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Efficient Approach for Minimizing Tool Paths Length for Bézier Surface from Iso-Scallop Technique

Piyush Tiwari[1], Kailash Kumar Borkar[2], Vijay Tiwari[3]

[1]Department of Mechanical Engineering, ITGGVV, Bilaspur, Chhattisgarh, India
[2]Department of Mechanical Engineering, ITGGVV, Bilaspur, Chhattisgarh, India, kailashborkar04@gmail.com
[3]Department of Mechanical Engineering, ITGGVV, Bilaspur, Chhattisgarh, India, vijaytiwarivsg@gmail.com
Author Correspondence: Email address: piy2358@gmail.com, Cell No. 8109280957

Abstract

This paper purposed an efficient and effective methodology to generate optimal tool path for machining operation using Numerical Control (NC) machine. Tool path design is highly desirable factor as point of view of high-speed machining (HSM) of sculptured surface, where frequent change of tool position and direction may lead to inefficient machining. NC paths with controlled accuracy using optimal tool path based on such an algorithm which is depends on a number of factor like selection of surface, part geometry, Cutter location (CL) points, scallop height, side step, forward step etc. The CL points are generated directly from part surfaces and interpolated by desired curves/surface. This work proposes a new approach for generating accurate iso-scallop tool paths in the process planning for parts that are subjected to Bézier surface. The simulation results shows that the effectiveness of the proposed methodology.

Keywords: Bézier Surface Machining; Iso-parametric; Iso-Scallop Height.

1. INTRODUCTION

The objective of this paper is to create an efficient and accurate tool path planning approach for smooth free-form surfaces in terms of cubic Bèzier curves, and to develop such a algorithm which reduces manufacturing and computing time as well as the cutter contact points while keeping scallop height constant. This paper primarily focuses on the following aspects of sculptured machining, i.e. TPG, desired surface, and iso scallop height technique. For each aspect basic concepts, fundamental research methods and problem domain has been introduced.

Freeform surface or sculptured surfaces which are widely used in various engineering applications are generally manufactured by CNC machining. Various methodologies and computer tools, like design software have been developed in the past to improve efficiency and quality of freeform surface machining [1]-[2]. In HSM milling processes, requires fast and accurate following of a specified tool path. And by using such type of synthetic curve tool path can be computed very efficiently. The reduced path generation time allows for improved performance in HSM operation [3].

Another important task is the method for calculating the side step between consecutive paths is suitable for part surfaces in different forms provided that the closest distance from a point to the part surface can be calculated. The step size is determined such that the maximum scallop height along a scallop curve coincides with a given tolerance (Fig. 1). Forward-step function and side-step function are necessary to calculating tool path. Forward-step function is the maximum distance between two cutter contact (CC) points with a given tolerance. Using the mathematical representation, it is possible to determine the optimum size of forward-step. Choi et al. [1] developed a method for side-step size by studying the geometry of the tool and the differential geometry of the designed part. They verified true machining errors by comparing machined and designed surfaces using the point cloud method. Cutter location (CL) data provides readable data on cutter locations and machine tool operating commands. The machine tool commands can be converted to specific instructions during post-processing, the final output is a part program in a word address format that can be post-processed for CNC machine tool on which the job will be accomplished [3, 5] (See Fig2).

In the proposed work, a computing procedure for calculating maximum scallop height is given. The procedure is effective and suitable for part surfaces in surface representations provided that the minimum distance from a point to the part surface can be calculated. The simulation results affirm that the proposed approach can produce high-quality bèzier NC tool paths.

2. Machining Geometry

Accurate representation and analysis of machining geometry is essential to the effective three-axis machining of free-form surfaces. In this work, we use Bézier surface patch as parametric surface and the methodology of iso scallop height are presented. Mathematically a parametric Bèzier curve is defined by

$$P(u) = \sum_{i=0}^{n} B_{n,j}(u) P_i \quad (1)$$

The Bézier patch is a function of two variables with an array of control points. Most of the methods for the patch are direct extensions of those for the curves. The matrix representation of the cubic Bézier patch allows specifying many operations with Bézier patches the matrix operations can be performed quickly on computer systems optimized for geometry operations with matrices. The Bézier patch is the most commonly used in surface representation and it can be used to calculate cutter offset in 3D NC machining. The Bézier curve is a function of one variable and takes a sequence of control points.

