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A new accurate curvature matching and optimal tool based five-axis machining algorithm †

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Abstract

Free-form surfaces are widely used in CAD systems to describe the part surface. Today, the most advanced machining of free from surfaces is done in five-axis machining using a flat end mill cutter. However, five-axis machining requires complex algorithms for gouging avoidance, collision detection and powerful computer-aided manufacturing (CAM) systems to support various operations. An accurate and efficient method is proposed for five-axis CNC machining of free-form surfaces. The proposed algorithm selects the best tool and plans the toolpath autonomously using curvature matching and integrated inverse kinematics of the machine tool. The new algorithm uses the real cutter contact toolpath generated by the inverse kinematics and not the linearized piecewise real cutter location toolpath.

Keywords: Five-axis NC machining; Curvature analysis; Toolpath planning; Tool selection

1. Introduction

Free-form surface parts are widely used in the aerospace, automobile, ship-building and mold/die manufacturing industries. CNC (computer numerical control) machining of free form surfaces is an important research topic [1, 2]. The ever increasing complexity of free-form parts makes the benefits of five-axis milling continuously grow by changing three-axis to five-axis milling. The whole sculptured surface milling process using three-axis NC and ball end mill is inefficient as noted by [3]. Due to the two additional degrees of freedom, five-axis NC machining offers many advantages over three-axis, such as better tool accessibility, faster material removal rates, reduced machining time and improved surface finish. However, collisions are prone to occur in five-axis machining. Collision problems in five-axis NC machining can be classified into two types: local and global collision. Local collision, one of the most critical problems in free-form surface machining refers to the removal of the excess material in the vicinity of the cutter contact (CC) point due to the mismatch in curvature between the tool swept surface and the part surface at the CC point. It results when a high curvature surface is machined using larger tool diameter or by a tool improperly oriented as shown in Fig. 1.Global collision refers to the accidental contacts (i) between the surface of the tool (or tool holder) and workpiece (or machine components), (ii) between workpiece and machine components), or (iii) between the moving machine components. Free form surfaces usually have irregular curvature distribution, which causes difficulty in machining. Machining of free-form surfaces requires the assistance of sophisticated CAD/CAM software to assist the numerical control (NC) programmer in the optimal cutter orientation and selection of cutter size. Manual planning and programming for sculptured surface machining is known to be error-prone and inefficient. The free

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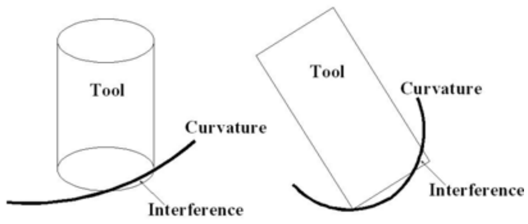

Fig. 1. Local Tool Interference.

form surface machining with more than three degrees of freedom needs high end commercial CAD/CAM system for the cutter location (CL) and orientation data [4].

Milling the surface is divided into three phases: roughing, semi-roughing and finishing. Careful planning is required to determine the five-axis toolpath for the finish machining of sculptured surfaces. In the finishing process of five-axis machining for free-form surface, there are drawbacks, such as complex tool movements, tool interference and tool undercut problem.

Thus it is necessary to find a method to select the optimal cutter size and tool orientation for the selected toolpath (i.e., spiral, zigzag, zig). Five-axis machining requires consideration of tool orientation, tool size, optimizing tool paths, avoiding interferences, and improving the metal removal rate. If the undercut and overcut material left by the finish machining operation are controlled, then the amount of grinding and polishing can be reduced or eliminated.

The objective of this paper is to develop an integrated automatic toolpath generation algorithm based on curvature matching for obtaining higher metal removal rate and surface finish using the best tool cutter size and optimal inclination angles (λ, ω). A new integrated automatic toolpath generation algorithm has been implemented in Mathematica®. A virtual Maho-600e five-axis CNC machine which is implemented in VeriCut® is used for virtual cutting. Unlike the traditional graphical verification and user-interactive correction of toolpath generation, the proposed algorithm selects the best tool and plans the toolpath autonomously based on curvature matching for free-form surfaces. The inverse kinematics of the machine tool is integrated in the toolpath computation.

