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OPTIMUM TOOLS BASED ON LOCAL FORMS FOR FINISHING FREE FORM SURFACES

M. Bey, M. Bendifallah, S. Kader, K. Boukhalfa
Centre de Développement des Technologies Avancées (CDTA), Algiers, Algeria
(E-mail : bey_mohamed@yahoo.com)

ABSTRACT:
This paper presents a new methodology for finishing sculptured surfaces on 3-axis CNC milling machines using ball end mill tools. The suggested methodology is based on the localization of local forms composing the surfaces and is divided into three stages. In the first stage, the surfaces are triangulated semi adaptively. In the second stage, the local forms of points are identified (concave, convex, plane, concave developable, convex developable and saddle), thereafter the triangles having the same local form are grouped into the same region and then each region is subdivided in sub regions. In the last stage, the final optimum set of tools is determined for each sub region. This methodology is more efficient when using machining centers and when the geometry of the surfaces is complex and composed of many distinguished regions. This approach allows us to obtain a significant reduction of machining times and hence the costs.
Keywords: Optimum tool, Free form surface, Local form, Ball end mill, Optimization.

1. INTRODUCTION
Free form parts commonly used in industry are used in the design and manufacture of molds, dies …etc, and are machined on 3-axis or 5-axis milling machines by considering many aspects. Due to the increasing complexity of their geometry, several researches are focused on the finishing of free form surfaces on CNC milling machines. Some of these researches only consider the cutting conditions of machining, others the optimal machining strategies and others the selection of the optimum tools. In [1] Choi studied the interference avoidance and in [2] the machining of compound surfaces. Duc [3] studied the parameters that affect the surface quality and generated the tool paths in the terms of planar B-Spline curves. Yang [4] proposed methods for global and local interference checking and then determined the optimal combination of tool sizes that minimize machining times. OuYang et al. [5, 6] used Voronoi diagram and Delaunay triangulation to select the optimal ball end mill tool to be used for finishing free form surfaces given by a cloud of points. In practice, free form surfaces are required to be machined in finishing using multiple tools. The NC part programmer needs to interact with CAM software for the selection of the tool dimensions which requires a tedious work. The selection of the optimal set of tools must take into account the irregular curvature distribution of free form surfaces and thus the different local forms that compose the surfaces. In this paper, a methodology is proposed for finishing free form surfaces on 03-axes CNC milling machines by the determination of the local forms of surfaces and the associated set of optimum ball end mill tools. This methodology is more efficient when using machining centers and the geometry of the surfaces is complex and composed of many different regions. This approach allows us to obtain a significant reduction of machining times and costs.

2. ADOPTED METHODOLOGY
Aimed to improve machining efficiency by using a set of optimal tools, a methodology based on local forms of free form surfaces is proposed (Figure 1). The proposed methodology is divided into three stages. In the first stage, the surfaces are approximated by a minimum number of triangles that verify a set of constraints. In the second stage, the geometric properties of vertices are calculated and the

local form of each vertex is identified. Thereafter, the regions are created and the associated theoretical tool radius is determined. In the last stage, the optimum tools are determined and the final tools are selected from a data base of tools.

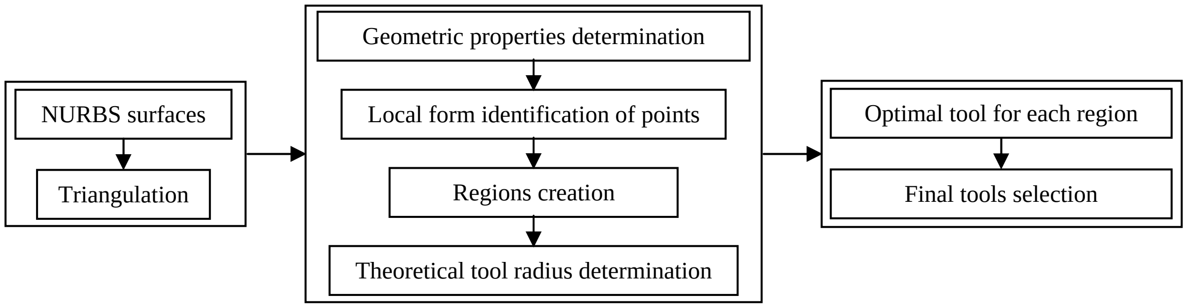


Figure 1. Flow chart of the proposed methodology.

