Efficient CNC Toolpath Generation Using Point Cloud

Mandeep Dhanda, Aman Kukreja, and S. S. Pande

1 Introduction

Today free form surfaces are widely found on parts used in automobile, aerospace, consumer product, and die/mold manufacturing industries. Computer-aided design (CAD) software provides excellent tools for the designers to model and edit such complex product shapes. These are commonly machined on multi-axis computer numerical control (CNC) machines, which need complex part programs to run them. However, the computer-aided manufacturing (CAM) systems which generate these CNC programs face a lot of challenges to generate the tool path [1] accurately and efficiently.

Free form surface CAD models are represented as parametric equations or mesh-based tessellated models during design. In practice, there are situations such as styling, reverse engineering on organ (medical) modeling, and worn out dies/molds wherein the exact surface equations or tessellated models are not available [2]. Point cloud data is gathered from the actual parts using a laser scanner to create the part geometry. This technique is commonly termed as reverse engineering (RE) [3].

Literature reports various research efforts made in RE, focusing on first fitting (triangulating) the surface from the point cloud and then using this surface model for CNC tool path planning. This approach is computationally complex, error-prone, and time-consuming [4–8]. Compared to the work on parametric or mesh-based CAD models, very few attempts have been reported on directly using point cloud for tool path planning, which circumvents the surface reconstruction issue and the associated problems. Zhen et al. [9] proposed multiple tool path patterns based on the projection technique. However, for a complex surface, the technique was not found

M. Dhanda
Production and Industrial Engineering Department, PEC Chandigarh, Chandigarh, India

A. Kukreja · S. S. Pande (✉)
CAM Lab, Mechanical Engineering Department, IIT Bombay, Bombay, India
e-mail: s.s.pande@iitb.ac.in

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efficient. Xu et al. [10] presented a method for CNC milling of a cloud of points by projecting guide curve techniques. The work was limited to only zigzag and contour-parallel tool paths. Xu et al. [6] reported a spiral tool path strategy by constructing the radial curves on a cloud of points. The method was not seen as suitable for complex models owing to the degeneracy in the tool path. To our knowledge, no CAM software exists as of now which accepts point cloud data as an input and generates CNC part programs (tool path) directly. In this regard, we have developed three novel toolpath planning strategies, viz. no region segmentation (NRS) adaptive planar, region-based strategy (RBS), and spiral-based strategy (SBS), to generate tool paths directly from point cloud, implemented and rigorously tested them. The three strategies are robust and efficient. However, their efficacy seems to be dependent on the part surface design. A comprehensive comparison of these strategies is not done till now. Thus, there is a need to objectively compare these strategies and come up with suitable recommendations based on productivity and quality. This paper is an attempt in this direction.

2 Toolpath Planning Strategies

Appropriate selection of toolpath patterns for CNC machining of the free form surface has a significant impact on productivity, product quality, and cost. The identification of the most efficient toolpath patterns is a complex problem with many issues involved. A proper path topology can result in the minimum path length, the minimum number of tool retractions, and the flexibility of being locally refined to match the surface's geometric properties. The direction parallel and spiral paths are most widely considered and used due to their simplicity and adaptability in engineering applications. All commercial CAM systems thus provide tool path planning based on these two paradigms.

In the present work, three tool path planning strategies, viz NRS, RBS, and SBS, have been proposed, implemented, and rigorously tested for their efficacy. The directional parallel zigzag adaptive tool path pattern has been followed for NRS and RBS strategies, whereas spiral path topology is followed in SBS. The three strategies have been developed for three-axis CNC machining to generate tool paths directly from point clouds for complex free form surfaces without the need for surface fitting. Algorithms for the strategies are briefly explained one by one in the sections to follow. For details of the individual strategies, readers are directed to the specific papers referred.

2.1 No Region Segmentation Strategy

NRS is a grid-based adaptive planar strategy. The modular diagram of the developed NRS system is shown in Fig. 1 [11].

