Title:
Optimal Tool Orientation Generation and Chip Volume/Cutting Force Predictions for 5-axis CNC Machining of Free-form Surfaces Using Flat-end Mills

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Introduction:

5-axis CNC machining is widely used to produce various components with complex curved surfaces while potentially providing better tool accessibility to complex surfaces, producing more accurate surface, increasing material removal rate, and reducing machine setup time [7].

Today, to avoid cutter-part surface interference/gouge at large curvature areas and to simplify toolpath/orientation planning, a small diameter ball-end mill is used during machining [12]. This leads to low machining efficiency and large cusps for areas of the surface with small curvature. Large diameter end cutters present a more rigid and capable tool with a varying cutter curvature from the radius of the cutter to infinity (in principle) to support better cutter-part curvature match, leading to much improved machining efficiency and surface quality [2]. Therefore, it is more beneficial to use flat-end mills for curved surface machining and to plan to tool path and tool orientation with the best curvature match between the cutter and the machined surface at the cutter contact (CC) point. However, flat-end mills cannot easily avoid curvature gouging problems. It is still challenging to tool orientations using a flat-end cutter for sculptured surfaces without gouging generation in 5-axis CNC machining. There are some researches about the gouging avoidance. Du [14] proposes a method to detect and avoid gouging using a fillet-end milling cutter by exact curvature matching between the cutter and part surface. However, an initial inclination angle is required to obtain the minimum principal curvature of the cutter. If the minimum principal curvature of the cutter is less than the maximum principal curvature of the concave surface, the initial angle should be increased to avoid gouges. In this method, the tool needs to be adjusted until gouging is eliminated or reduced to a specified tolerance zone, which results in curvatures that are no longer matched and the effectiveness of the PAM is reduced at the CC point [4]. Rao [10] presents a mathematic method to detect and eliminate local gouging using flat-end tools by calculating curvature of the tool envelope surface. This method is limited to the machined surface and cannot be extended to other types of cutter [3]. The machining configuration space (C-space) which is the tool tilting and inclination parameter areas without gouging generation is used to find optimal tool orientations by different machining constraints [1, 6, 9]. This method considers local, rear, and global gouges in machining [5]. After construction of the C-space, there is an optimization process to select smaller tilt angles and the minimum changes of tool orientations. Although C-space is able to monitor all the possible tool orientations, it requires lots of computing time to reach the optimal solutions. The methods mentioned above can avoid gouges, however, only concave surfaces are considered. For a complex surface with concave, convex and saddle shapes, the machining efficiency cannot be the highest if only considers machining with gouge free. The closest curvature match and the longest cutting edge should also be considered to achieve the maximum machining efficiency and the surface quality.

In this work, an optimal tool orientation based on the combination of the surface normal method for convex surface and Euler-Meusnier Sphere (EMS) method for concave surface without surface gouge has been integrated to achieve maximum machining efficiency and surface quality. The surface normal based cutter orientation planning method is used to obtain the closest curvature match and longest cutting edge; and the EMS method is applied to obtain the closest curvature match and to avoid local gouging by matching the largest cutter Euler-Meusnier sphere with the smallest Euler-Meusnier sphere of the machined surface at each cutter contact (CC) point. For surfaces with saddle shapes, selection of one of these two tool orientation determination methods is based on the direction of the CNC toolpath relative to the change of surface curvature.