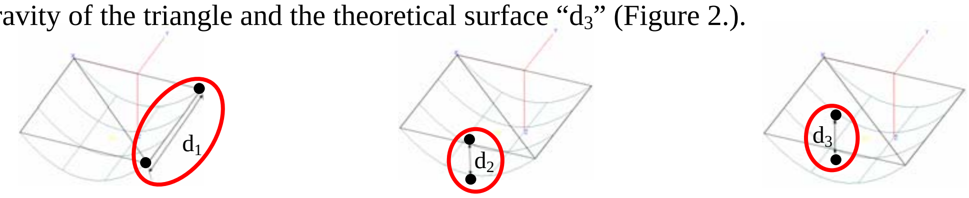
3. LOCAL FORMS OF NURBS SURFACES

Free form parts are designed by the junction of an important number of complex surfaces that are described generally by the parametric formulation such as Bezier, Rational Bezier, B-Spline and NURBS. In this work, the NURBS formulation is used [7]. The local form of the surface in the neighborhood of a point of parametric coordinate's *u* and *v* are determined from the minimum and the maximum principal curvatures k_1 and k_2. From the differential geometry of parametric surfaces, six local forms can be distinguished that are concave, convex, saddle, concave developable, convex developable and planar depending of the values of k_1 and k_2 [7].

4. PROCESSUS STEPS

4.1. Triangulation of surfaces

In this work, a semi-adaptive triangulation is used. The triangles are first created in the parametric plane and then the verification of the set of constraints for each triangle is carried out in 3D. The imposed constraints are: maximum length of each segment of the triangle "d_1", distance between the medium of each segment of the triangle and the theoretical surface "d_2", distance between the center of gravity of the triangle and the theoretical surface "d_3" (Figure 2.).

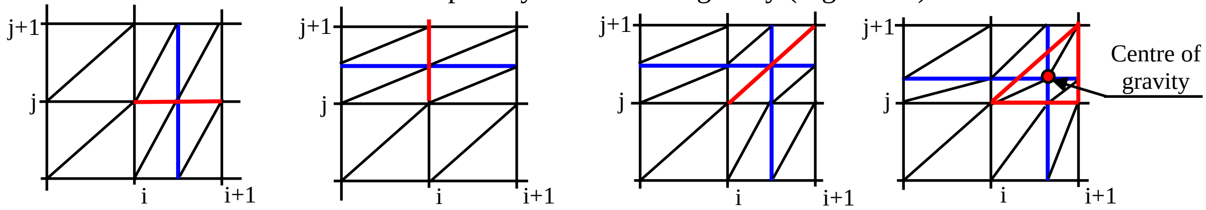


a 1st condition. *b. 2nd condition.* *c. 3rd condition*

Figure 2. Criteria of subdivisions.

The semi adaptive triangulation is described by the following algorithm:

1. Determine the increment *Δu* and *Δv* such that the first horizontal segment, the first vertical segment and the first diagonal segment verify the first and the second conditions.
2. If the horizontal, vertical and diagonal segments do not verify the two first conditions, divide the entire column, the entire row and the entire column and the entire row (Figure 3.a, 3.b, 3.c).
3. If the center of gravity does not verify the third condition, divide the entire column and the entire row and constrain the created lines to pass by the center of gravity (Figure 3.d).



a. Horizontal segment. *b. Vertical segment.* *c. Diagonal segment* *d. Center of gravity.*

Figure 3. Subdivision in the parametric plane.

In the end, for each vertex, calculate the unit normal vector and the principal radius of curvatures and then the unit normal vector to each triangle.

