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CNC tool path planning for multi-patch sculptured surfaces

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A new CNC tool path generation method for a multi-patch sculptured surface in the parametric plane is developed to obtain a minimum number of cutter location points while maintaining the required machining accuracy. In this study, a method to obtain intersecting points is suggested to generate the continuous tool path among different patches. In addition, a method of selecting a reference plane and a simple error analysis method are proposed to determine the step and side-step sizes. The effectiveness of the proposed method is demonstrated through simulation and experimental study.

1. Introduction

Once a multi-patch sculptured surface has been represented by one of the parametric representation methods in the CAD system, the next step is to obtain CNC tool paths (CL file) for the given sculptured surface part in the CAM system.

The accuracy and efficiency of the production process is dependent on the final data in machining the sculptured surface. In automatic tool path generation, the main objective of the automatic tool path generation is to obtain efficient cutter location data within an allowable machining error (Yau and Menq 1991). In general, the greater number of cutter locations, the more precise the surface will appear. However, it requires more memory storage and machining time, which increases manufacturing costs (Loney and Ozsoy 1987).

There are two types of tool path planning techniques: one is Cartesian-based, and the other is parametric-based. In Cartesian-based tool path planning, tool paths are planned on the Cartesian plane. In this method, it is common practice to plan the tool paths to be in parallel straight lines on the Cartesian plane. Then, by projecting straight lines back to the surface, actual tool paths on the object s surface are obtained. This is equivalent to finding intersecting curves between the part surface and vertical planes. The basic idea of the parametric-plane-based tool path generation is for the tool paths to be parallel straight lines on the parametric plane. The cutter paths are selected on the parametric plane, converted into Cartesian coordinate values, and used as tool paths (Bobrow 1985). The parametric plane-based method is the popular method in commercial CAD/CAM systems for sculptured surface machining because the parametric surface data can be directly utilized in the tool path generation. As a result, several NC tool path generation algorithms in the parametric plane were suggested and applied on the CAD/CAM system.

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2. Review of tool path generation methods for multi-patch sculptured surfaces

In tool path generation for multi-patch sculptured surfaces, the Cartesian-based tool path method has been used because the strategy developed for single-patch surfaces can be directly applied to the multi-patch or composed surface. This is due to the fact that the tool path is generated in the Cartesian coordinates; therefore, there is not a big difference between single-patch or multi-patch surfaces.

However, there are some drawbacks in Cartesian-based tool path planning. In the CC-Cartesian method (Choi *et al.* 1988), the most important drawback is that the cutter contact point can only be obtained through a numerical iteration method such as Newton s method. Therefore, the method is computationally very expensive, and the correct solution can only be obtained when the initial condition is well selected. In the polyhedron method (Duncan and Law 1989), which is one of the Cartesian-based methods, unavoidable errors always exist since the tool path is generated based on an approximated facet surface. The surfaces generated by NURBS (Non-Uniform Rational B-Spline) and approximated by a polyhedron method are shown in figure 1. Another disadvantage is that the tool path cannot be generated before converting the parametric surface s representation into the facet surface. In other words, the tool path cannot be generated recursively unless the distinct point sets are obtained. That may cause relatively long computational time and storage problems. Therefore, the tool path generation for a multi-patch surface in the parametric plane is more practical, because parametric-plane-based tool path planning is much simpler than the Cartesian-based tool path planning. This is due to the fact that the parametric surface data can be directly utilized in tool path generation (Chen *et al.* 1991).

Recently, Chen *et al.* (1993) studied the parametric plane to generate the tool path for multi-patch surfaces. In this study, the tool paths are generated for each patch individually. The generated paths of each patch are then sorted to connect the curves at the boundary. After sorting the curves, all calculated tool path curves are linked from the ending index point of one curve to the starting index point of the next curve to connect tool paths across the surfaces. However, in the sorting and connecting process, tool paths may not be connected to each other. Therefore, the tool movement should be modified to connect two paths at the boundary.

