appearing during the machining of the zones is the determination of the number and geometry of zones. Indeed:

- The number of zones should not be too high to avoid spending too much time going from a zone to another one.
- The number of zones should not be too small to keep the feed rate direction not so far from optimal value in every point of the zone.

To minimize the global machining time of a given surface, this study concerns the optimization of the number and geometry of the zones. This paper is organized as follows: Section 2 presents the notions related to the machining strategy that will be used in the optimization problem definition presented in Section 3. After having reviewed the main optimization methods that could be used, Section 4 presents their limits in the context of this paper and will argue the choice of the Adaptive Multi-Agent System (AMAS) approach. Section 5 presents the multi-agent system implemented as well as behavior of the agent. Finally, after having presented in the part Section 6 the experimental results and their analysis, Section 7 concludes and mentions the perspectives of improvement that are envisaged.

2. Reminder

2.1. Machining direction

The surfaces studied in this paper are the free-form surfaces, they present a set of curved zones. The geometry is obtained by successive passes of a tool. For this study the toric end mill with cutter radius R and torus radius r is used (Fig. 1), and the adopted machining strategy is the parallel planes of type one-way. During the machining, tool moves tangentially to the workpiece at the contact point C_c. At this point the tool can move in any direction α. This parameter α is called feed motion direction, it is directly influenced by the topology of the surface. The optimal direction

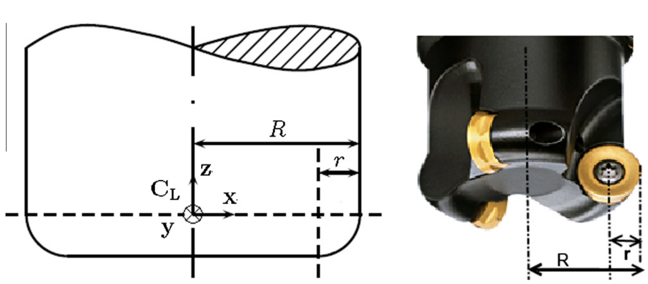

Fig. 1. The toric tool.

at a given point of the surface is the direction of steepest slope. For example, let be an inclined plane ($S = 30^\circ$) and a toric end mill cutter ($R = 5$ mm, $r = 2$ mm) presented partially by a quarter of torus. Fig. 2 illustrates two cases of movement of this tool. The blue-lined curve presents the trace left by the tool on the workpiece at C_c.

1. During the movement of the tool following a direction perpendicular to the steepest slope direction ($\alpha = 90^\circ$), the trace left by the tool at contact point C_c is a curve with a radius of curvature greater than R.
2. During the movement of the tool along the horizontal direction ($\alpha = 0^\circ$), the trace radius of curvature left by the tool is equal to r.

For the same path length, the quantity of material removed in the case (1) is much more important than in the case (2), then the number of paths required to machine the whole surface in the case (1) is inferior than in the case (2). So, the time required to machine the surface in case (1) is less than the machining time for the same surface in case (2).

The previous example illustrates that the choice of the feed direction has an important role on the radius of the trace left by the tool on the surface. The more the radius of this trace is important and the more the machining time decreases. The radius of curvature of the trace left by the tool at C_c is called effective radius R_{eff}. The toric end mill enables to keep a large effective radius while avoiding unsightly marks.

2.2. Effective radius

At the contact point C_c, the trace left by the tool on the surface is the swept curve. Effective radius corresponds to the radius of curvature of the swept curve projected in a plane normal to the feed direction along a direction parallel to the feed direction. Redonnet, Djebali, Segonds, Senatore, and Rubio (2013) demonstrates that, at contact point C_c, the effective radius is equal to the ellipse radius – resulting from the projection along the feed direction in a plane normal to the feed direction of the center-torus circle-increased by an exterior offset with a value equal to the torus radius of tool r. This gives us the analytical equation of the effective radius:

$$R_{eff} = \left(\frac{(R - r)\cos(\alpha - \varphi_{Cc})^2}{\sin(S)(1 - \sin(\alpha - \varphi_{Cc})^2 \sin(S)^2)} + r \right) \qquad (1)$$

With:

- $\begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}$: the normal of the surface at the contact point C_c.
- $\varphi_{C_c} = \arctan\left(\frac{n_y}{n_x}\right)$: steepest slope direction.
- $S = \arccos(n_z)$: the slope angle of the workpiece at a given point.
- Z_s: tool axis.
- α: the feed direction angle relatively to x axis.

This analytical expression of R_{eff} is easy to handle. It depends on the feed direction angle α and on the slope angle (Fig. 3).

2.3. Step-over distance and toric end mill conditions

Step-over distance P_t corresponds to the distance between two successive and parallel tool paths while not overpassing the imposed scallop height criteria h_c. Generally h_c is in the order of 0.01 mm, then the following hypothesis are made: