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EXPERIMENTAL COMPARISON OF ISO SCALLOP, ISO PLANAR AND ISO PARAMETRIC ALGORITHMS IN MACHINING SCULPTURED SURFACES

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ABSTRACT

Sculpture surfaces are extensively used in designing complex shapes such as automobiles bodies, turbine blades and etc. As the great deployment of CAD/CAM software and application of them in industries, the problem related to machinability (machining time, surface roughness and...) have large importance. In this paper first we introduce 3 algorithms that used by CAD/CAM software for machining this type of surfaces and the comparison between them , then with an experimental comparison upon machinability we will offer the optimum algorithm for machining of sculpture surfaces.

KEYWORDS: Sculpture Surface, Tool Path, ISO-Parametric, Iso-Planar, ISO-Scallop

Sculpture surfaces are widely used in the design of complex products with aerodynamic shapes. These free-form surfaces are often produced by 3-axis Computer Numerical Control (CNC) machine tools using ball-end milling cutters. The utilization of CNC machines to manufacturing complex surfaces has driven extensive research works, especially in the area of tool path generation (Dargomatz and Mann., 1997). Two criteria are generally used to evaluate the generated tool paths. One deals with the validity of the tool paths and the other with their optimality (Martin Held., 2009). Research on optimal tool path generation has been aiming at achieving two conflicting objectives: quality and efficiency. This has led to the determination of optimal intervals between successive tool paths to optimize the two conflicting objectives .A large tool path interval result in a rough surface while a small interval increases machining time, making the process inefficient.

The main objective of tool path generation is to compute a sequence of cutter location points from the design surface. Various investigators have given a detailed description and classification of various tool path generation methods. Tool path generation methods are classified as either the CC-based method or the CL-based method depending on the type of tool path generation surface.

In the Cutter Contact (CC)-based method, tool paths are generated by sampling a sequence of CC-points from the part surface and then each CC-point is converted to a Cutter Location (CL)-point. Tool path generation is done on the design surface. This method can be classified into three main categories, Iso parametric, Iso planar, Iso scallop tool path planning techniques.

In the Cutter Location (CL)-based method the CL-surface is used as a path generation surface. In most of previous work in this area the offset surface was approximated as the CL-surface (Kim et al). there are two ways to defining a CL-surface from a design surface: CL-surface by z-map (Inverse Tool Offset algorithm), polyhedral machining.

In general the method of generating of tool paths for the machining of complex surfaces classified into three categories.

The method of Iso-parametric machining takes advantages of the parametric representation of the sculptured surfaces and is widely used. This method is one of the earliest techniques used for machining sculpture surfaces (Sata T Kimura et al., 1981). By keeping one of the two parameter constant, the Iso-parametric curves are formed and employed as the tool paths. The generation of tool paths is straightforward with this method (Cox et al., 1994).

The method of Iso-planar machining uses parallel plane-surface intersection curves as the tool paths This method is characterized with a uniform interval between adjacent tool paths in the Euclidean space. Each interval is determined according to the scallop-height requirement (Chen et al., 1993). The milling tool moved along this planes that called drive planes. Haapaniemi et al and Hermann all use plane surface intersections (Haapaniemi et al., 1986; Hermann., 1988).

In Iso-scallop machining tool path planned in a such way that the scallop height be constant in all of the surface. the tool path generation to achieve constant scallop height was first reported by Suresh and Yang (1994). Improvement on this preliminary work were later proposed by Lin and Koren (1996) and Sarma and Dutta (1997) Sarma and Dutta (1981) used swept sections along the tool path to calculate the tool path intervals.