4.2. Localization of regions

The selection of the optimal set of ball end mill tools to be used must take into account the different local forms that compose the surfaces. So, assume that a region is a local form that is defined by a set of triangles having the same local form. The determination of the different regions passes by three stages. First, identification of local form of all triangles based on the local form of their vertices. Second, grouping all triangles of the same form in a same list. Third, subdivision of each list into sub regions based on the neighbors of each triangle. To manufacture a sub region of a free form surface without interferences at all vertices, the largest radius of the theoretical tool that is less than the smallest value of all principal radiuses of curvature of this sub region is used [1].

4.3. Optimum tool for each region

To determine the final optimal tool for each sub region, the vertices are supposed to be the contact points. The main objective of the tool correction is the determination of a new optimum tool radius that transforms the interference point on the spherical (active) part of the tool (Figure 4). For this, the following algorithm is used:

- For each vertex q that creates interference with a vertex S:
  1. Determine the perpendicular plane to the vector $\overrightarrow{Sq}$ that passes by the middle point M of the segment Sq.
  2. Calculate the new tool center C_{new} by the intersection between the plane and the line (SC_{old}).
  3. Calculate the new tool radius from the distance between the points S and C_{new}.

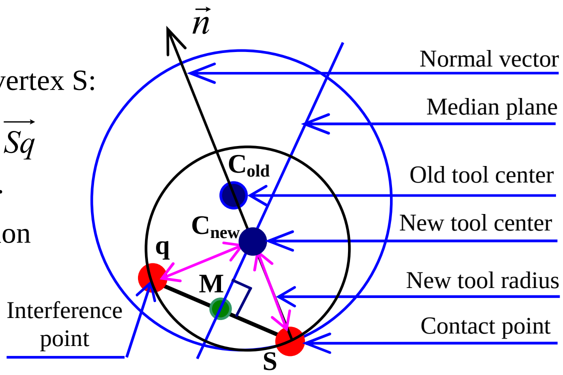


Figure 4. Tool radius correction.

The optimum tool to be used for a given sub region is the minimum of calculated tools for all vertices belonging to this sub region.

5. RESULTS AND DISCUSSIONS

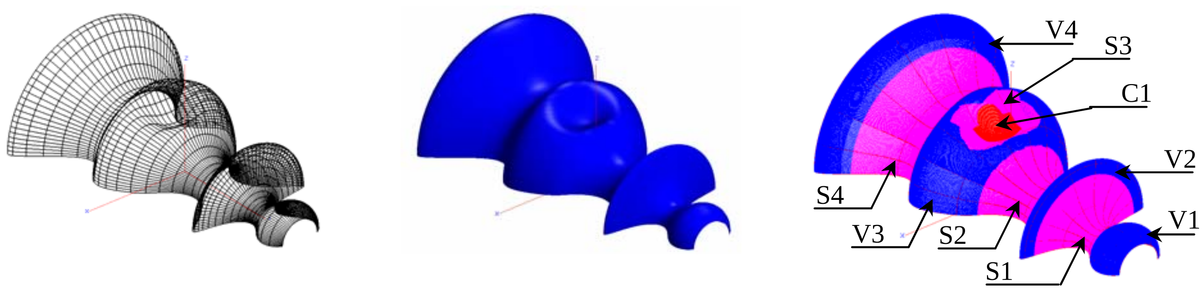
The proposed methodology has been implemented under Windows using C++ Builder and the graphics library OpenGL [8]. This software is designed for any NURBS surfaces to be machined on 3-axis CNC milling machines using ball end mill cutters. For the demonstration of the effectiveness of the proposed methodology, an example is tested. The considered surface is defined by a network of 19×11 control points with the degrees 3 and 2 in the two directions *u* and *v* and the global dimensions are 91.19mm×128.52mm×45.60mm (Figure 5.a, 5.b).