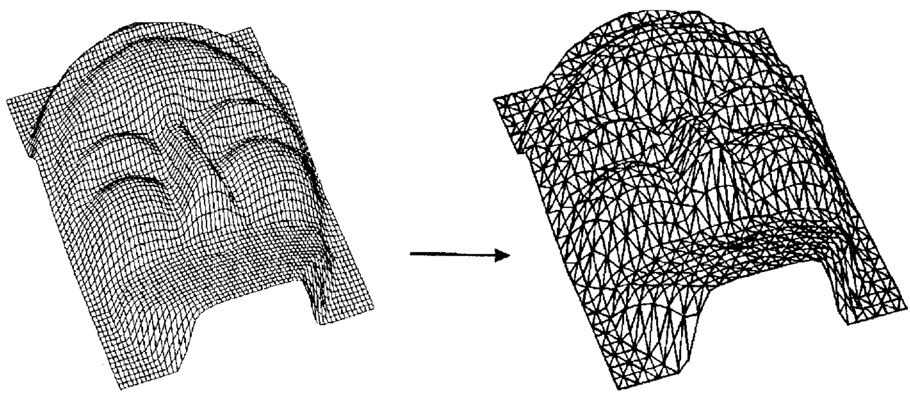


Figure 1. Comparison between surfaces generated by NURBS and polyhedron.

3. Proposed tool path generation method for multi-patch sculptured surfaces in the parametric plane

The tool path generation of multi-patch surfaces is developed for three-dimensional (3-D) CNC machining operations in the parametric domain. The proposed method can be summarized as follows.

3.1. *Preparation of CAD database*

Generally, surface models deal only with the geometric information of objects; therefore, the surface models are ambiguous when multiple patches are combined. The CAD database generated for this study contains the information of edges and control points, i.e. the topological information and geometric information. The edge data represent the boundary between two surfaces and the surface control points represents the geometric data of each surface. The sculptured surface of a mask is designed based on the NURBS representation. The mask is composed of two patches. Each patch of the mask is made of 20×50 control points, and the right side patch is a mirror of the left side patch. Both patches are joined together by adjusting the surface control points (Rogers and Adams 1990) as shown in figure 2.

3.2. *Reference plane and intersecting points*

The reference planes and intersecting points in a multi-patch sculptured surface are shown in figure 3. The reference plane is determined based on the cusp height of

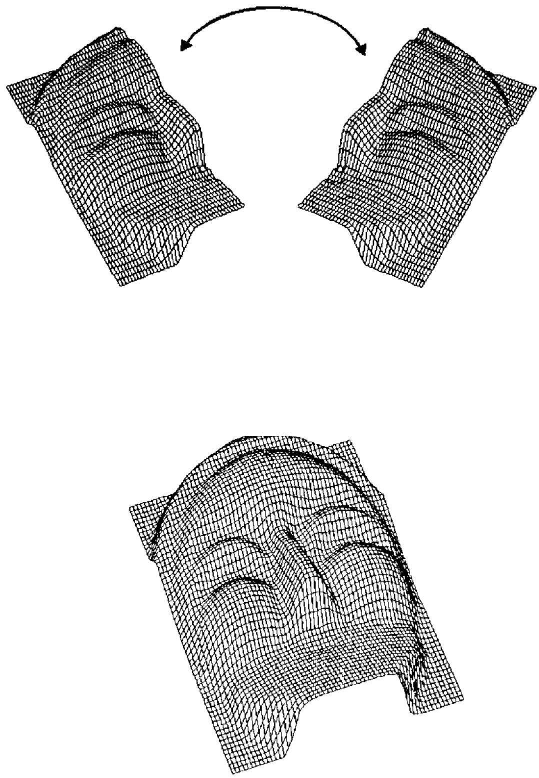


Figure 2. Design of multi-patch sculptured surface: Mask.