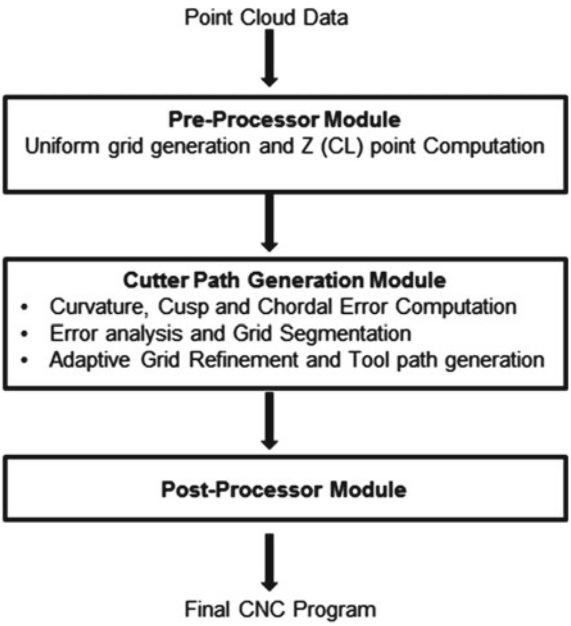


Fig. 1 Modular diagram [11]

The system has three functional modules: Data pre-processor, toolpath generation, and post-processor. The input to the system is part model point cloud data (X, Y, and Z coordinates) that can be obtained using a laser scanner. Important steps to generate toolpath using NRS algorithm are as follows [12].

1. The pre-processor module generates a uniform 2D grid (in X–Y) and Z (cutter location-CL) grid point (Fig. 2) using the inverse tool method.

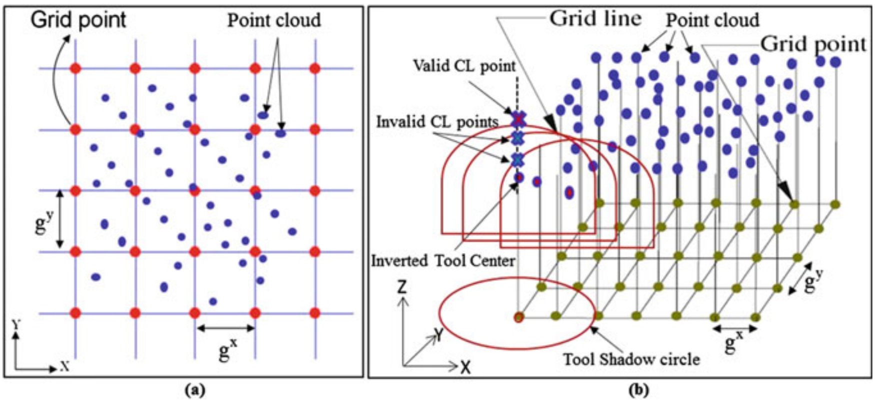


Fig. 2 **a** Uniform 2D mesh-grid generation; **b** Valid CL points generation [12]

2. Cutter path generation module estimates the value of the chordal deviation (forward error) in the *X*–*Z* plane and cusp (scallop) height (sidestep error) in the *Y*–*Z* plane.
3. Local surface curvatures are calculated in both *X* and *Y* directions from the initially generated uniform CL grid points.
4. Analysis of the estimated machined surface error is carried out independently in both the forward and sidestep directions from the generated uniform CL points. If the estimated surface error exceeds the user-specified tolerance, the grid of points is refined through segmentation. Procedure is repeated adaptively till the surface errors are under tolerance specified by the user.

Finally, the refined grid CL points are joined together in a zigzag manner to generate the adaptive planar toolpath and post-processed to generate a CNC program in ISO format. Algorithm is explained at length in our paper [11].

2.2 Region-Based Adaptive Toolpath Planning Strategy (RBS)

Though efficient, the NRS strategy sometimes produces redundant tool paths in regions of gentle slopes (near flat) of the part. To reduce the redundancy of tool paths for improving the productivity and program efficiency, RBS strategy was proposed to segment the point-based surface into different regions. Each region is machined separately, to achieve overall high machining efficiency [13].