$$P(u,v) = \sum_{j=0}^{m} \sum_{i=0}^{n} P_{i,j} B_{i,n}(u) B_{j,m}(v) \quad (2)$$

3. Tool Path Generation Approach

In Iso-parametric tool path surface points are calculated as a function of (u, v) parameter space, the tool path indexed along the surface by incrementing (u) and (v). Tool path planning is accomplished by holding the (v) parameter constant and indexing the (u) parameter, which is forward step. Forward step increment (s) in (u) direction must be carefully chosen since tool movements are linearly interpolated and the chordal deviation between the straight lines and the actual surface must be less than the desired tolerance (δ). Step-over increment in (v) direction (side step g) must be small enough to keep the scallop height between spherically shaped cutter paths to less than the desired tolerance. In sculptured surface milling, the code sent to CNC controllers is usually computed after (1) discretization of the surface into a set of trajectories, and (2) discretization of the trajectories into linear segments. The rest discretization involves an error retracted as the scallop height error h. The second gives the chordal error c. The distance between two consecutive trajectories is called step-over. The distance between consecutive points of a trajectory is referred to as the step forward.

3.1 Iso Scallop Height Tool Path Generation

The generation of iso scallop height tool paths for efficient five-axis freeform surface machining is now addressed. The present method first identifies the scallop curve of an initial tool path. The next adjacent tool path to the given tool path is then determined from the established scallop curve. The maximum distance criterion for the corresponding points on the adjacent scallop curves is employed in the determination of the next tool path in order to facilitate maximized machining efficiency.

3.2 Numerical Procedure for Computation of CL Points

The concept of the scallop surface, which is an offset surface from the design surface by the specified scallop height h, is used in the establishment of the scallop curve from a given CC tool path. For a typical parametric surface $P_{sc}(u,v)$ the scallop surface can be expressed as:

$$P_{sc}(u,v) = P(u,v) + n.h$$

(3)

Where h is the scallop height and n the unit normal vector from the surface Where P_u represents the partial derivative of P with respect to the parameter u and P_v with respect to v. In 3-axis surface machining with ball end mills, the given CL path is an offset curve of the corresponding CC path on the surface normal by a distance equal to the cutter radius R. This relationship can be expressed using the parameter't' as,

$$CL(t) = CC(t) + n.R$$

(4)

$$CL(t) = P[\,u(t), v(t)\,] + \frac{(P_u \times P_v)}{|P_u \times P_v|} \times R = \begin{bmatrix} X_{CL}(t) \\ Y_{CL}(t) \\ Z_{CL}(t) \end{bmatrix}$$

(5)

The parameter equation of the swept tool envelop surface is derived by formulating the generating curve in a movable work coordinate system along the given CL path. This local Cartesian coordinate system $X_wY_wZ_w$ is created by setting (1) a point on the CL path (Such as C1) as the origin; (2) the surface normal n corresponding to C1 as the Z_w axis; and (3) the tangent of the CL path at C1 as the Y_w axis.

Transforming Eq. (4) to the fixed model coordinate system (MCS) XYZ, the parametric equation of the tool envelope surface is obtained:

$$R_u(t,\theta) = w^{M_{[R]}}.R_w(\theta) + C_1$$

(6)

Where

$$w^{M_{[R]}} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix}$$

$$C_1 = \begin{bmatrix} X_{CL}(t) \\ Y_{CL}(t) \\ Z_{CL}(t) \end{bmatrix}$$

$$\begin{bmatrix} t_{13} \\ t_{23} \\ t_{33} \end{bmatrix} = j_w \times k_w = i_w$$

In the above formulation i_w , j_w and k_w are unit vectors in the positive X_w, Y_w and Z_w directions, respectively. With Eq. (12) and (13), the scallop curve can be identified by solving the following equation:

$P_{SC} - R_m = 0$

Eq. (6) is solved by a numerical procedure that identifies the corresponding scallop point for a given CL points on the circular generating curve $R_w(\theta)$. The scallop point is found when its distance between a point on $R_w(\theta)$ and the design surface requires finding the corresponding (closest) Point on the surface.