The paper is organized as follows. A review of related work is presented in Section 2. Section 3 presents curvature matching and optimal tool based five-axis machining and an integrated automatic toolpath generation algorithm. The proposed algorithm followed by an example is presented in Section 4 and the last section is the conclusion.

2. Literature review

The CAD/CAM technologies for five-axis machining complex parts such as turbine blades or impellers are investigated in [5-7]. The commercial CAD/CAM systems have well developed ball end machining capacities. Ball end machining is widely used in sculptured surface machining. When using a flat end mill to machine a free-form surface, the conventional practice has been fix the inclination angle of the tool relative to the surface. This machining process is referred to as a Sturz milling method used in [8]. The tool is inclined at a fixed angle from the surface normal as the cutter moves along the surface of the part. In industry, a typical inclination angle between 5° and 15° is chosen to minimize the local gouging. The problem for this method is that the local gouging may occur when the cutter is not inclined far enough from the surface.

A manufactured part is produced by an NC program containing a series of coded instructions called NC code that directly affects the accuracy and cost of manufactured parts. In the aerospace industry, it takes tens or even hundreds of hours to machine a free-form surface part from a solid block in preparing detailed operation plans and NC part programs for sculpture surface machining. It is difficult for human planners to select the optimal machining strategies due to complex interactions among tools size, part shapes, and tool trajectories [9].

Today, many commercially available CAM softwares for five-axis machining such as Mastercam, UGS NX, CATIA, Delcam's PowerMILL and Open Mind's hyperMILL, provide gouge detection and correction. However, an intensive user interaction is still needed while using this software to avoid collisions. These CAM systems are unable to accomplish the collision avoidance autonomously [10].

A new five-axis cutter orientation algorithm is proposed based on curvature matching between the cutter and local machined surface regions by applying differential geometry techniques [11, 12]. A technique is developed to determine the flat-end cutter orientation based on slope and curvature matching for five-axis machining [12, 13]. The curvature radius is considered as a function of both inclination and tilt angles, and the curvatures are similarly compared to detect local gouging.

An automatic tool selection method developed by [14] has been implemented using C-language on the existing ROBLINE system. A cutter selection algorithm for fillet-end cutters is based on curvature matching machining, in which local-gouging, rear-gouging, and global-collision are considered. A multi-axis tool path generation algorithm is described in [15] where tool orientation is adapted to avoid machine collisions and to increase material removal. The developed modules are integrated within an existing CAM system. Although references [14] and [15] provide an algorithm for curvature matching, it is highly inaccurate because the linearized tool path is used. The correct way to compute the real tool path is discussed in detail in [16].

Many of the above methods are based on curvature matching in only one direction. In this paper, an accurate and efficient method is proposed for five-axis CNC machining of free-form surfaces. A new algorithm proposed in this study selects the best tool and plans the toolpath autonomously using curvature matching and integrated inverse kinematics of the machine tool. With regard to the local gouging avoidance, curvature matching techniques are employed such that the two curvature radii of the effective tool cutting shape, one along the feeding direction and another one perpendicular to the feeding direction, are smaller than those of the corresponding curves on the free-form surface.

3. Curvature matching and optimal tool based five-axis machining

Free-form surfaces usually have irregular curvature distribution, which causes difficulty in machining. To mill a surface, the CAD/CAM system moves the cutter along a number of curves, usually iso-parametric curves or projection curves on the surfaces. Scallops are produced between the successive tracks machined on the surface. The term “scallop” refers to ridges, cusps and other surface protrusions left between adjacent overlapping tool passes that extend above a design surface profile. It depends on the type of cutting tool, tool size, tool orientation and the distance between the cutter paths.

The ability to classify the sculptured surfaces into different regions can be applied to determine the optimal tools in free-form surface machining. If the surface is locally convex, the cutter may be oriented with its axis in the direction of surface normal without gouging. If the surface is locally concave or saddle, gouging will occur. It is required to orient the tool by using curvature matching. The local surface shape around the point can be divided into convex, concave and saddle. Surface curvature plays a key role in selecting a cutter size and orientation angles (λ, ω) (See Fig. 2) to avoid gouging. In five-axis machining with a flat-end milling cutter, the tool axis orientations can be adjusted to avoid gouging. Gouging is the main problem in finishing a free-form surface. Finishing removes the final layers of material to obtain a surface with a certain distance. Cutter interference has to be controlled. Cutter interference may occur when the free-form surface has high curvature. Traditionally, the orientation of the flat end mill has remained fixed (being set to an angle that ranges from 5 to 15 degrees of the principal spindle axis) during tool motion. The traditional fixed-orientation practice cannot effectively prevent gouging problems during toolpath planning.

