Title:
Pattern Detection for Toolpath Generation on Triangular Meshes for 5-axis CNC machining

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Introduction:
Toolpath generation of freeform triangulated surfaces is of interest to the 5-axis machining research community because of the availability of 3D scanning and finite element methods. A common approach to generate a 5-axis toolpath for a triangulated surface is curve offsetting (iso-planar, iso-scallop) [9]. The iso-parametric toolpath strategy can also be applied to triangulated surfaces after flattening i.e. mapping the surface onto a parametric domain [19]. An important issue in toolpath generation is selecting an appropriate toolpath strategy. Usually, it is selected semi-automatically based on the features of the design surfaces, machine configurations, and experience of a CAD/CAM expert. As a result, the final toolpath may not be efficient enough. The idea of a toolpath following an optimal feed direction (OFD) has been discussed for decades [2]. By considering full machining configurations, including the designed surface properties, workpiece setting, and machine kinematics, the OFD vectors can be determined at each cutter contact (CC) point [6]. However, connecting the CC points following the OFD field, given that the final toolpath should be continuous, smooth, not redundant, and without self-intersection [19] is still an open problem.

Using mesh parameterization methods, the OFD can be transferred from the 3D space into the 2D space for further analysis [19]. The most popular methods to generate toolpaths aligned with the OFD field are the streamline approach [7], [2], [11], [12], [8], [18] and the heuristic search [16], [15], [20], [13]. On parametric surfaces with a smooth, continuous OFD field, the streamline integration method works very well; however, triangulated surfaces often generate non-homogeneous irregular OFD fields. As a consequence, the streamline approach cannot be utilized and needs to be transformed into a continuous vector field [7]. Next, the search is performed to find the optimal walk, based on the local directions of the OFD vectors.

While both approaches work for a variety of smooth parametric surfaces, they are not always applicable to surfaces represented by industrial formats, such as IGES, STL (triangulated surface), or STEP. In addition, toolpaths generated by the above methods are highly redundant and generate irregular toolpath patterns.

Main idea:
In this paper, a procedure to generate a piecewise discrete orientation field (OF) of a triangulated surface in a parametric domain is described. Next, a pattern recognition algorithm using moment invariants of the vector field is developed to classify the OF into an appropriate template pattern (curl, radial, spiral, or parallel). Transfinite interpolation (TFI) is utilized to generate grids such that their orientations are approximately aligned with the OF. The toolpath is generated using the obtained TFI grids.

Orientation Field Generation
From each vertex of the triangular mesh, the OFD vectors are determined using the specified machining efficiency measures. The OFD vectors are then transferred onto a parametric domain using a conformal map. Using barycentric interpolation, a piecewise discrete orientation field (OF) is obtained on a rectangular grid (See Fig. 1).

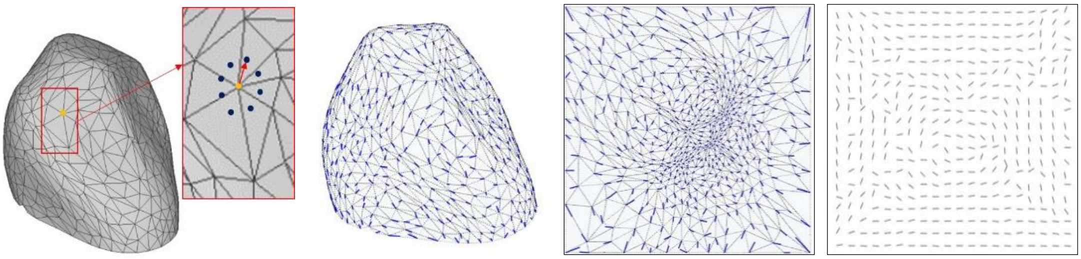

Fig. 1: OF generation process: (a) 3D triangular mesh and feeding sample, (b) OFD vectors on the 3D mesh, (c) OFD vectors on the flattened mesh, and (d) the OF.

