

Tool path generation for sculptured surfaces with 4-axis machining

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Abstract. Sculpted surfaces are widely used in engineering applications in industries like aerospace, automotive and medical. Commonly, these types of surfaces are manufactured by the process of 5-axis CNC machining. 5-axis machining improves the effectiveness and reduction in machining times compared to the 3-axis process, but also increases the complexity of the operations. This paper presents a four-axis toolpath generation gouging free methodology as an alternative to the five-axis machining to reduce the complexity of the process, maintaining similar benefits respect to conventional three-axis machining. Rolling ball method is first applied to compute the most suitable tool for the surface and prevent gouging. A process procedure is the carried out to optimize the tool fixed position and compute tool location at each cutter contact point of the surface. The results show the effectiveness of the method in terms of reducing machining time and maintaining similar surface finishing compared with three-axis machining. The method can be used as a cost-effective option for multi-axis machining.

1 Introduction

Freeform surfaces, also called sculptured surfaces are commonly used to produce components in aerospace, automotive and medical industry [1]–[3]. These surfaces are designed to meet aesthetic or functional requirements and are usually produced using 3- and 5-axis machining. In 5-axis machining, the tool orientation can be adapted at each contact point to have a better approximation of the surface geometry leaving small cusps of the desired surface [4]. In comparison, 3-axis machining tests are usually produced using ball-nose end mill cutters, where significant longer tool paths in comparison to 5-axis machining are required to achieve the desired shape and satisfy the requirements of tolerance. Despite the advantages of 5-axis machining, this technology still presents some drawbacks that require additional considerations due to the complexity of the system to calculate appropriate tool machining parameters at each point and to prevent gouging and collisions.

Previous research has been focused to solve the drawbacks of 5-axis machining to increase the effectiveness of the technology and gouging prevention [5]. Gray et al. [6] combined the best features of principal axis method and multi-point method to develop a simple method to reduce time computation of tool positioning and avoiding gouge correction call rolling ball method (RBM). Roman et al. [7] extended the application of the RBM to generate tool path planning and tool orientation strategies for 3+2-axis machining. These methodologies use local geometry data to determine the tool position and tool orientation along the path for each surface partitioning, reducing gouging possibilities. Wang [8] presented a 3D

method for gouge detection and elimination with the curvature match in 5-axis machining. The *Euler-Meusnier Spheres* concept is the basis for this method. Gouge detection and elimination helps to find an optimal cutter size and tool orientation. Fard et al. [9] introduced two new principles for tool orientation quality. Different to other methods that used the criteria of curvature matching, to optimize tool orientation, infinitesimal machining volume (IMV) and infinitesimal machining area (IMA) are presented to increase material removal and reducing tool path length. Liu et al. [2] implemented configuration space method for efficient tool positioning with emphasis in local gouging avoidance using a flat-end mill and torus mill for point clouds.

Several studies for tool path planning exists for 3 and 5-axis machining [10], in many cases they cannot be directly applied to 4-axis machining, which may be suitable for specific applications or as a transitional path into multi-axis machining. The purpose of this paper is to present the methodology developed for the implementation of the 4-axis machining for freeform surfaces using a 3-axis vertical machining center. The considerations for this work include tool selection, tool orientation, and tool path generation, as well as gouging prevention.

2 Methodology

The following section describes step by step the methodology applied to 4-axis machining.

2.1 Parametric surface

The work starts with the definition of a surface to get the parameters for its analysis used in the upcoming steps of the methodology. In this study, the freeform surface is represented by an algebraic equation (1), where x run from 0 to 100 and y runs from 0 to 40 as shown in Figure 1.

$$z = 50 - 40(x/60)e^{[(x/60)^2 - (y/30)^2]} \quad (1)$$

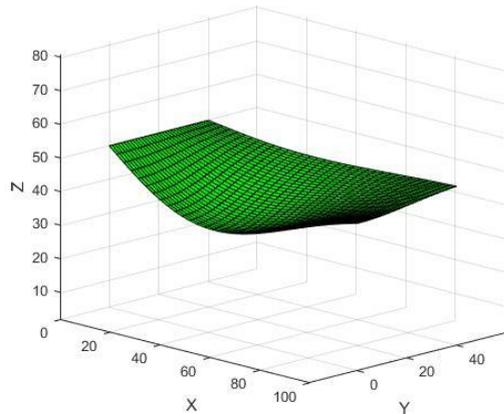


Figure 1. Algebraic surface representation

Once the surface is defined, the surface coordinates and unit normal vectors are computed, the former is necessary for calculations of tool position while the latter is required for tool orientation. Surface coordinates are defined as a certain number of sample points defined by the user. These sample points serve as the cutter contact points (CCP).