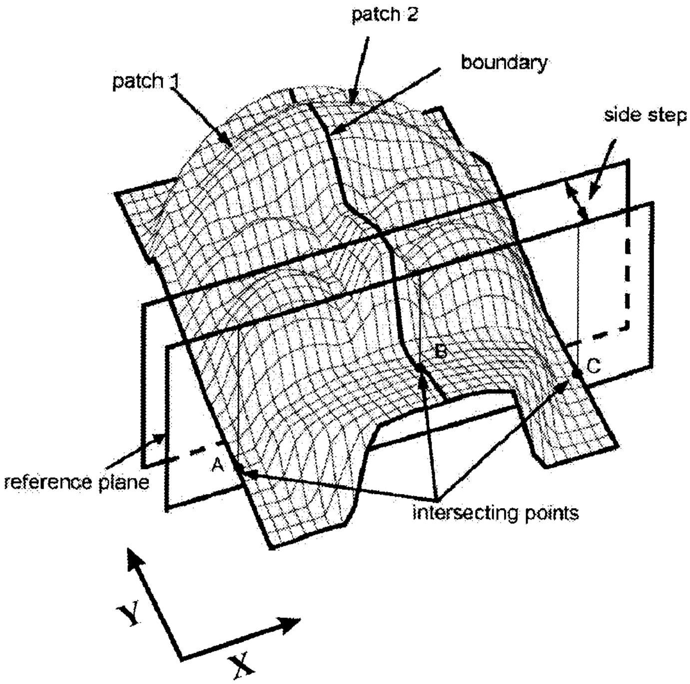


Figure 3. Reference planes and intersection points.

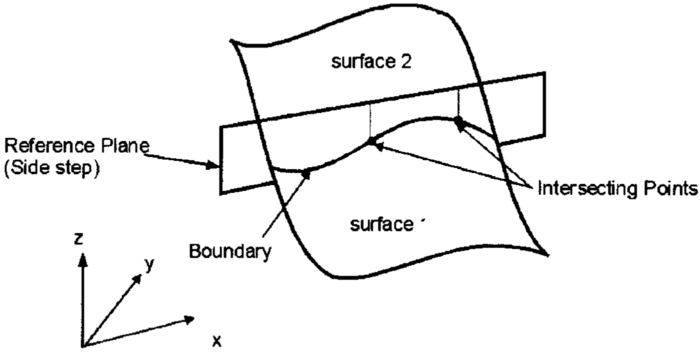
the tool path. The distance between the reference planes is the step size of the tool paths. The method to determine the step size of the tool path will be explained in section 3.3. Once the reference plane is determined, then the intersecting point between the reference plane and the boundary curve on the multi-patch surface can be obtained. The boundary curve, denoted as $C(t)$, can be represented by using a rational B-spline curve as follows:

$$C(t) = \sum_{i=0}^{n} B_i \cdot S_i, \tag{1}$$

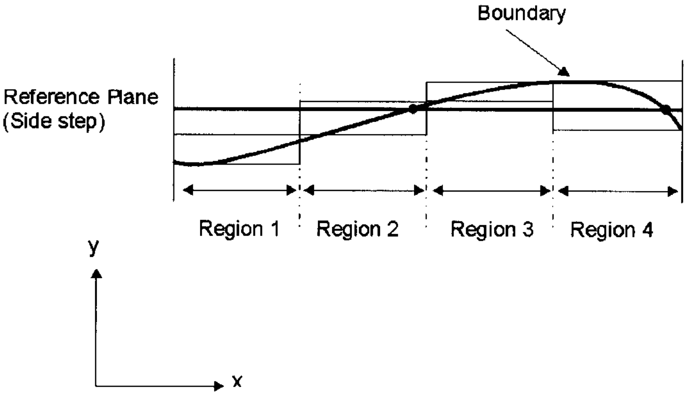
where B_i represents the control points and S_i represents the bivariant rational B-spline basis function. If the reference line, denoted l, is defined as the projected line on the xy-plane, then the intersecting points can be obtained by equating the boundary curve and the reference line.

However, to solve equation (1), the numerical iterative method is required since this is a nonlinear equation. The NewtonRaphson method is employed for this study. As shown in figure 3, there are three intersecting points, which are denoted as A, B and C. Among them, the point B is in the boundary curve between patch 1 and 2. However, the number of intersecting points on the boundary curve may be greater than one depending on the shape of the boundary curve.