After optimal CNC tool paths for the workpiece and the optimal 5-axis tool orientation for every point on the tool path are generated, the remaining machining parameters are the instant cutter feed-rate and cutting depth. The optimal or maximum allowable feed-rate and depth of cut for best productivity is constrained by the no-chatter maximum allowable cutting force. This, in turn, requires the accurate cutting chip volume and force estimates using the geometric model. There exist several methods to represent volumetric models in the NC simulation process, such as the voxel model and dexel model [11]. The dexel model represents an object with a grid of long columns compacted together extending along z-axis direction, while the voxel model consists of many small cubes in a regular lattice [15]. The difference between dexel and voxel model is the object of z-axis. In voxel model, the height of model is divided into many small pieces. For dexel model, the volume along z-axis is continuous without separating into pieces. In this research, instant cutting forces and cutting volume predictions are mainly considered to optimize feed rate and depth of cut to achieve high machining efficiency and surface quality in 5-axis CNC machining using flat-end mills. A Tri-dexel model is applied as a workpiece model defined by many rectangles extending along the z-axis to calculate chip volume and cutting forces. Tri-dexel locations are confirmed by a 2D grid in the xy-plane and physically extend the z-axis of the Tri-dexel coordinate system. Grid points are uniformly distributed along x, y and z axes by distances dx, dy, and dz respectively. The size of each Tri-dexel cube dx, dy, and dz are determined by a user specified tolerance. The higher the tolerance, the more accurate calculation of chip volume and cutting forces there will be. However, high tolerance causes long computing time. To resolve this problem, the regular Tri-dexel mode is improved by slicing the Tri-dexel workpiece into many 2D laminated planes. All Boolean intersections and subtractions are performed on the laminated planes and the plane heights are given by user. In the Tri-dexel model, each slice shares the same height information. It is unnecessary to store the data of height information for every Tri-dexel cell which could save storage memory and generate fast updating workpiece.

<u>Optimal Tool Orientation Generation:</u>

An optimal tool orientation is generated based on the combination of the EMS method and surface normal variable control method. EMS [13] is a method for concave surfaces to avoid local gouging by matching the largest cutter Euler-Meusnier sphere with the smallest Euler-Meusnier sphere of the surface at each cutter contact (CC) point. Surface normal is the most efficient tool orientation approach for convex surfaces, due to the largest Euler-Meusnier sphere is generated at the surface normal direction without generating gouges. Selection of one of these methods in tool orientation determination for saddle shapes is based on the direction of the CNC toolpath in relative to the surface curvature change. In Fig. 1, it can be seen that if the Meusnier sphere of cutter is larger than that of the workpiece, gouge would be generated. The EMS method provides a generic local solution for gouge detection and elimination in sculptured surface machining. For convex shapes, the surface curvature and the tool curvature are opposite, therefore no gouging is generated, and the most efficient cutter orientation is along the surface normal direction with the largest cutting edge.

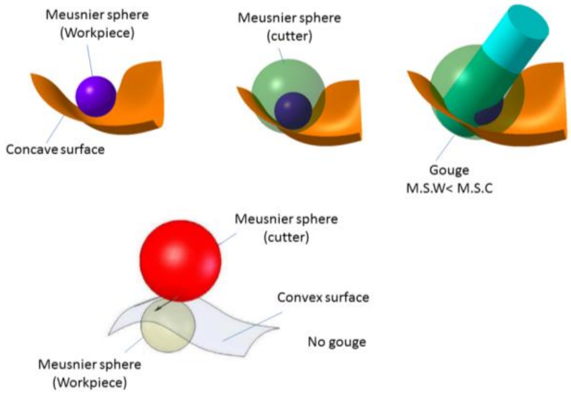

Fig. 1: Machined surfaces and cutter Meusnier sphere.

A NURBS surface is used in the paper to show optimal tool orientations in different surface features. The machined surface is roughly divided into concave, convex, and saddle shapes by Gaussian curvature and mean curvature. The relationship between surface features and curvatures can be seen in the Tab. 1.

Surface features	*Gaussian curvature $C_{Gaussian}$*	*Mean curvature C_{mean}*	*Gouging possibility*	*Tool orientation methods*
Concave	$C_{Gaussian}>0$	$C_{mean}<0$	Certain	EMS
Convex	$C_{Gaussian}>0$	$C_{mean}>0$	Impossible	Surface normal
Saddle	$C_{Gaussian}<0$	$C_{mean}<0/C_{mean}>0$	Uncertain	EMS/Surface normal

Tab. 1: Relationship of surface features, curvatures, gouging and the tool orientation methods.