We can use this block diagram to show the CC-based Fig.1

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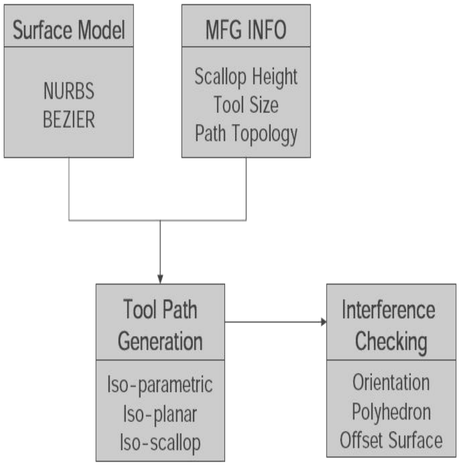


Figure 1. **CC-based tool path generation block diagram**

The object of this paper is finding the most suitable algorithm for machining free-form surface using an experimental comparison between this methods.

TYPE OF TOOLPATH AT CAD/CAM SOFTWARE

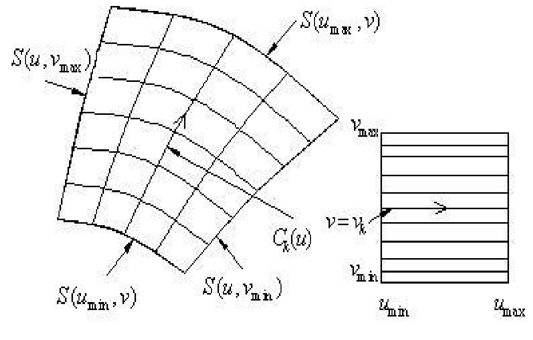
In this research tree type of toolpath at cad/cam software described and used for machining at CNC machines as follows:

- Iso-parametric
- Iso-planar
- Iso-scallop

ISO-PARAMETRIC MACHINING

A schematic illustration for the Iso parametric machining paths shown in Fig. 2.Here we choose one of the surface parameters(say u)as the machining(or forward) direction and one of the boundary curves at ($v = v_{\min}$)as the initial CC path.

v Surface parameters



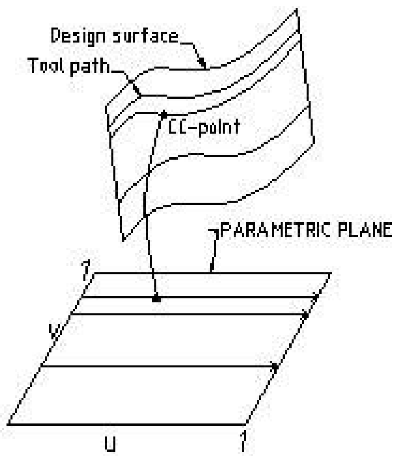


Figure 2. **Iso parametric machining paths**

Let the k th CC path be denoted by $C_k(u) = S(u, v_k)$.Note that the curve of $v = v_k$ in the parametric ($u - v$) domain correspond to the CC path C_k in the Cartesian ($x - y - z$) domain. The side parametric value can be determined one by one, i.e., $V_{k+1} = V_k + \Delta V_k$ where ΔV_k (the parametric side interval between two adjacent CC paths)is determined based on the scallop-height limit, h .Usually the Iso parametric CC path does not correspond to a constant scallop height ,and a conservative ΔV_k is determined so that the maximum scallop height along the CC path will not exceed .We need first to find ρ the radius of the curvature in the side direction. It can be calculated by (Faux and Pratt.; 1981).

$$\rho = \frac{e\alpha^2 + 2f\alpha + g}{a\alpha^2 + 2b\alpha + c}$$

Where

$$\alpha = \frac{\frac{\partial S}{\partial v}.T}{\frac{\partial S}{\partial u}.T}, \quad e = \frac{\partial S}{\partial u}.\frac{\partial S}{\partial u}, \quad f = \frac{\partial S}{\partial v}.\frac{\partial S}{\partial v},$$

$$g = \frac{\partial S}{\partial v}.\frac{\partial S}{\partial v}, \quad a = \frac{\partial^2 S}{\partial u^2}.N, \quad b = \frac{\partial^2 S}{\partial u \partial v}.N,$$

$$c = \frac{\partial^2 S}{\partial v^2}.N$$

Δm	step distance of the planes in iso-planar machining
ρ	Radius of surface curvature in the side step direction
B	Unit vector in the side-step or path interval direction
C	Cutter-contact path

h	Scallop height limit
L	Cutter-location path
M	Unit normal vector to the planes in iso-planar machining
N	Unit normal vector to the surface
r	Radius of the ball-end cutter
S	Parametric surface
T	Unit tangent vector in the CC path direction
t	Spatial parameter along the CC path
U	$u-v$ curve in the parametric domain
u,v	Surface parameters
V	Feedrate along the CC path