In this strategy, curvature parameters estimated over the point data were used to partition the surface into convex, concave, and saddle-like regions by using measures of curvature, viz. Gauss (K) and mean (H) [13] (Table 1). The computation of these curvatures is carried out with the help of the first and second fundamental differential geometric coefficients of a surface [14].

Figure 3 shows the results of a typical case study. Point cloud (10,201 points, work size 100 × 100 × 50 mm) is divided into three different regions by using the estimated Gauss (K), mean (H), and combined K&H curvature parameters.

The developed NRS algorithm (Sect. 2.1) is applied in each segmented region separately within its respective segment-wise boundaries. Depending upon the type of region (surface), viz. concave, convex, or saddle-like, different tool diameters can be chosen for each region. This is primarily done with a view of achieving high

Table 1 Combined K&H conditions

Condition	Type of surface
$K > 0$ and $H < 0$	Convex
$K > 0$ and $H > 0$	Concave
$K < 0$ and $H < 0$ or $H > 0$	Saddle-like
$K = 0$ and $H = 0$	Flat

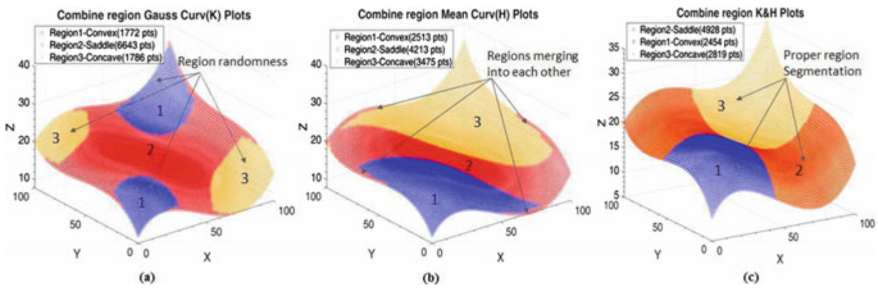
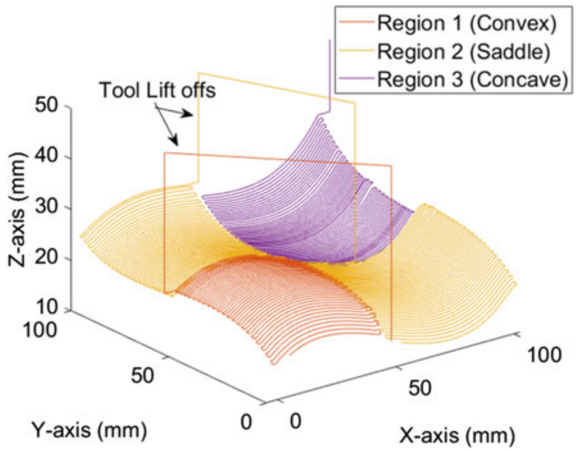


Fig. 3 Segmentation of point cloud by estimate. **a** K; **b** H; **c** combined K&H

Fig. 4 Tool path generated by RBS strategy [15]



machining efficiency by using cutters of different sizes for the segmented machining regions [13]. The tool path generated by RBS strategy is shown in Fig. 4.

In addition to the region-by-region machining, a strategy to stitch the region-wise tool path was also developed to minimize the tool lifts and tool marks. The detailed explanation of RBS strategy is presented in our paper [15].

2.3 *Spiral Grid-Based Adaptive Toolpath Planning Strategy (SBS)*

SBS is an adaptive circular (spiral) grid-based tool path planning strategy particularly aimed for parts geometries having near-circular or complex irregular shape boundaries to improve productivity and part quality. Figure 5 shows the modular diagram of the SBS system.