Fig. 2 (a) shows optimal tool orientations by the combination of the EMS and surface normal methods for a NURBS surface. Saddle points are considered as concave points as the toolpath is along *u* direction. In Fig. 2 (b), black arrows denote new tool orientations. It may be surface normal or the tool axis in the EMS method. Red arrows represent surface normal vectors and blue arrows are the minimal principal curvature directions.

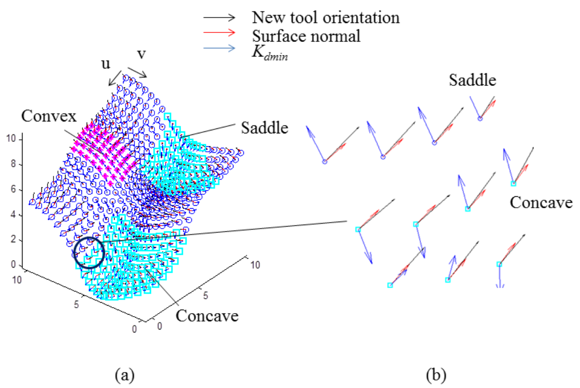

Fig. 2: (a) Optimal tool orientations for the NURBS surface, (b) Display of the new tool orientations, surface normal, and minimal surface curvature directions.

The Tri-dexel Method of Chip Volume and Cutting Force Predictions for Free-form Surfaces:
To reduce the complexity of 3D Boolean subtraction, 2D laminated planes Boolean subtraction is used by combining all planes along z-axis direction. The Tri-dexel model of the workpiece is divided into many layers. The number of layers depends on the depth of cut and the resolution defined by user. On each layer, it consists of m by n grid points. The number of layers is depended on the tolerance defined by user. Chip volume and cutting forces are relative to chip thickness, obtained by moving the tool along a distance of feed per tooth. To simulate the machining process and find chip thickness, a layer of the workpiece is used to display the generation of chip thickness and the Boolean subtraction. The projection of a flat-end mill on a plane is an ellipse. The ellipse is relative to two neighboring NC points, which are denoted by (x_{i-1}, y_{i-1}, z_{i-1}, α_{i-1}, β_{i-1}) and (x_i, y_i, z_i, α_i, β_i). x, y, z are coordinates of the tool, α and β are two rotational angles. The equations of the ellipse at the i^{th} NC point can be obtained from [8]:

$$X_{iellipse} = r\cos\theta\cos\beta_i - r\sin\theta\sin\beta_i\cos\alpha_i + \sin\beta_i\sin\alpha_i\frac{h_i - r\sin\theta\sin\alpha_i - \triangle z_i}{\cos\alpha_i} + \triangle x_i \tag{1}$$

$$Y_{iellipse} = r\cos\theta\sin\beta_i + r\sin\theta\cos\beta_i\cos\alpha_i - \cos\beta_i\sin\alpha_i\frac{h_i - r\sin\theta\sin\alpha_i - \triangle z_i}{\cos\alpha_i} + \triangle y_i \tag{2}$$

$$Z_{iellipse} = |h_i| \qquad (Z_{\min} \le h_i \le 0) \tag{3}$$

where, r is the tool radius, θ is the immersion angle, α_i is lead angle, β_i is tilt angle, hi is height of the plane, Δx_i and Δy_i are translation steps along x and y axes at the ith NC point.