Ball end mills have been widely used in curved-surface machining because historically these have been easy to position with three-axis machines and require simple cutter compensation. However, compared to the flat end-mill, the ball end mill produces poor geometry matching between cutter and surface and has zero cutting speed at the axis of rotation. Fig. 2 shows the terminology in five-axis machining with a flat end mill tool.

A local coordinate system and tool coordinate system are defined to analyze the cutting operation. The tool coordinate system should have the axis XL tangent to the real CC tool path (XL, YL and ZL form a Frenet system) shown in Fig. 2. The tool coordinate system X_t, Y_t, Z_t passes through the CC point and the tool center line. Fig. 3 shows the error when the linear approximate toolpath (along $X_L^{'}$ axis) is used instead of the real curved CC toolpath (along X_L axis).

Several researchers have developed techniques to avoid local gouging by calculating the effective cutting curvature of the tool swept surface and comparing it to the normal curvature of the surface at the CC point [17-23]. The traditional steps adopted to detect and avoid local gouging are (1) determining the effective cutting shape E (θ) (referred to as a tool swept section); and comparing the curvature of the effective cutting shape (referred to effective cutting curvature) the normal curvature of the surface in the plane of tool swept section. Changing tool orientation affects the effective cutting shape E (θ) as shown in Fig. 4.

The effective cutting radius on the XY plane and ZY plane of cutter with tool orientation can be determined by using Eqs. (1) and (2). To avoid gouging, the effective radius $R_{eff,XL}$ and $R_{eff,ZL}$ in X_L and Z_L directions should be no larger than the radius of the local surface curvature.

$$R_{eff,XL} = g1(r, \lambda_L, \omega_L) = \frac{r(\cos\omega_L)^2}{\sin\lambda_L} \tag{1}$$

$$R_{eff,ZL} = g2(r, \lambda_L, \omega_L) = \frac{r(\sin\omega_L)^2}{\sin\lambda_L} \tag{2}$$

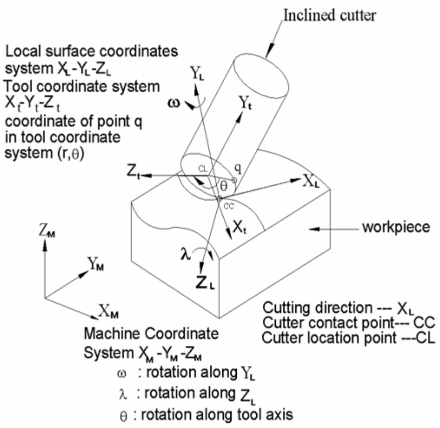

Fig. 2. Inclined tool by rotating along Y_L and Z_L.

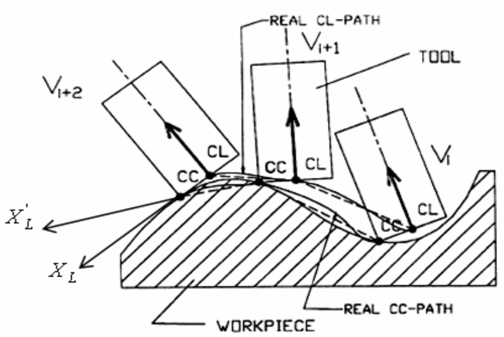

Fig. 3. Convex/Concave Part- CC and CL points.

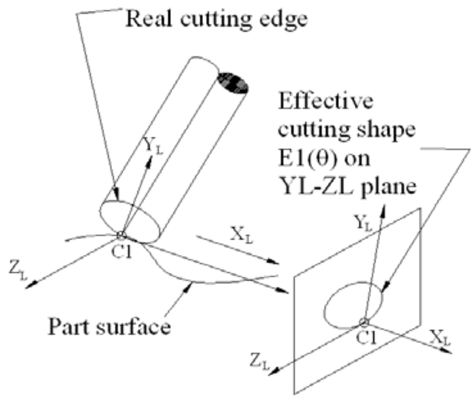

Fig. 4. Effective cutting shape.