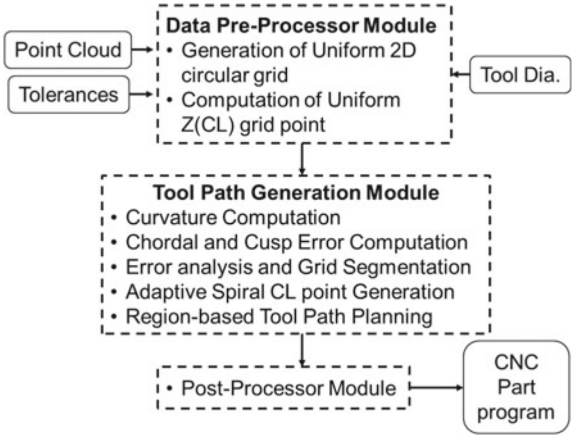


Fig. 5 Modular diagram of the spiral tool path system [16]

The point cloud data generated is given as an input to the pre-processing module, which is followed by the tool path generation for obtaining the final adaptive CL points. Post-processor module connects these CL points to create a continuous spiral tool path and generate the CNC part program.

Important steps of the computation of tool path CL points are as follows [16].

1. The point cloud data (in 3D space) is projected onto the *XY* plane to find out the extent and to form a uniform circular grid (Fig. 6a).
2. After the construction of the grid, it is shifted by the point cloud center *C* and mapped to the input point cloud data.
3. Using the circular mesh-grid, Z_{CL} points are computed at each grid point in radial and circumferential directions using the inverse tool offset algorithm (Fig. 6b).
4. The tool paths are defined as a sequence of valid CL points using linear interpolation.

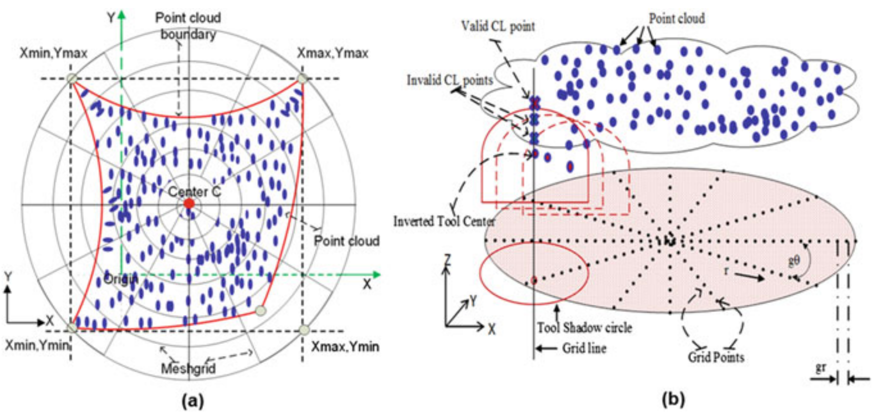


Fig. 6 **a** Grid mapping to point cloud; **b** Computation of ZCL at grid points

5. The initial (uniform) grid-based spiral tool path generated is analyzed for chordal and scallop errors likely to be produced, and the grid is adaptively refined to generate the adaptive spiral tool path.
6. These adaptive spiral tool paths are further refined to eliminate the redundancy in machining and generate optimum region-wise tool path planning to minimize the tool lifts and generate the final adaptive CL points. The CL points are post-processed to generate the final CNC part programs in the ISO format.

The detailed explanation of SBS strategy is presented in our paper [16].

3 Comparison of the Strategies

The developed strategies are compared in terms of their relative performance parameters (machining time, tool path length, code length, and average scallop) along with the commercial software Mastercam to benchmark their performance. For the comparison purpose, two typical free form part models (Bezier and Mouse) have been taken, and the results are analyzed.

3.1 Case Study 1

Figure 7 shows the part model point cloud data (X, Y, and Z coordinates) of a complex parametric Bicubic Bezier Surface Patch of work size $100 \times 100 \times 40$ mm. It was designed with 16 control points, and 10,201 uniform points on the model were extracted from it to form the point cloud.

The toolpath is generated using the three different strategies over the point cloud CAD model as shown in Fig. 8.