Pattern Detection using Moment Invariants
Consider an original OF given by $v(x,y)=(v_x(x,y),v_y(x,y))$. The modified OF is represented by a complex function $f(x,y)=e^{i\theta(x,y)}$, where

$$\theta(x,y)=\begin{cases}\arctan\left(\dfrac{v_y}{v_x}\right), \text{if } v_x\neq 0,\\ -\dfrac{\pi}{2}, \text{otherwise.}\end{cases} \tag{1}$$

In practice, $\theta(x,y)$ is doubled to exclude cancellation of opposite vectors during the integration process [10]. The complex moment c_{pq} of an integrable complex function $\hat{f}(x,y)=e^{i2\theta(x,y)}$ is calculated by [3]:

$$c_{pq}=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x+iy)^p(x-iy)^q\hat{f}(x,y)dxdy\,. \tag{2}$$

A set of independent moments of the order $p+q\leq 2$ is given by [17]:

$$M=\{c_{01},c_{00}c_{02},c_{11}c_{02},c_{10}c_{02}^2,c_{20}c_{02}^3\}. \tag{3}$$

To classify the OF, the moment vector M of the OF within the area cropped by a moving window is compared with the moment M_0 of a template, using a classification threshold [5].

Grid Generation
The TFI grid is generated in such a way that it aligns with the detected OF pattern [4]. By selecting boundary constraints, different grid structures, O-gird, C-grid, or H-grid, can be used (Fig. 2). The corresponding toolpath is extracted from the grids [15]. The appropriate distance between the neighbouring TFI tracks is found by bisection. If the Hausdorff distance between the tracks is larger than the allowable machining strip width, a new grid line is inserted. The 2D path structure obtained from the TFI grid is mapped back onto the 3D surface to obtain a CC path. The tool orientations are set to avoid gouging and to obtain smooth angular transitions. The cutter location path can now be determined and converted into an NC program using the kinematic transformations of the machine [14]. Fig. 3 shows an example of a toolpath generation by the proposed method.

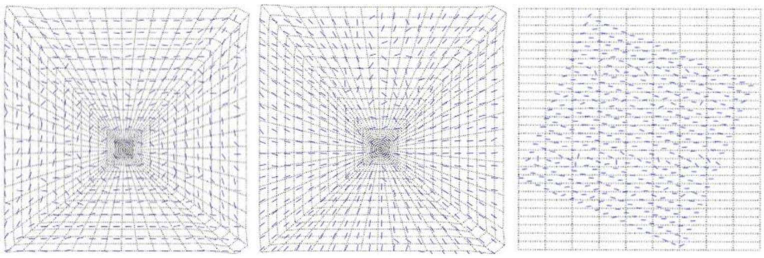

Fig. 2: TFI grids: (a) O-grid aligned with curl OF, (b) O-grid aligned with radial OF, (c) H-grid aligned with parallel OF.

Let $CC_k, k = 1,2,\ldots,N_{CC}$ be a toolpath where N_{CC} is the number of CC points, and F_k is the feed rate between CC_k and CC_{k+1}. The total machining time is then given by [6]:

$$T = \sum_{k=1}^{N_{CC}-1} t_k \;, \tag{4}$$

where $t_k = \dfrac{l_k}{F_k}$ and $l_k = \| CC_{k+1} - CC_k \|$.

Numerical Experiments

The proposed method has been tested against the iso-parametric toolpath, a popular option "follow periphery" of NX 11 (Siemens) [21] (Example 1, Tab. 1), and the space-filling-curves approach (SFC) [1] (Example 2, Tab. 2). The proposed toolpath outperforms the competing methods in terms of the machining time, toolpath length, and number of CC points. The toolpath generation for a synthetic triangular mesh (Example 1) is shown in Fig. 3, the machining time is given in Tab.2.