And T is unit tangent vector in the CC path direction and N is the unit normal vector to the surface. Then the suggested side step distance Δl for each evaluated point can be calculated by

$$\Delta l = \sqrt{\frac{8\rho h}{\rho \pm r}}$$

Δl Distance of the side step

Where h is the limit for the scallop height, r is the cutter radius, the plus-minus ($\pm$) depends on which case the surface in the side direction is convex or concave. Note that the side step direction is orthogonal to the CC path direction (T) and the surface normal(N).Because Δl is in distance unit (mm)and it is usually not in the v direction, a conversion from Δl to the parametric side interval Δv is needed. A schematic description for this conversion is shown in Fig. 3.Based on the geometrical relationship shown in Fig. 3, we can have $\Delta l = B.(\partial S/\partial V)\Delta V$, where B=N*T is a unit vector in the side direction. Finally, the candidate path interval $\Delta V_{i,k}$ for the i st sampled point on the kth path can be calculated by

$$\Delta V_{i,k} = \frac{\Delta l}{(N*T).\dfrac{\partial S}{\partial V}}$$

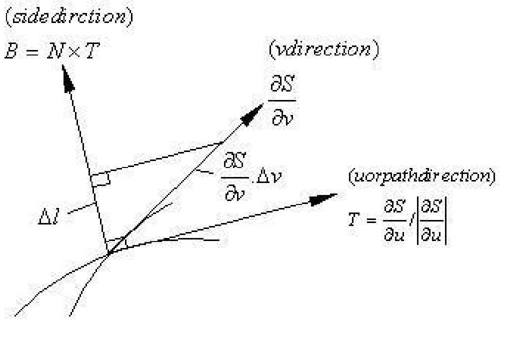


Figure 3. **Iso parametric machining paths**

With the CC path scheduling algorithm and the path interpolation and tool offsetting algorithms, the Iso-parametric surface interpolator can be implemented in a CNC machine tool (Chih-Ching, 2000).

ISO-PLANAR MACHINING

A schematic illustration for the Iso-planar machining paths shows in Fig. 4.As can be seen, the CC paths are the intersection of the parametric surface and a parallel vertical planes (drive planes).In this paper the unit normal vector to these vertical planes is denoted by $M = (m_x, m_y, 0)$ while the distance between two adjacent parallel planes is denoted by Δm.

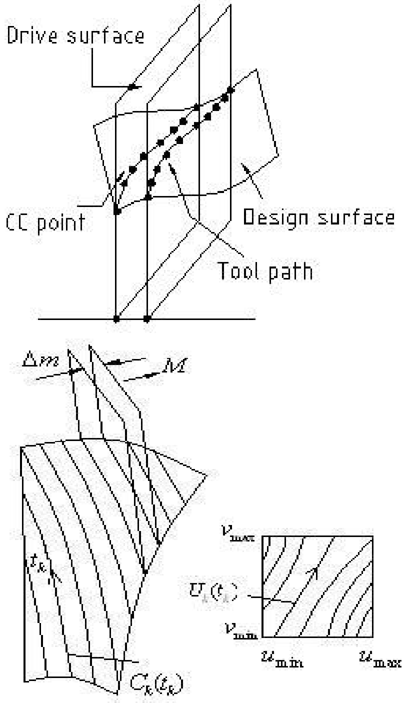


Figure 4. **Iso parametric machining paths**

The proposed path scheduling method for the Iso-planar case is similar to the Iso-scallop case. For both cases, each CC path C(t) correspond to a specific curve U(t) in the parametric domain, i.e., C(t)=S(U(t)).In the scheduling U(t) is obtained recursively by ,where .The major difference between the iso scallop and the Iso planar cases is the way to calculate the parameter increment, .