Fig. 5 shows a flow chart for integrated automatic toolpath generation algorithm which is implemented in Mathematica® [24].

In this study, surface curvature information is first evaluated to determine the optimal tool diameter size and orientation angles (λ, ω) which are based on the curvature matching. The inverse kinematics of the machine tool is integrated in the toolpath computation. For the CL data generated by this method it is assumed that the tool path between two CL points is a straight line relative to the workpiece. The solid curved lines in Fig. 3 show the real CL and CC point patch. In five-axis machining the real toolpath between two CL-points is not linear but curved.

3.1 Finding optimal tool orientation

In programming for five-axis machining, it is common to predefine the cutter orientation (λ, ω) as gouging is affecting the machining accuracy. In this section, the surface curvature is used to calculate the cutter orientation by matching curvature in X_L and Z_L direction. To avoid local gouging, it must be ensured that the effective cutting curvature (also referred to as the curvature of effective cutting shape) is not less than the effective surface curvature.

3.1.1 Finding tool inclination angle (λ)

In five-axis machining, it is easier to define the tool orientation based on the local surface property than that based on the machine global coordinate system. A local coordinate system is defined to analyze the cutting operation. Fig. 2 shows the local coordinate system, inclination angle and tilt angle represented by X_L, Y_L and Z_L axes.

The minimum tool inclination angle λ_L can be defined by avoiding over cutting on both the ZY plane and XY plane. Initially, tilt angle ω_L is set to be 0. As shown in Fig. 6, if the curvature K_{XL} on XY plane is non-positive ($K_{XL} \leq 0$), which means the surface is convex or saddle, the tool inclination angle λ_L is set to a small default angle. If the surface is concave ($K_{XL} \geq$