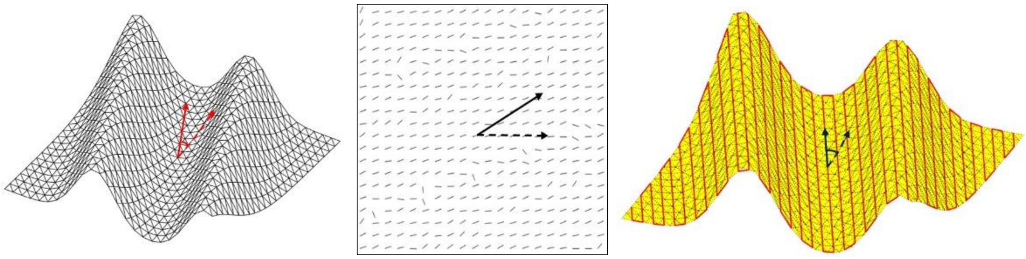

Fig. 3: Example 1. Toolpath for a synthetic triangular mesh (dashed arrow: reference axis, solid arrow: the main OF direction): (a) STL surface, (b) OF, and (c) Toolpath aligned with OF.

Methods	*Scallop height, h = 0.1(mm)*			
	No. of CC points	*Length (mm)*	*Time (s)*	*Advantage in time* (%)
Iso-*u*	4210	$2.55\ 10^4$	467.6	78.31
Iso-*v*	4811	$0.87\ 10^3$	561.9	81.95
NX11	5547	$0.10\ 10^3$	658.9	84.61
Proposed	1963	$0.53\ 10^3$	101.4	-

Tab. 1: Machining time of the synthetic triangular surface.

Fig. 4(a) shows a crown tooth STL surface (Example 2). The OF is given in Fig. 4(b) and the corresponding toolpath generated by the proposed method is shown in Fig. 4(c). Testing against the conventional methods is presented in Tab. 2.

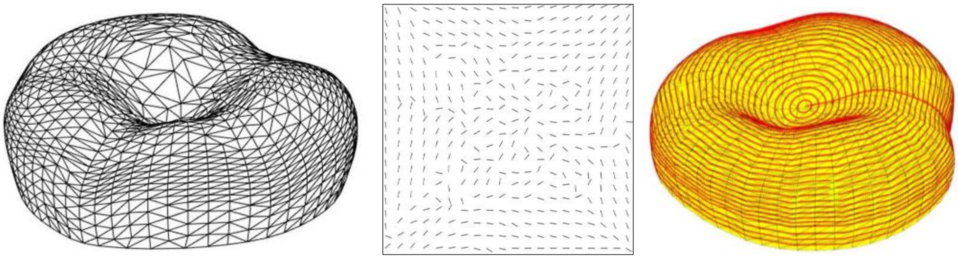

Fig. 4: Example 2. Toolpath for a crown tooth model: (a) STL surface, (b) OF, and (c) Proposed toolpath.

Methods	*Scallop height, h=0.1(mm)*			
	No. of CC points	*Length (mm)*	*Time (s)*	*Advantage in time* (%)
Iso-u	7388	$1.78\ 10^{5}$	4864	60.67
Iso-v	6846	$1.47\ 10^{5}$	4744	59.67
SFC	6085	$1.59\ 10^{5}$	3493	45.23
Proposed	4446	$9.40\ 10^{4}$	1913	-

Tab. 2: Machining time of crown tooth mesh surface.

Conclusions:

This paper offers a novel technique for 5-axis toolpath planning for triangular meshes. The method relies on pattern detection of the vector field of optimal directions using moment invariants and a set of prescribed templates. A suitable toolpath strategy is selected, based on the detected pattern. Numerical experiments show that the proposed method helps to select appropriate toolpath strategies and provides outstanding results, compared to “blind” toolpath generation methods. The proposed method could be integrated into toolpath planning software to support efficient, machine dependent decisions. The method can be generalized to multiple-pattern cases and complex template structures.

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