Given the kth curve , the Iso planar increment curve is ,where .For a pair of points on and ,the corresponding CC points and are both located on the surface. The difference vector between the two points, , can be approximated by:

Geometrically this difference is located on a cross-section that is expanded by the side vector M and the tool-axis vector (Z).Consequently, we can have

Based on the x and y components of this Eq., we can solve and ,and there by find .If the initial curve for the Iso planar scheduling does not coincide with a boundary of the u-v domain(see Fig. 4),we need first to create it. Here we propose a simple method to get .Let the machining start at the left bottom corner and the four representive points on be in the directions .The initial CC path , ,is located on a vertical plane that is deviated from the surface corner by .Accordingly any point on must satisfy

Consequently, we can let respectively, and substitute the in the last Eq., and then solve the four solutions.

With the CC path scheduling algorithm and the path interpolation and the tool offsetting algorithms the Iso planar interpolator can be implemented in a CNC machine tool (Chih-Ching, 2000).

ISO-SCALLOP MACHINING

the geometric elements relevant to the derivation in the present work are defined in this section(Fig.5).As in most computer-aided manufacturing literature, the cutter location(CL)path represent the trajectory of the cutter center for a particular tool path. The cutter contact (CC)path represent a tangential trajectory between the ball-end mill and the design surface. In the machining of a 3D surface, the CL path are actually on an offset surface that is generated by offsetting the design surface in the surface normal direction by an amount equal to the cutter radius(Inverse Tool Offset Algorithm)(Fig.6) (Matthieu Rauch et al., 2009). this offset surface is called the tool center surface. As the cutting tool moves along the tool path, a tool envelope surface is created (Matthieu Rauch , 2009). This envelope can be defined by sweeping a circle of the cutter radius along the CL path.

The horizontal distance between two adjacent tool paths is referred to the tool path interval or sidestep, which results in the scallop on the machined surface. The scallop curve is defined as the 3D curve tracing the machined scallop .The scallop height represent the distance between the scallop curve and the design surface, For constant scallop height machining, the scallop curves are on an offset surface (scallop surface)of the design surface with the scallop height as the offset distance. In fact the scallop curve is the common intersection curve of the two tool envelope surfaces of the adjacent tool paths on and the scallop surface (Blackmore and Leu MC, 1992).

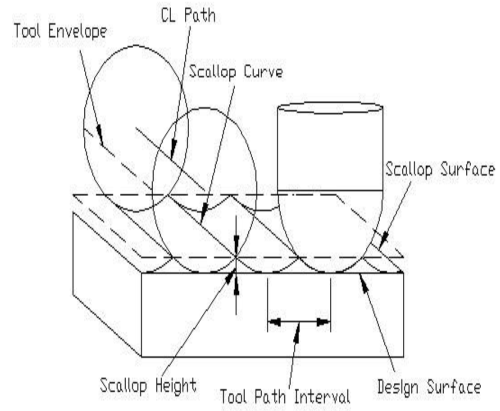


Figure 5. Geometric elements of a machined surface

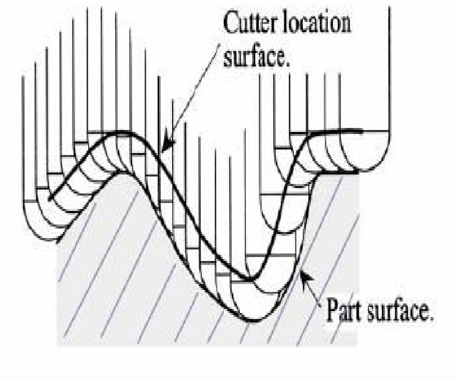


Figure 6. Creating CL surface form design surface

Tool path for constant scallop-height machining are determined by following two sequential steps. First a given tool path and the scallop height requirement are used to identify the corresponding scallop curve in the side step direction. Second, the known scallop curve is using to establish the next tool path.Fig.7 shows two adjacent CL paths and the common scallop curve for a machined surface. For a point on CL path1, the plane perpendicular to its tangent will intersect the scallop curve at and will lie on a circle of the cutter radius centered at in the perpendicular plane. The tangent of the scallop curve at is in general not parallel to the tangent of the CL path 1 at .Similarly, the plane perpendicular to the scallop curve tangent at will intersect the next CL path(CL path 2)at and (as well as)will lie on a circle of the cutter radius centered at in the perpendicular plane. The tangent of CL path 2 at is not parallel to the tangent of the scallop curve at .We assumption that these tangent vectors are parallel (Blackmore and Leu MC, 1992).