Figure 4 shows multi-intersecting points on the boundary curve. In this case, the boundary curves are divided by a certain number k. Then the lower and upper limits of each subdivided region are checked as to whether or not the boundary includes the reference line. If the boundary includes the reference line, the Newton–Raphson



(a) Multiple solution for intersection points.



(b) Separate regions for detecting multiple intersection points.

Figure 4. Multiple intersecting points in the boundary curve.

method is applied and the intersecting points are obtained. The calculation will be continued until all the intersecting points are found in the separated region.

Generally speaking, each edge can be represented by the boundary of one or two surfaces. If a surface contains both edges that are detected as an intersecting curve, the surface can be easily obtained from the topological information. However, the intersecting points may be obtained at the vertex as shown in figure 5. If the tool path is assumed to move point 1 to point 2, the tool paths are generated on surface C. In this case, the surface C will be found based on the previous point 1 and the current point 2 among the surfaces containing the vertex.

3.3. *Generation of cutting tool path*

The tool path should be continuously generated from the end of one surface (surface 1) to the other end of another surface (surface 2), as shown in figure 6.

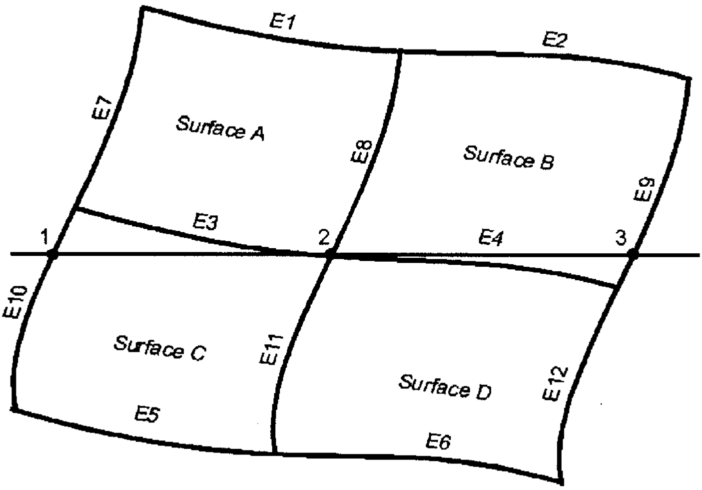


Figure 5. In case of the vertex intersected.

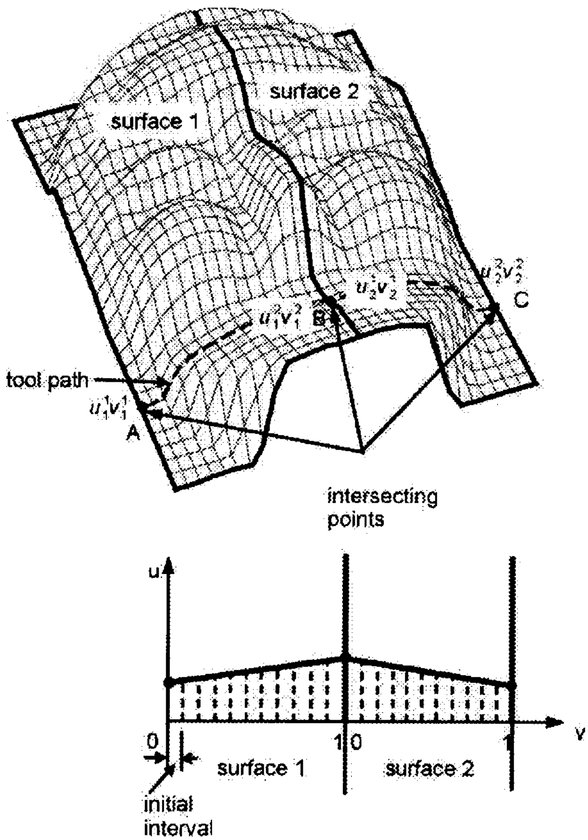


Figure 6. Parametric values of surfaces.