3.3 Calculating of Forward Step Increment

The choice of forward step length depends on the calculated tolerance (δ) between the true curve and the chord between successive points on the curve. The maximum deviation occurs at [r (u+1/2Δu)] for a sub-segment from (u) to (u +Δu) (See fig. (6)). This leads to a straightforward algorithm of the maximum for general parametric curves. The maximum normal distance (δ) for the chord joining the points at (u=0) and (u=1) is valuated, because parameter transformation can be used to transform any segment ($u_i \leq$u $\leq u_{i+1}$) into (0 ≤ u‘ ≤1).

$$u = (1-u)' \; u_i \quad + u' \, u_{i+1} \qquad (15)$$

$$p = \left[r\left(\frac{1}{2}\right) - r(0)\right] - \frac{c.\left[r\left(\frac{1}{2}\right) - r(0)\right]}{c^2} \times c$$

In general (λ ≈ ½) then the formula can be simplified as:

$$p = r^{0.5} - 0.5 \times \left[r\left(\frac{1}{2}\right) - r(0)\right]$$

This equation has been used in this work to compute a sequence of segments of maximum length which are within the tolerance specified, that is:

$$|p| \leq \delta$$

To convert cutter contact points to cutter location points, the result of calculating the forward step is a CC point that can be any point on the tool, to reduce machining errors, it has to be converted to a CL point by which the tool moves along the surface.

4. Implementation and Results

The developed formulations for calculating tool path interpolation points and side steps have been successfully implemented in MATLAB (ver. 7.8). The optimization routines simulation results obtained from MATLAB and Solid works. All the virtual experiments are carried out on a personal computer. These results are listed in Table 2. The unit of the length is taken in millimeter. The maximum and minimum limit of co-ordinate of X, Y, Z and the parameter value of u and v has been defined in the developed software. Now the plot can be generated for surface using curve fitting or using command. Then from workspace of MATLAB intermediate point (P_X, P_Y, P_Z) of curve can be obtained. Further the co-ordinates of all points of the surface are imported into Solid Works 2012. By calculating the coordinates of start and end points of each line segments, it becomes possible to generate the required part program. The above result shows that when patch size increases the length of tool path increases, also it provides better surface finish. The above mentioned points are valid for iso-parametric method and most suitable for proposed approach.

Table-1 a bi-cubic Bèzier surface is defined by 4×4 control point’s matrix

Control Point	X, Y, Z						
P00	0, 0, 5	P10	50,0,18	P20	100,0,30	P30	150,0,30
P01	0, 50, 18	P11	50, 50, 24	P21	100, 50, 45	P31	150, 50, 36
P02	0, 100, 24	P21	50, 100, 6	P22	100,100,30	P32	150,100,30