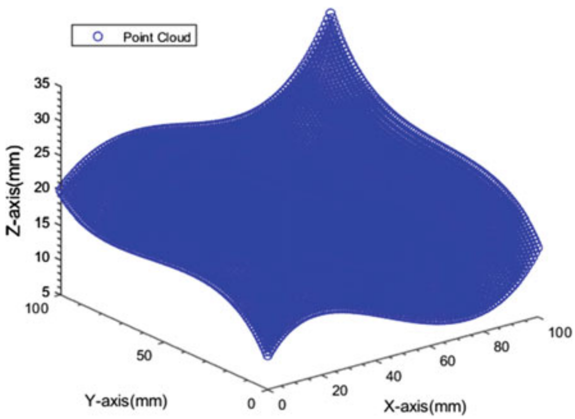


Fig. 7 Point-based CAD model-case 1

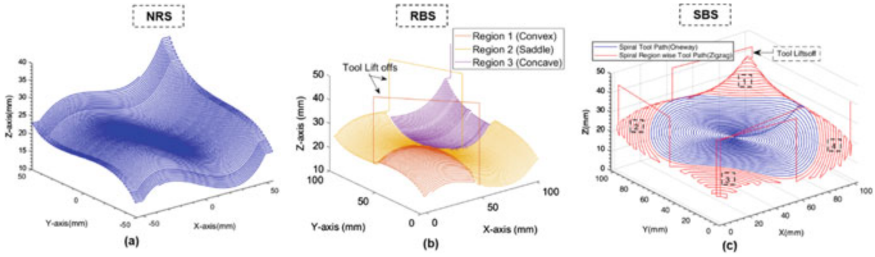


Fig. 8 Tool path **a** NRS; **b** RBS; **c** SBS—case 1

Table 2 Comparison of the strategies—case 1

Strategy	Performance parameter			
	Machining time (MM: SS)	ToolPath length (mm)	Code length (No. of blocks)	Average scallop (μm)
RBS	78:14	10,005	2987	40
NRS	91:23	11,732	3704	38
SBS	93:13	12,028	3926	32

Results show that all three strategies are robust and consistent in generating adaptive tool paths. To find an optimal strategy, a comparison has been done in terms of performance parameters of the tool path (Table 2).

It is seen that the performance parameters (machining time, tool path length, and code length) for RBS strategy are less than their corresponding values given by NRS and SBS strategy. The average scallop is seen to be under control (user specified 50 μm) for all the strategies. There is no significant difference in the performance parameters given by NRS and SBS strategy.

3.2 *Case Study 2*

Figure 9 shows a part model point cloud data (X, Y, and Z coordinates) of a computer mouse taken from GrabCAD [17]. The part model has a size of 100 × 60 × 35 mm; 32,852 points were extracted from the STL model to form the point cloud.

The toolpaths were generated for the three different strategies over the point-based mouse model as shown in Fig. 10.

All strategies generated robust and consistent adaptive tool paths. (Fig. 10).

Table 3 shows the comparison of the performance parameters for the various strategies. It is seen that for this typical complex part, the performance of the SBS strategy is better than NRS, and the machining time, tool path length, and code length are reduced by 2–3%, while the average scallop value is less by 25%.