Once intersecting points A, B and C are obtained, the corresponding parametric values can be found from the topological data of the edge database.

In order to generate the tool path in a parametric plane, the reparametrization technique is employed for calculation convenience. The parametric values of two given points can be reparametrized by using the following equation:

$$P = P_1 + t(P_2 - P_1), \tag{2}$$

where P is u or v and t is 0 to 1. Therefore, the u and v values of points A, B and C can be obtained from the following equation.

$$\begin{aligned} u &= u_1 + t(u_2 - u_1) \\ v &= v_1 + t(v_2 - v_1). \end{aligned} \tag{3}$$

Then, the tool path (i.e. CL-file) is generated through linear interpolation in the parametric coordinates by considering chordal deviation and required tolerance. The proposed method starts with the subdivided small interval, i.e. the initial interval. When the cutting error is smaller than the required tolerance in the initial interval, the initial interval is extended by 1.5 times. If the cutting error of the extended interval is also within specification, then the intervals are combined into one interval and the combined interval is checked. If the combined interval is within the tolerance again, the interval is again extended by 1.5 times the extended interval. (i.e. 1.5×1.5 of the initial interval). The procedure is continued until the cutting error is over the specified tolerance. If the cutting error is greater than the input tolerance, the new cutter location point is added at 0.9 times the initial interval, and is then checked for tolerance. The interval is reduced by 0.9 times the previous interval until the cutting error is within the specified tolerance, and the reduced interval is checked. The scheme of the employed algorithm is shown in the inner loop of figure 7.

In this research, the simple method of calculating chordal deviation is suggested based on the following assumptions.

(1) The maximum error occurs at the middle point of two cutter contact points.
(2) The surface between the two cutter contact points is considered as the arc of the sphere since the distance between the two cutter contact points is very small.

The distance d between the cutter location and surface point at the middle point can be calculated with the following equation:

$$d = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2 + (p_z - q_z)^2}, \tag{4}$$

where p is the cutter location of the middle point and q is the middle point on the surface. Then, the chordal deviation can be calculated for cases of both concave and convex regions as shown in figures 8(a) and 8(b), respectively, based on the following equation:

$$d = |R - d|, \tag{5}$$

where R is the radius of the tool and d is the chordal deviation. As a special case, when the cutter location is lower than the surface point, the chordal deviation is obtained as follows as shown in figure 7(c):