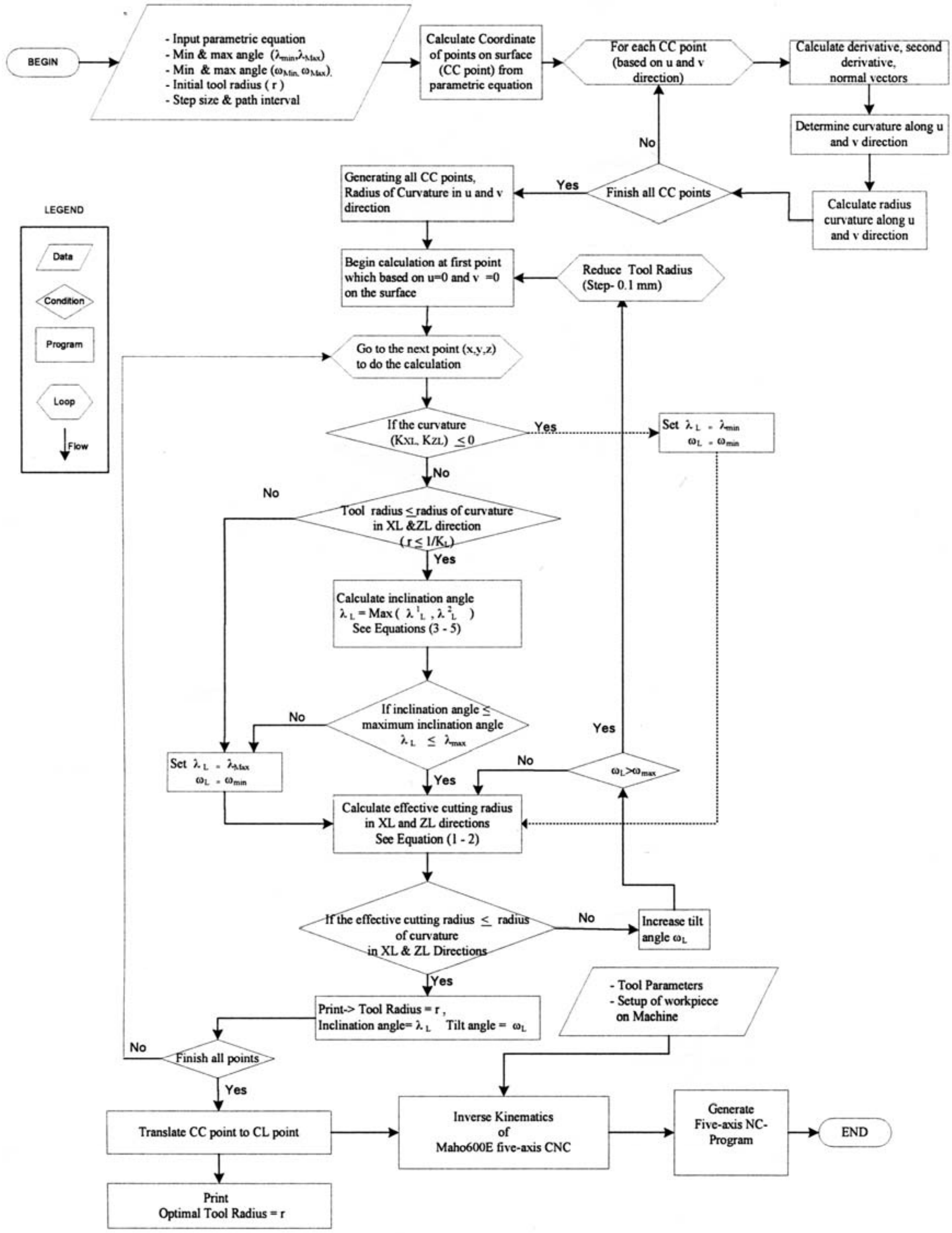

Fig. 5. A flow chart for integrated automatic toolpath generation algorithm.

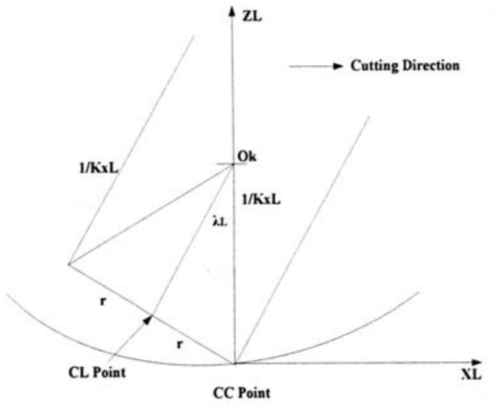

Fig. 6. The inclination angle λ_L in ZL –XL.

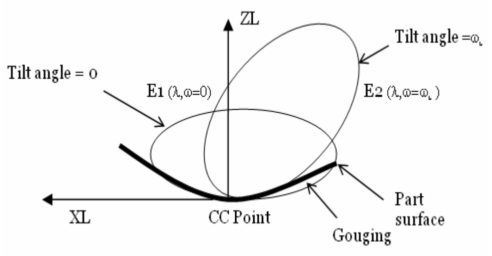

Fig. 7. Adjust tilt angle ω_L to avoid local gouging (Cutting direction out from the paper).

0), the tool inclination angle λ_L to avoid over cutting on the XY plane can be calculated by using Eq. (3) according to the local surface curvature K_{XL}.

$$\lambda_L^1 = \sin^{-1}\left[\frac{r}{\rho_{XL}}\right] \quad \text{if } r \le \rho_{XL} \text{ and } K_{XL} > 0 \tag{3}$$

To avoid gouging on the YL – ZL plane, the inclination angle λ_L is calculated by Eq. (4).

$$\lambda_L^2 = \sin^{-1}\left[\frac{r}{\rho_{ZL}}\right] \quad \text{if } r \le \rho_{ZL} \text{ and } K_{ZL} > 0 \tag{4}$$

The minimum tool inclination angle λ_L is determined with equation (5) below.

$$\lambda_L = Max[\lambda_L^1, \lambda_L^2] \tag{5}$$

λ_L is selected by using Eq. (3), (4) and (5). To get a real solution of λ_L, the radius should be no larger than the radius of curvature ($r \le \rho$). If the cutter size r is larger than the local radius of curvature, searching for a new tilt angle ω_L is needed to ensure the effective cutting radius $R_{eff} < \rho$ along both the X_L and Z_L direction.