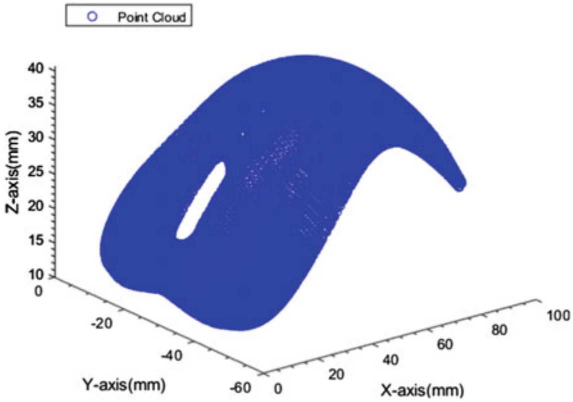


Fig. 9 Point-based CAD model—case 2

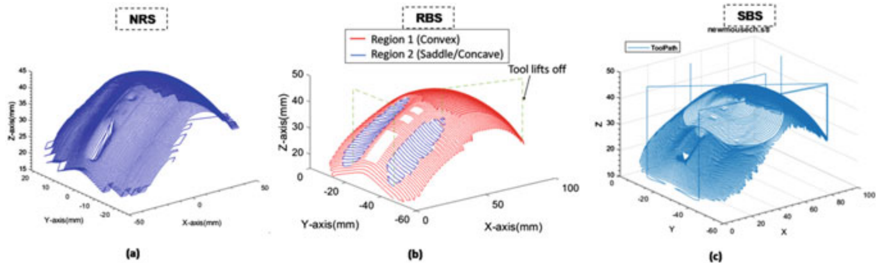


Fig. 10 Tool path **a** NRS; **b** RBS; **c** SBS—case 2

Table 3 Comparison of different strategies—case 2

Strategy	Performance parameter			
	Machining time (MM: SS)	Tool path length (mm)	Code length (No. of blocks)	Average scallop (µm)
RBS	62:41	8194	2717	46
NRS	67:43	8903	2870	40
SBS	65:37	8714	2793	32

For both the case studies, the performance parameters (machining time, tool path length, and code length) for RBS strategy seem superior (less) than their corresponding values given by NRS and SBS strategy. However, the relative reductions between them seem to be dependent upon the part geometry as well the strategy. In particular, the reductions in values for RBS systems compared to NRS are machining time (7–14%), tool path length (8–15%), and code length (5–19%). The reductions in values for the RBS system compared to SBS are machining time (4–16%), tool path length (6–16%), and code length (3–23%). For the case study (C1), performance parameters for NRS are less as compared to SBS. While, for case C2, the parameters for SBS are less compared to NRS.

The average scallop is seen to be under control (user specified 50 μm) for all the strategies. The average scallop of SBS strategy is seen to be less (20–30%) as compared to other strategies indicating that SBS strategy can produce better surface part quality as compared to NRS and RBS, but at the cost of some loss of productivity. It is also seen that NRS performs better than RBS in terms of average scallop, giving reduction of 15–20% but again at the expense of some productivity. The % reduction varies from part to part.

All our developed strategies (NRS, RBS, and SBS) perform better than commercial software Mastercam [11, 15, 16] and are unique as no commercial CAM software is able to generate CNC tool paths directly from the point cloud.

3.3 Observations and Inferences from Case Studies

Based on the critical quantitative comparison of the three developed strategies (NRS, RBS, and SBS), the following recommendations have been made to choose the efficient strategy.

1. Considering productivity point of view, the RBS strategy can be chosen as the most suitable candidate, provided the surface can be segregated into different regions (convex, concave, and saddle).
2. From the surface quality and constant tool-workpiece engagement, the SBS strategy can be preferred. It is also best suited for part geometries with near-circular or complex irregular shaped boundaries.
3. For rectangular/square part shapes with less undulation, the NRS strategy is found to be more efficient and can be preferred over the other strategies.

4 Conclusions

This work presented a critical quantitative comparison and guidance to choose an efficient toolpath planning strategy for machining a complex free form surface directly from the point cloud representation without the need for surface reconstruction. Three algorithms (NRS, RBS, and SBS) were proposed, implemented, and rigorously tested. It was concluded that for rectangular/square part shapes with less undulation (low variation in curvature), the NRS strategy could be preferred over the other strategies. If a part shape has more undulation (more variation in curvature) and can be segmented into proper convex, concave, and saddle regions, the region-based (RBS) strategy is always better than the other strategies. RBS strategy is superior from the productivity point of view. For circular or near-circular/irregular/complex part shapes, the spiral strategy (SBS) is a better candidate, being preferable from the part quality consideration also. All the strategies are robust, accurate, and generic in nature.

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