The simulation of cutting process is equivalent to the Boolean subtraction of tool volumes from the machined workpiece. Fig. 3 shows chip thickness generation and the 2D Boolean subtraction. As the tool moves from the previous position P_0 to current position P_1, new intersections of the Tri-dexel workpiece and current tool's boundary are found and stored in the current list. They are denoted by C_1, C_2 ... C_j, j is the number of intersections. Line segments which run from the current tool centre to the points from current list are connected to get the intersections with the previous tool edge. These intersections are stored in the previous list, denoted by P_1, P_2…P_j. From here, a polyline arc-shape along the tool edge is generated by connecting intersections in the previous and current lists. The polyline arc-shape is regarded as the chip area on each slice. It can be calculated by adding all areas of small polygons, such as the polygon $C_1C_2P_1P_2$ show in Fig. 3. As the polygons are very small, they can be considered as rectangles to calculate the area.

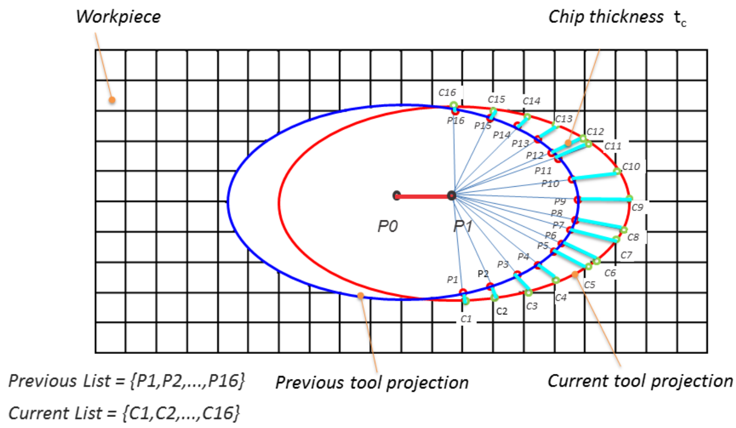

Fig. 3: Boolean subtraction and chip thickness generation in the Tri-dexel workpiece.

Lines connected by points from current and previous lists are chip thickness, denoted by C_j P_j in Fig. 3. Chip thickness can be obtained once the intersections of the workpiece and current and previous tool edges are confirmed. Let (x_{cj}, y_{cj}, z_{cj}) be the coordinates at the current tool projection point C_i; (x_{pj}, y_{pj}, z_{pj})

represents the coordinates of the previous tool projection point P_j. The chip thickness t_j in the 3D Euclidean space is:

$$t_j = \sqrt{(x_{cj} - x_{pj})^2 + (y_{cj} - y_{pj})^2 + (z_{cj} - z_{pj})^2} \quad (4)$$

Fig. 4 shows the same method can be used to get chip thickness on different layers of a chip shape. The chip volume and cutting force calculation can be calculated by the chip thickness.

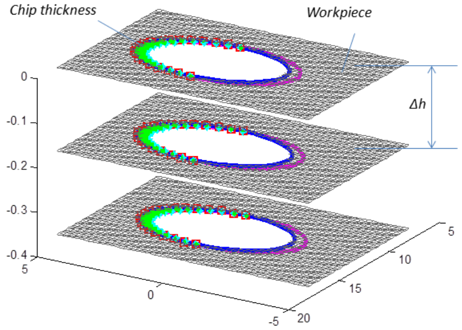

Fig. 4: Chip thickness on the Tri-dexel workpiece.

Summary:
An optimal tool orientation method by the combination of the Euler-Meusnier Sphere (EMS) method and the surface normal variable control method is proposed to avoid gouges and improve machining efficiency in a 5-axis CNC machine using a flat-end mill. A Tri-dexel workpiece model is generated to predict removal material volume and cutting forces by updating the machined workpiece and subtracting the cutter-workpiece engagement zone. The 3D Tri-dexel workpiece is sliced into many 2D laminated layers to reduce the complexity of 3D Boolean operations. On each slice, the instantaneous chip thickness is determined by the intersections of the tool cutting edge and the workpiece line segments. Simulations of cutting forces and chip volume for 5-axis CNC machining will be carried out by the Tri-dexel workpiece method. A validation experiment in controlled cutting conditions will be conducted to verify the simulation results.