3.1.2 Finding tilt angle (ω)

The tilt angle ω_L is initially set to the minimum value of the tilt angle. If the surface is convex or saddle ($K_{XL} \le 0$), there is no need tilt the tool ($\omega_L = 0$). As shown in Fig. 7, local gouging occurs when the cutter (E1) over cuts the adjacent surface. The cutter can be tilted with a tilt angle (ω_L) to avoid gouging as E2. If the inclination angle λ_L found in equation (5) exceeds the limit ($\lambda_L > \lambda_{Limit}$), the inclination angle λ_L is set to λ_{Limit}. The new tilt angle can be determined by using Eq. (6) (7).This new tilt angle in (6) and (7) has to make the effective radius smaller than the radius of curvature in both XY and ZY directions.

$$\omega_L^1 = \cos^{-1}\left[\sqrt{\frac{\sin(\lambda_{\lim it})}{rK_{XL}}}\right]$$
$$if \ldots \left[\frac{r}{\sin(\lambda_{\lim it})}\right] > 1/K_{XL} and (K_{XL} > 0) \tag{6}$$

$$\omega_L^2 = \cos^{-1}\left[\sqrt{\frac{\sin(\lambda_{\lim it})}{rK_{ZL}}}\right]$$
$$if \ldots \left[\frac{r}{\sin(\lambda_{\lim it})}\right] > 1/K_{ZL} and (K_{ZL} > 0) \tag{7}$$

$$\omega_{L,\min} = Max\left[\omega_L^1, \omega_L^2\right] \tag{8}$$

3.2 Calculation of maximum cutter size and optimum orientation angles

A maximum effective cutter radius selection is a critical problem before the toolpath generation is carried out for free-form surface machining. The objective is to maximize the removal of material with the largest feasible cutter that does not cause local gouging. In general, the larger the cutter diameter is, the better the removal of material. However, a large cutter may inevitably cause gouging and/or collision at certain points on given surface.

Smaller the gouging with curvature matching can be corrected in two ways:

1. Change the inclination angle (λ) and tilt angle (ω).
2. Change tool diameter.

The maximum and minimum of the inclination angle and tilt angle are not only limits of the machine but also workpiece and collision. Local gouging occurs when the curvatures between the cutter and surface at the point do not match each other. An initial cutter radius (r), minimum and maximum values of inclination angles (λ) and (ω) are inputs for an algorithm. Use K_{XL} and K_{ZL} (based on XL and ZL direction) by choosing the minimum positive value (concave) and tool radius to calculate tool inclination angles.

The lead angle is defined in a plane parallel to the feed direction. Compare the tool inclination angle with the maximum lead angle that we have set. If the tool inclination angle is greater than the maximum lead angle, we need to select a new smaller tool diameter. If the effective cutter radius is smaller than the radius of curvature, set an inclination angle equal to the inclination that we have calculated and set a tilt angle equal zero, else calculate a tilt angle. If the tilt angle is greater than the maximum tilt angle we need to select a new smaller tool diameter; if not, set an inclination angle and tilt angle equal to the angle that we have calculated. It can be considered only a critical point (the point that has the maximum positive curvature) because this point is the most serious point which will cause gouging first, or consider all points for dynamically changing the lead and tilt angles during tool path generation. The algorithm computes all CC points of surface in XL and ZL directions. Finally, the optimum tool radius (the largest tool radius) is calculated on all CC points of the surface. Inclination angles (λ) and tilt angles (ω) are computed for each the CC point of the given surface. See algorithm details in Fig. 5.

4. An example

In this section, a convex/concave surface shown in Fig. 8 is presented.

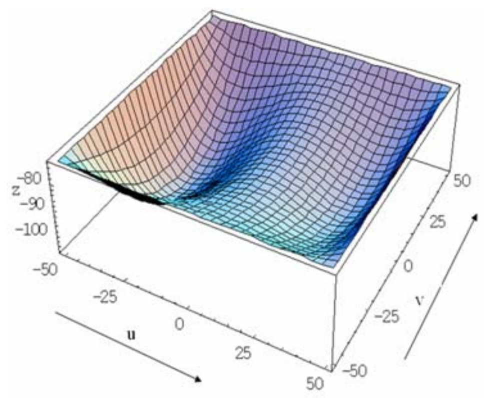

Fig. 8. A convex/concave part surface.