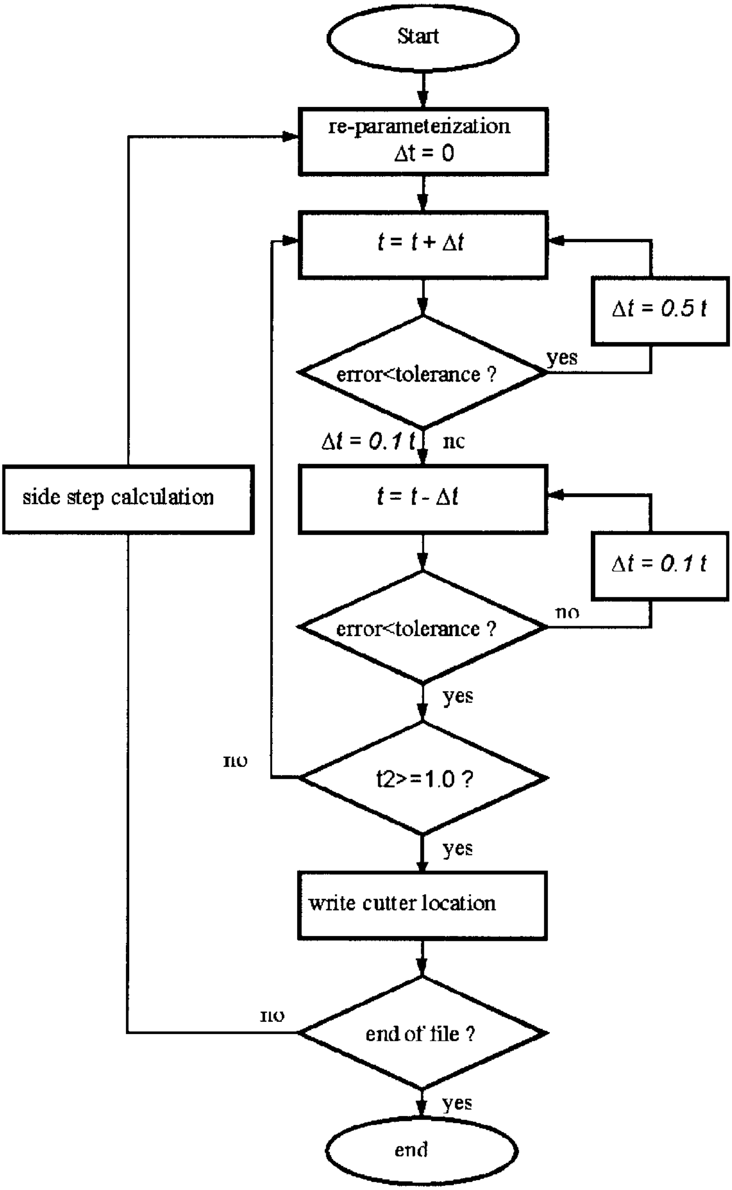
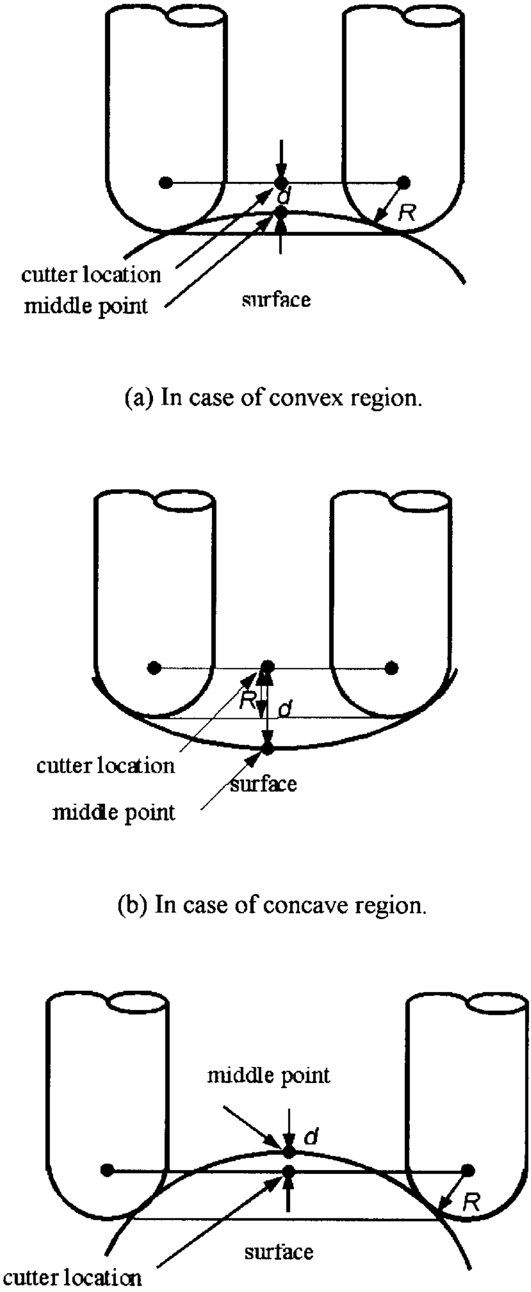


Figure 7. A simplified flow chart of the new variable step algorithm.

$$d = |R + d|. \tag{6}$$

Once the cutting tool path in one reference plane is chosen, then the next reference plane, which is a side step, will be chosen by considering cusp height and given tolerance. The cusp height can be calculated with the following equation.

$$h = R - \sqrt{R^2 - \frac{L^2}{4}}, \tag{7}$$



(a) In case of convex region.

(b) In case of concave region.

Figure 8. Chordal deviation.

where L is the distance between two cutter locations and h is the cusp height. The employed schemes are shown in the outer loop of figure 7. After generating the cutter location file, the last procedure of the proposed application is to check the tool interference. The tool interference detection and correction algorithm was presented previously (Cho and Kim 1996).