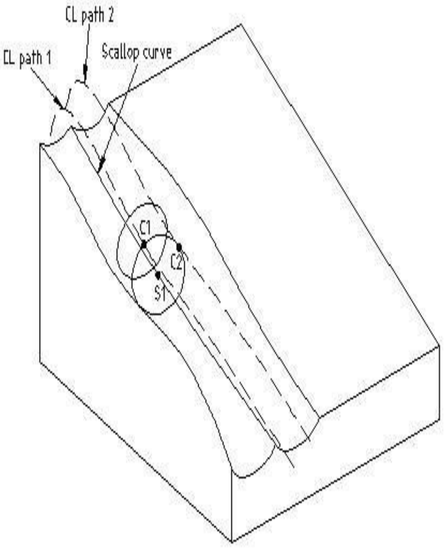


Figure 7. **Typical adjacent CL paths and the common scallop curve**

EXPERIMENTAL WORK

In this section we are machining a sculpture surface with the illustrated machining strategies in the above section. This surface is a double curvature surface with this dimension X200, Y100, Z50mm. (Fig.8).

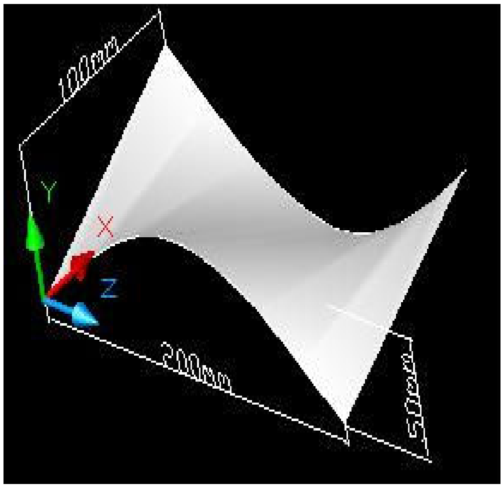


Figure 8. **Sculpture surface used in the machining experiment**

The machining parameters are as below:

Cutter radius(r=4mm),Feedrate(f=300mm/min),Spindle speed (s=1500rev/min), scallop height limit(h=0.15mm), machining tolerance 0.01 mm,work piece material (CK45) and tool material (tungsten carbide).

We use CATIA software for machining this surface. After setting the machining parameters and complement the machining we can comparison the condition of machined surface to the design surface by analysis of the surface. The cases noted in table 1 found by this versatility of the software (remaining material &tool gouge).

We use a vertical CNC milling machine with FANUC OM plc to machining these surfaces. We use form tester measuring machine after machining the parts. The accuracy of the machine is .In this method the measuring probe moved along the surface and the curves on the surface (tool paths) with*200 magnifications can be seen and measured. In all of machining (finishing) we use new tungsten carbide ball-end tool to have a constant machining condition in all cases. The surfaces machined by these 3 strategies show in Fig. 9, 10, 11

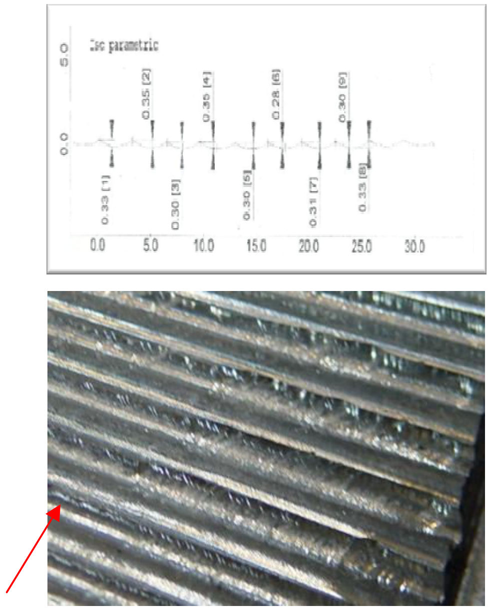


Figure 9. **Iso parametric machining surface and its measuring results (in mm).It can be seen chatter marks in some area of the surface. → Shows the measuring direction.**