A free-form surface is derived by parametric surface Eqs. (9), (10) and (11). Equations below are plotted in Mathematica® [24] for a surface (Fig. 8).

Table 1 shows the input setup parameters of this example using the proposed new algorithm (see Fig. 5).

$$x = 100u - 50 \tag{9}$$

$$y = 100v - 50 \tag{10}$$

$$z = -((3.55u - 14.8u^2 + 21.15u^3 - 9.9u^4)v \\ (v-1)100/(-0.2)) - 72 \tag{11}$$

4.1 Toolpath generation

The simple tool path that use in this study is the Zig (one way) tool path which cuts the workpiece in one direction (along v direction). It starts from the u = 0, v =0 to u=1, v=1 as shown in Figure 8 by specifying path interval (0.5).

First, all the CC points and radius of curvature in u and v directions are computed by algorithm. The value of the path interval is the value of u interval .The ideal method is specifying the interval value of both u and v as small as possible in order to get properties data, i.e., surface curvature of every point on the surface, but in practice we cannot get all points on the surface so the value of the interval should represent the surface accurately. In other words, specifying the interval value of both u and v is smaller than the minimum surface curvature.

4.2 Machining simulation

Vericut® simulation software [25] is used for machining simulation. A virtual five-axis model is implemented by using real five-axis Maho 600e CNC machine parameters. The NC file generated using the algorithm is uploaded to Vericut® for geometric material removal. By selecting tool type, tool size and

Table 1. Input setup parameters.

Setup parameters in proposed new algorithm in Mathematica®	Setup Parameters in a virtual machine simulation in Vericut®
Parametric Equation (9,10,11)	A block of 100x100x100 mm
Step-size (mm) – 0.5	Tool length 179.512 mm
Min-Max (λ) (Deg)- [0.01- 60]	Workpiece coordinate See Fig. 9
Min-Max (ω) (Deg)- [0.01-60]	
Tool-Radius (mm) (100)	

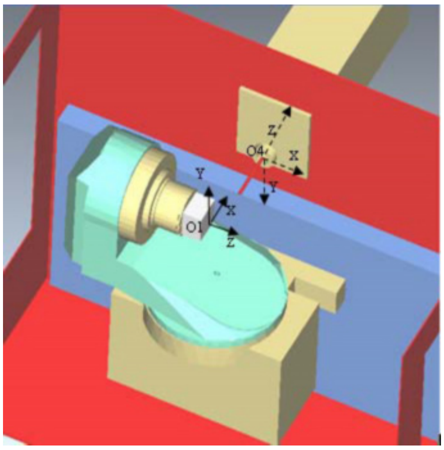

Fig. 9. Maho600e Virtual Machine in Vericut®.

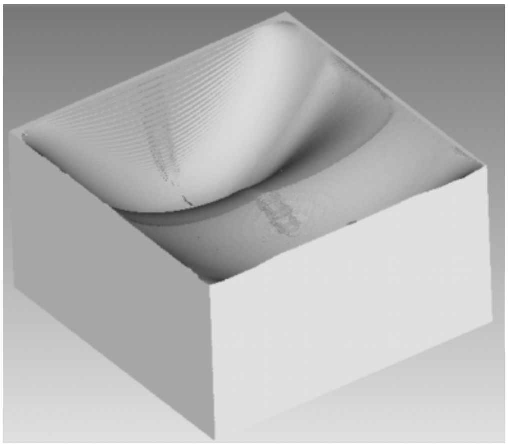

Fig. 10. A cut model using proposed algorithm.

workpiece, setup parameters, the five-axis virtual machine maho600e is simulated (See Fig. 9).

An optimal tool radius of 6 mm computed by the algorithm is used for cutting the whole surface. Fig. 10 shows a cut model simulated with our proposed algorithm. The proposed method is compared with a traditional method by using UGS NX®. Fig. 11 shows a simulated cut model using UGS NX®.