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References

[1] Chiou, C. J.; Lee, Y. S.: A shape-generating approach for multi-axis machining G-buffer models, Computer-Aided Design, 31(12), 1999, 761-776.http://dx.doi.org/http://dx.doi.org/10.1016/S0010-4485(99)00069-X.
[2] Fard, M. J. B.; Feng, H. Y.: Effect of tool tilt angle on machining strip width in five-axis flat-end milling of free-form surfaces, International Journal of Advanced Manufacturing Technology, 44(3-4), 2009, 211-222.http://dx.doi.org/10.1007/s00170-008-1828-3.
[3] Gong, H.; Cao, L.-X.; Liu, J.: Second order approximation of tool envelope surface for 5-axis machining with single point contact, Computer-Aided Design, 40(5), 2008, 604-615.http://dx.doi.org/10.1016/j.cad.2008.02.003.

[4] Hosseinkhani, Y.; Akbari, J.; Vafaeesefat, A.: Penetration-limination method for five-axis CNC machining of sculptured surfaces, International Journal of Machine Tools & Manufacture, 47(10), 2007, 1625-1635.http://dx.doi.org/10.1016/j.ijmachtools.2006.11.002.

[5] Jun, C. S.; Cha, K.; Lee, Y. S.: Optimizing tool orientations for 5-axis machining by configuration-space search method, Computer-Aided Design, 35(6), 2003, 549-566.http://dx.doi.org/10.1016/s0010-4485(02)00077-5.

[6] Li, S. X.; Jerard, R. B.: 5-axis machining of sculptured surfaces with a flat-end cutter, Computer-Aided Design, 26(3), 1994, 165-178.http://dx.doi.org/http://dx.doi.org/10.1016/0010-4485(94)90040-X.

[7] Lin, T.; Lee, J. W.; Bohez, E. L. J.: A new accurate curvature matching and optimal tool based five-axis machining algorithm, Journal of Mechanical Science and Technology, 23(10), 2009, 2624-2634.http://dx.doi.org/10.1007/s12206-009-0724-6.

[8] Luo, S.; Dong, Z.; Jun, M. B. G.: Chip volume calculation and simulation in 5-axis CNC machining with flat-end mill, in Virtual Machining Process Technology conference, 2015.

[9] Olling, G., et al., Five-axis Control Sculptured Surface Machining Using Conicoid End Mill, in Machining Impossible Shapes. 1999, Springer US. p. 366-375.

[10] Rao, A.; Sarma, R.: On local gouging in five-axis sculptured surface machining using flat-end tools, Computer aided design, 32(2000), 2000, 409–420.

[11] Ren, Y.; Lai-Yuen, S. K.; Lee, Y.-S.: Virtual prototyping and manufacturing planning by using tri-dexel models and haptic force feedback, Virtual and Physical Prototyping, 1(1), 2006, 3-18.http://dx.doi.org/10.1080/17452750500283590.

[12] Wang, Y. J., Curvature Gouge Detection and Prevention in 5-axis CNC Machining 2007.

[13] Wang, Y. J.; Dong, Z.; Vickers, G. W.: Euler-Meusnier Sphere Based Milling Cutter Model for Curvature Gouge Avoidance in Curved Surface Machining, Society of Manufacturing Engineers, 2008, 1-9.

[14] Weinert, K., et al.: Swept volume generation for the simulation of machining processes, International Journal of Machine Tools and Manufacture, 44(6), 2004, 617-628.http://dx.doi.org/http://dx.doi.org/10.1016/j.ijmachtools.2003.12.003.

[15] Zhu, W.; Lee, Y.-S.: Dexel-based force-torque rendering and volume updating for 5-DOF haptic product prototyping and virtual sculpting, Computers in Industry, 55(2), 2004, 125-145.http://dx.doi.org/http://dx.doi.org/10.1016/j.compind.2004.07.003.