4. Experiment

To machine sculptured surfaces, the process must go through rough, semi-finish, and finish machining processes. The rough cutting removes excess volume from the row material, while the finish cutting accurately builds the part shape, as expected. The purpose of the rough cutting was to reduce the machining time rather than consider the accuracy of the shape. In this study, two rough cuttings were conducted by designing the two layers.

In tool path generation for finish cutting, both the maximum chordal deviation and maximum cusp height were set to 0.025 mm. Therefore, the imposed tolerance was 0.05 mm. The tool path for the multi-patch surfaces was generated based on the developed parametric-plane-based tool path generation method. After the cutter location file was generated, the cutter locations were checked for tool interference by implementing the proposed tool interference detection method.

The cutter location file was post-processed to interface to the CNC machine while checking tool interference. Machine G-code was the machine code to run the CNC machine. The machine code provided the machine commands, such as alignment of working coordinate, feed rate, spindle speed, and coolant supply. The given cutter location coordinates were linearly interpolated. Therefore, the greater number of cutter locations, the more precise the surface that was made. In this experiment, the tool path for the mask had a total of 56,375 cutter location points. The generated G-code with other necessary programs were listed in Cho (1995).

For the sculptured surface machining, the KIWA (model EXCEL-510) CNC machining centre (vertical type) was used. This KIWA CNC machining centre had position resolution of ±0.0025 mm, ±0.002 mm and ±0.003 mm for the x-axis, y-axis, and z-axis, respectively. The run-out of the inner face of the spindle bore was 0.001 mm at the proximal portion of the test bar and 0.013 mm at the position of 300 mm.

For the workpiece, $152 \times 200 \times 152\,\text{mm}^3$ wax blocks were used instead of steel blocks; thus reducing cutting time. The wax blocks used had the required hardness for machining and measuring. The spindle speed and feed rate were set to 3000 rpm and 350 mm/min in the G-code program, respectively. As a cutting tool, the ball nose cutter (standard length—4 flute type carbide) was used. The cutter radius was 3.175 mm (1/8 inch) and 6.35 mm for finish cutting and rough cutting, respectively.

Since the G-code programs for models require more memory than the existing CNC controller memory, the total program could not be transmitted to the CNC

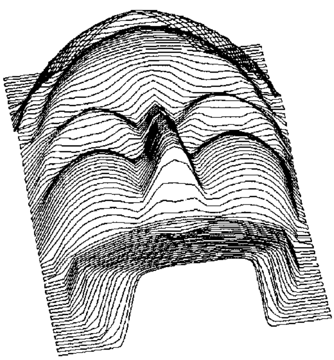


Figure 9. Generated tool path.

controller memory all at once. Additional CNC software was used to transmit the program part by part continuously, according to the machining procedure, through a RS232 cable from the PC to the CNC controller. The generated tool paths are shown in figure 9.

5. Conclusions

The purpose of this study was to construct an integrated CAD/CAM system for multi-patch sculptured surfaces by developing a new method concerned with CNC tool path planning in the parametric plane.

Cartesian-based tool path planning has some drawbacks. The most important of which is that the cutter location point can only be obtained through numerical iteration, which is computationally expensive, and the correct solution can only be obtained when the initial condition is well selected. In addition, unavoidable errors always exist in the Cartesian-based tool path planning methods since the tool path is generated based on an approximated facet surface.

Therefore, a new tool path generation method for multi-patch sculptured surfaces in the parametric plane was developed to obtain the minimum number of cutter location points while maintaining the required machining accuracy. The following are suggested to achieve the above-mentioned objective.

(1) The CAD database was reconstructed to contain the topologic and geometric information.
(2) The method of obtaining intersecting points was suggested to generate the continuous tool path among different patches.
(3) The method of selecting the reference plane and the simple error analysis method were proposed to determine the step and side-step size.
(4) The effectiveness of the suggested strategy was demonstrated through simulation and experimental study.

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