Fig. 12 shows a flowchart of using UGS NX®. A comparison table shown in Table 2 was constructed to prove our proposed algorithm and compare the material removal, accuracy and preparation time between the two methods.

UGS NX® computes the curvature match based on a piecewise linear CC point toolpath. It is much less accurate than our integrated approach as shown by the simulation results in Table 2.

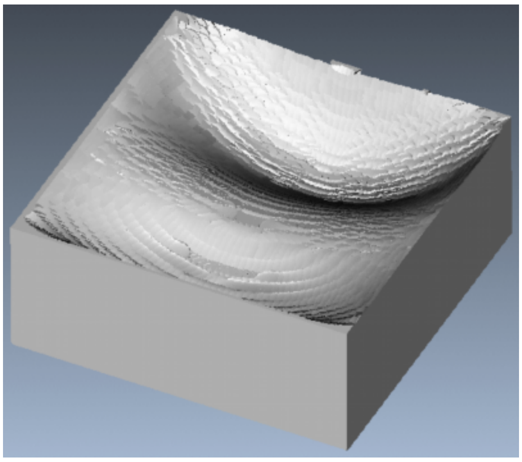

Fig. 11. A cut model using UGS NX®.

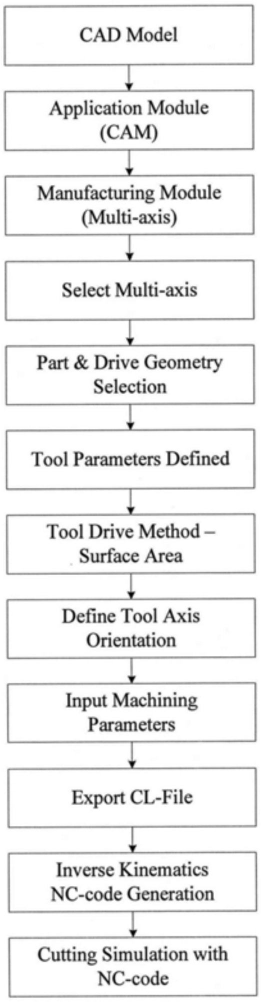

Fig. 12. Flowchart five-axis toolpath generation in UGS NX®.

Table 2. A comparison of two methods applied.

	UGS NX®	Integrated Automatic Toolpath Generation algorithm Proposed
NC program preparation time (hr)	10	1
Tool diameter (mm)	8 (estimated value base on minimum radius of curvature checked in UGS NX®)	12 (computed by algorithm)
Inclination angle (λ) (Deg)	10° (Fixed)	0~15° (Variable)
Tilt angle (ω) (Deg)	0° (Fixed)	0~1° (Variable)
Type of toolpath	One way	One way
Step size (mm)	0.5	0.5
Feed rate (mm per min)	800	800
Maximum size of undercut (mm)	4.98	2.74
Total number of undercuts	4098	1316
Maximum size of over-cut (mm)	4.98	3.98
Total number of over-cuts	4095	3684
Rt (maximum height between peak and valley) (mm)	9.96	6.72

5. Conclusion

An accurate and efficient method is presented for five-axis CNC machining of free-form surfaces. In this approach, the surface is first analyzed and classified into convex, concave, and saddle. A developed integrated automatic toolpath generation algorithm selects the best tool and plans the toolpath autonomously using curvature matching. The proposed integrated automatic tool path generation algorithm has been implemented using Mathematica®. A virtual five-axis maho600e CNC implemented in VeriCut® is used for virtual cutting simulation and checking accuracy. The new approach uses the real curved CC toolpath and not the piecewise linear approximation resulting in a much higher accuracy.

With the use of the proposed approach, the accuracy of undercut and overcut can be adjusted to meet the required accuracy by changing the step size. As a result, if we can use a bigger cutter, then we can have higher material removal rate; thus we can save the cutting time. The proposed algorithm can be customized for a wide range of applications in three-, four- or five-axis machine, and it can be used to automate the programming of the toolpath for the machining of a free-form surface.

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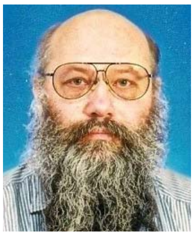

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