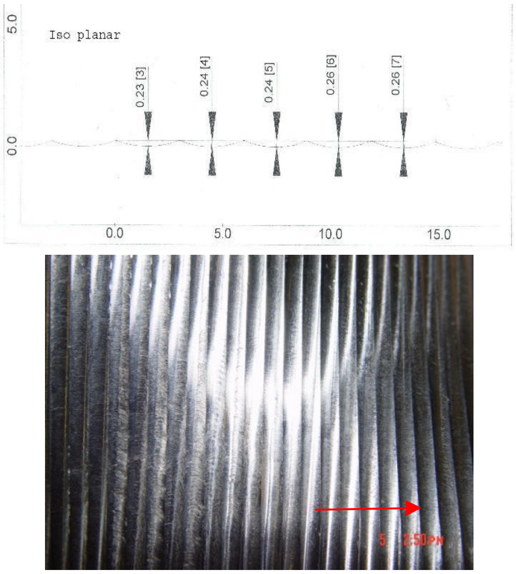


Figure 10. **Iso planar machining surface and its measuring results (in mm). → Shows the measuring direction**

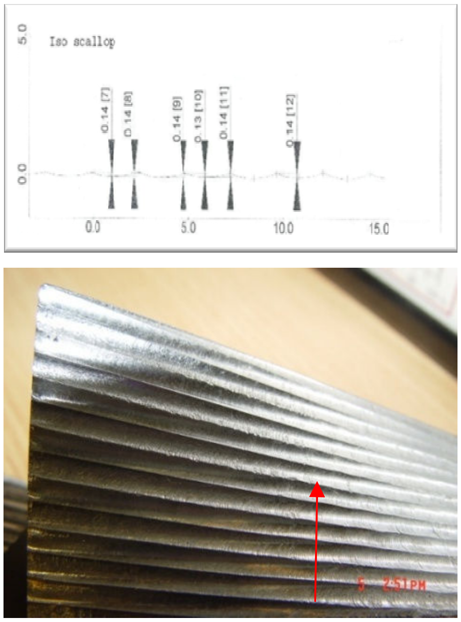


Figure 11. Iso scallop machining surface and its measuring results(in mm). shows the measuring direction

After machining this surface with this 3 strategies we found these results. The generated Iso parametric tool paths are, often much denser in one surface region than others due to the non uniform transformation between the parametric and Euclidian spaces. This results in varying scallop-height distribution on the machined surface non optimal machining time. As seen in table 1 the Iso planar machining are not optimal in general and to get a design surface roughness the machining time will be too big. In the case of the scallop-height (surface roughness) Iso scallop machining shows 233% and 173% improvement than the Iso parametric and Iso planar machining respectively. We have 1480, 199 and 21 remaining material in Iso parametric, Iso planar and Iso scallop machining respectively. We have only one gouge point at the start of machining in Iso scallop machining (table1)

Table 1. Machining results of sculpture surface

		Machining time	Scallop height	Remaining material	Tool gouge
1	Iso parametric machining	25'20"	0.30-0.35mm	1480 point	16 point
2	Iso planar machining	21'35"	0.23-0.26mm	199 point	4 point
3	Iso scallop machining	24'23"	0.13-0.15mm	21 point	1 point

CONCLUSION

An experimental comparison between sculptured surface machining strategies is presented in this paper. We use a double curvature surface that covering most of sculpture surfaces for comparison machining strategies .After machining this surface with these strategies it showed that the Iso scallop machining is the optimal strategy for machining free-form surfaces.

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