P03	0,150,28	P31	50, 150, 30	P23	100,150,32	P33	150,150,50

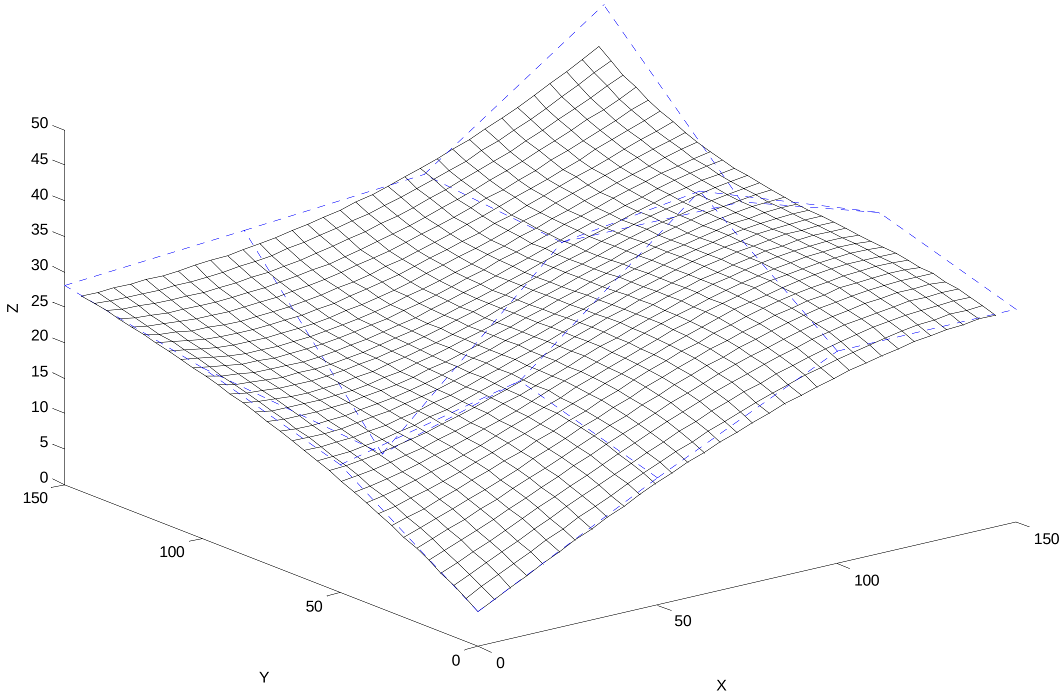
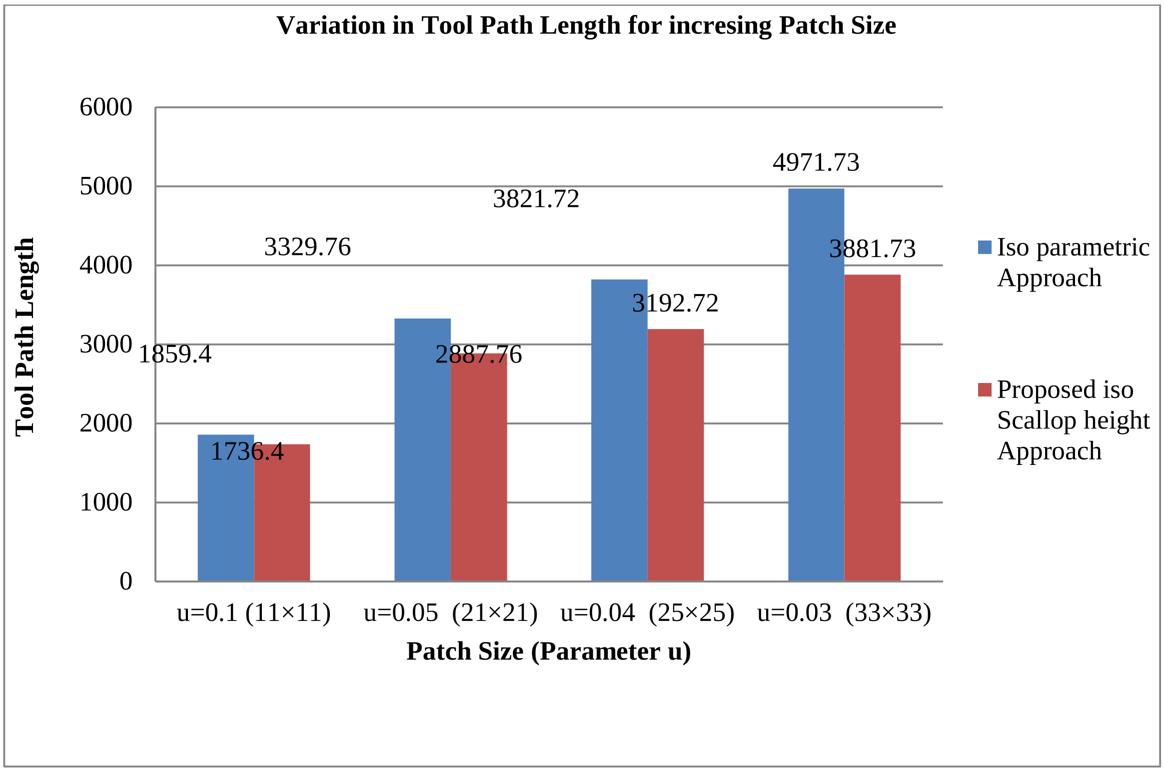


Figure 1 Bézier Patch in X-Y-Z (3D)

Table-2 Tool path length for different types of Bèzier Surface

S. No	Parametric value of u and v	Patch size	Tool Path Length (mm) Iso-parametric	Tool Path Length (mm) Proposed iso-scallop height Approach	Improvement %
1.	0.1	11×11	1859.4	1736.4	6.615
2.	0.05	21×21	3329.76	2887.76	13.274



5. Conclusions

For the theoretical simulation and virtual experimental analysis it can be concluded that the selection of patch size plays important role to minimize the tool path length. If large patch size is used then the surface finish is obtained better and cutting time is optimum. This paper can concluded that the selection of patch size plays important role to decide tool path length and it should be minimum, surface finish should be better as the patch size is maximum and cutting time should be optimum. The contribution is related to mathematical representation of manufactured surface through the use of parametric curve and surface depending on Bézier form.

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