2.2 Rolling ball method

This method consists in rolling a variable radius ball along every Cutter Contact Point (CCP) and place the tool inside the ball to obtain the radius in the most concave region to select the optimal radius of the tool, which guarantees that the surface is free of gouging. This method only requires the surface coordinates and normal points that are extracted from the parametric surface and can be easily calculated from other types of free-form surfaces.

The critical point of this method is to compute the radius of the ball, defined in equation (2). First, a grid of concentric circles around the CCP called the shadow-checking area is calculated (Figure 2-c). The shadow area is divided into five circles with 100 data points each one.

$$\rho = \frac{-\vec{E} \cdot \vec{E}}{2x \hat{n} \cdot \vec{E}} \quad (2)$$

Where ρ is the pseudo-curvature radius, \vec{E} is the shadow checking – CCP, \hat{n} is the surface normal at CCP and ρ is the pseudo-radius of curvature.

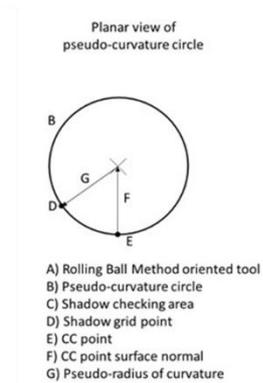
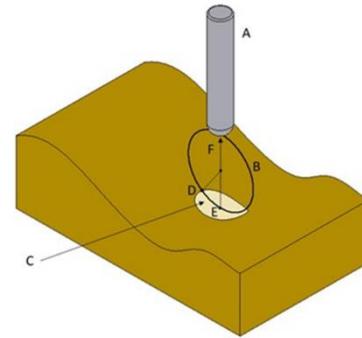


Figure 2. Rolling ball method. Adapted from [5]

2.3 Tool orientation and positioning

After selection of the optimal tool radius, tool orientation and positioning are computed to adapt the 4th axis. Figure 3 shows the algorithm followed for the computation in this step.

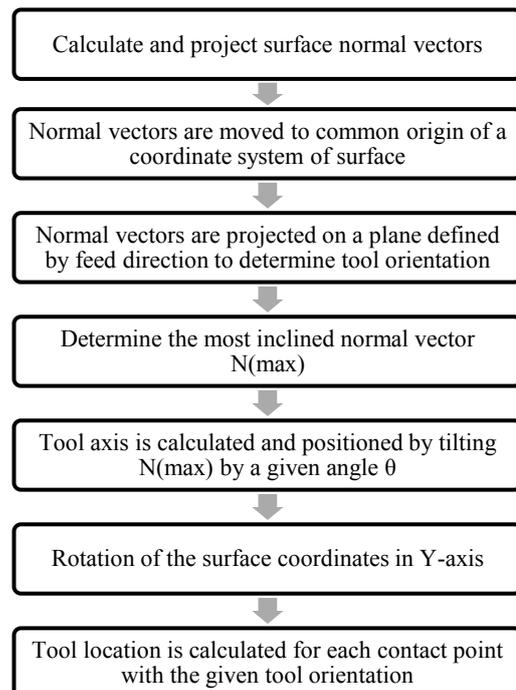


Figure 3. Algorithm for tool orientation and positioning

As shown in Figure 4, the normal unit vectors are projected on a plane following the feed direction in X-axis and moved to the origin. The two extreme vectors N_{max} and N_{min} and both angles are calculated with respect to N_{center} , the vector with the minor angle is selected to give the orientation with equation (3).