The first step is the triangulation of the surface. For this, the values of d_1, d_2 and d_3 are fixed equal to 1mm and the results of the triangulation are given in Table 1.

Table 1. Results of the triangulation.

Number of vertices	Number of segments	Number of triangles	Maximum length of segments	Maximum deviation of segments	Maximum deviation of centers of gravities
152550	455845	303296	0.974mm	0.0079mm	0.0058mm

The main objective of the next step is the localization of the different sub regions and the determination of the optimum theoretical radius. The results show that the surface is composed of 04 convex regions (letter V), 04 saddle regions (letter S) and 01 concave region (letter C) (Figure 5.c).



a. Wireframe model of the surface.   *b. Shaded model of the surface.*   *c. Sub regions of the surface.*

Figure 5. Considered surface and its different regions.

Table 2 gives the results of the third step that are the theoretical radius, optimum radius, used tool radius and the associated feedrate for each sub region.

Table 2. Tool radiuses for each sub region of the considered surface.

	V1	V2	V3	V4	S1	S2	S3	S4	C1
Theoretical radius mm	infinite	infinite	infinite	infinite	4.796	10.1814	7.999	5.345	4.716
Optimum radius mm	8.249	14.266	10.493	21.007	4.724	9.945	6.783	5.259	4.711
Used tool radius mm	8	14	10	20	4	9	6	5	4
Feedrate mm/min	300	600	450	800	180	400	250	200	180

This surface is machined using “Z-Constant” machining strategy with a depth of cut equal to 0.5mm by considering a tool for each sub region and a single tool for all sub regions. The simulated machining times are respectively 01h26’24” and 02h14’06”. The results show that a substantial saving of machining time. For this example, a significant reduction of machining times equal to 35.82% is obtained if multiple radius tools are used.

6. CONCLUSION

In this paper, a new methodology for finishing free form surfaces on 3-axis CNC milling machines using ball end mill tools is proposed. This methodology enables us, from CAD models of surfaces, the approximation of the surfaces using semi adaptive triangulation, the determination of the different sub regions of the surfaces based on the local forms of their vertices, the association of the optimum ball end mill tool that avoid the interference problems. This methodology is tested for different examples and demonstrates that machining times is reduced considerably and hence costs. Besides, the tool life and the productivity are increased especially when machining centers are used and the surfaces are composed of multiple regions of different forms. Notice that the percentage of the machining time reduction is proportional to the area of the sub regions machined with the small tool relative to the total area of the surfaces.

7. REFERENCES

[1] B. K. Choi, C. S. Jun.: Ball-end cutter interference avoidance in NC machining of sculptured surfaces, Computer Aided Design, Volume 21, pages 371-378, 1989.

[2] B. K. Choi, C. S. Lee, J. S. Hwang and C. S. Jun.: Compound surface modeling and machining, Computer Aided Design, Volume 20, pages 127-136, 1988.

[3] E. Duc. : Usinage de formes gauches contribution à l’amélioration de la qualité des trajectoires d’usinage, Thèse de doctorat, Ecole Normale Supérieure de Cachan, France, 1998.

[4] D. C. H. Yang, Z. Han.: Interference detection and optimal tool selection in 3-axis NC machining of free-form surfaces, Computer Aided Design, volume 31, pages 303-315, 1999.

[5] D. OuYang, B. A. Van Nest, H. Y. Feng.: Automatic Ball-End Milling Tool Selection from 3D Point Cloud Data, Flexible Automation and Intelligent Manufacturing, FAIM2004, pages 253-260, Toronto, Canada, 2004.

[6] D. OuYang, B. A. Van Nest, H. Y. Feng.: Determining gouge free ball-end mills for 3D surface machining from point cloud data, Robotics and Computer Integrated Manufacturing, volume 21, pages 338-345, 2005.

[7] G. Farin.: Courbes et surfaces pour la CGAO, Edition Masson, France, 1992.

[8] M. Dixon, M. Lima.: OpenGL programming guide, Addisson-Wesley Publishing Company, 1997.