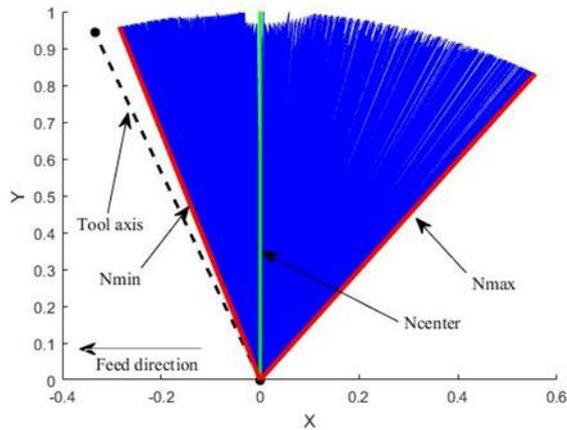


Figure 4. Projected unit normal vectors

$$T = \frac{N}{|N|} * \cos(\theta) - \frac{(N \times F) \times N}{|(N \times F) \times N|} * \sin(\theta) \quad (3)$$

Where θ is set with a value of 3° to give safety position, N is the unit normal vector and F is the feed direction. To apply the concept of 4-axis machining, the surface is rotated with respect to the Y-axis for a tool fixed position (Figure 5). The method to achieve this is using transformation equations at each contact point with an angle calculated from tool axis orientation and N_{center} . New surface contact points are given by equation (4):

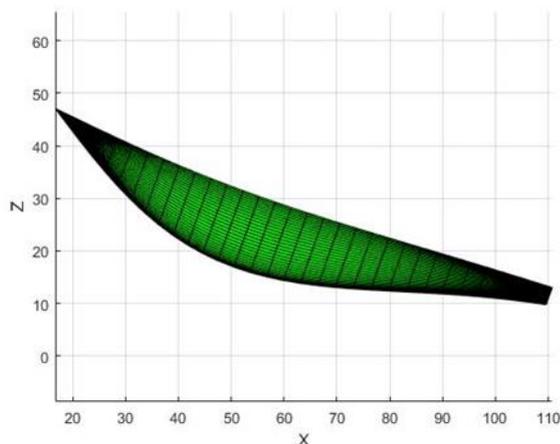


Figure 5. Surface rotation about Y-axis

$$\begin{bmatrix} x^* \\ y^* \\ z^* \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (4)$$

Where θ is the angle of the tool axis with respect to the N_{center} shown in Figure 4. Once the tool orientation is calculated, tool position is computed for each CCP, this is given by equation (5). This refers to the location of the bottom of the center of the tool at each CCP. The equation

used is for toroidal shape tool, this is convenient because it can be modelled both ball nose and flat endmill.

$$TL = ccp + R_2N + \frac{N-(N \cdot T) \cdot T}{|N-(N \cdot T) \cdot T|} * R_1 \quad (5)$$

Where R_1 is the tool radius and R_2 is the radius of the insert, and T is the tool axis orientation.

2.4 Tool path generation

The final step is to select the topology of the tool, this refers to the way the tool is moved along the entire surface. For this work, a parallel direction was implemented following a zig-zag displacement, this is one of the most commonly used in machining operations.

One parameter to consider is the sidestep distance between each pass, equation (6) and equation (7) are used for this purpose.

$$effective_radius = \frac{R}{\sin \phi} + R_{insert} \quad (6)$$

$$side_step = \frac{2(2(effective_radius)(scallop_height))^{1/2}}{\quad} \quad (7)$$

Figure 6 shows the result with all the calculations for tool orientation and the tool path generated for the surface. The dotted line in blue represents the trajectory of the tool using the coordinates of the center of the tool, not the contact point between the tool and the surface.

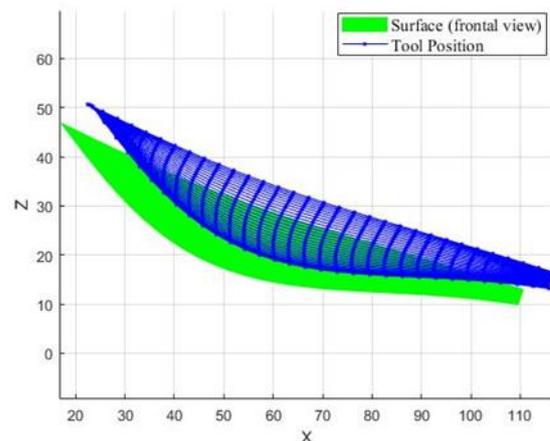


Figure 6. Tool path generated for 4-axis machining

3 Application and results

The computation of all the methodology was conducted using MATLAB® software. The script created was implemented in a notebook (Intel Core i5, 2.5 GHz CPU, 8GB of RAM) operating under Microsoft Windows 10 system. The main outputs of the script are the surface coordinates with their tool orientation, and the radius of the tool.

Machining tests were conducted in the 3-axis vertical center Haas MiniMill, and a tilting vise was adapted and

fixed in the machine for the 4-axis tests as shown in Figure 7. Two flutes 12 mm diameter carbide ball nose tools were used for the test in 3-axis and 12 mm diameter and 1.5 mm corner radius toroidal shape for the 4-axis test, the radius of the tools is obtained from RBM. The tests were made in Aluminum 7075 both with feed speed of 1900 mm/min and 4800 rev/min spindle speed.

Comparison of the results of the machining tests are shown in Table 1. The machining time was obtained when the tool does the first contact with the surface until the final contact with the surface occurs. The results showed substantial saving of 25% approximately in machining time and tool path length when the 4-axis method is applied.

Table 1. Comparison of 3 and 4-axis methods

Method	R ₁ (mm)	R ₂ (mm)	Angle of rotation (°)	Tool path length (mm)	Machining time (min)
3 axis	6	---	---	5928	3.12
4 axis	6	1.5	19	4408	2.32



Figure 7. Set up of the workpiece and rotary tilting vise

Measurement of the surface tolerance tests were conducted after the machining experiments for validation purposes. The measurements were conducted on Alicona Infinite Focus machine. This optical system allowed conducting surface roughness measurement tests to verify that the scallop height between the tolerance bounds is below 0.0254 mm. Surface roughness *Rz* value was obtained following ISO 4288 and compared with the tolerance established before. Five representative points of the surface, shown in Figure 8, were measured to get an average value. Table 2 shows the results of the values at each point of the surface. As can be observed in the table, the value of *Rz* in each point is below of the value of tolerance 0.0254 mm.

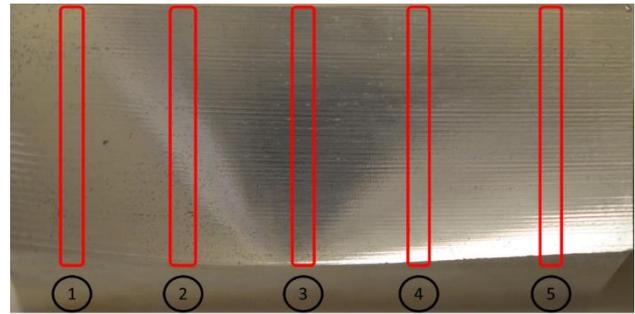


Figure 8. Representative points of surface roughness evaluation

Table 2. Representative points of surface roughness evaluation

	3-axis	4-axis
Point	Rz (μm)	Rz (μm)
1	16.2	19.01
2	21.7	18.43
3	22.09	22.65
4	18.04	19.25
5	18.03	18.11
Average	19.212	19.49

4 Conclusion

This work presents a novel methodology to conduct 4-axis machining using 3-axis equipment. This strategy was tested on a freeform surface and was validated using measurement. The methodology proposed is simple and easy to implement in a 3-axis machine and includes considerations to prevent gouging.

The approach implemented in this work shows that 4-axis machining can be a cost-effective option for multi-axis machining, the simplicity of the method helps to reduce the complexity found in simultaneous 5-axis machining due the final tool path works with movements as those found in 3-axis machining. Considering optimal tool diameter and tool orientation, the results show savings in time machining and shorter tool path lengths in the proposed surfaces compared to traditional 3-axis machining.

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