Recent development in CNC machining of freeform surfaces: A state-of-the-art review

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ABSTRACT

Freeform surfaces, also called sculptured surfaces, have been widely used in various engineering applications. Freeform surfaces are primarily manufactured by CNC machining, especially 5-axis CNC machining. Various methodologies and computer tools have been developed in the past to improve efficiency and quality of freeform surface machining. This paper aims at providing a state-of-the-art review on recent research development in CNC machining of freeform surfaces. This review primarily focuses on three aspects in freeform surface machining: tool path generation, tool orientation identification, and tool geometry selection. For each aspect, first concepts, requirements and fundamental research methods are briefly introduced. The major research methodologies developed in the past decade in each aspect are presented with details. Problems and future research directions are also discussed.

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1. Introduction

Freeform surfaces, also called sculptured surfaces, have been widely used in aerospace, automobile, consumer products and the die/mold industry. Freeform surfaces are usually designed to meet or improve an aesthetic and/or functional requirement. The definitions of freeform or sculptured surfaces are intuitive rather than formal [1]. Often they are defined as surfaces containing one or more non-planar non-quadratic surfaces generally represented by parametric and/or tessellated models.

3- and 5-axis CNC machines have been most widely used in machining freeform surfaces. Five motions can be continuously and simultaneously controlled in a 5-axis machine. Translational motions in the X, Y and Z directions and two rotational motions are either applied to the tool holder or the machine table or both [2]. Compared to 3-axis machines, 5-axis machines can produce complex surfaces with better quality and efficiency. 3 ½ machines have also been used due to a lower initial and operational cost. They have better stiffness compared to 5-axis machines because the rotary axes are locked during the cutting movement of the tool [3]. However unlike 5-axis machines, in 3 ½ machines orientation cannot be continuously adjusted during cutting process [2], thus requiring longer machining time.

Stages to complete freeform surface machining are usually classified into rough, semi-finish, finish, clean-up and final polishing and treatment. In rough cutting, most of the material is removed from the surface to generate an approximate shape of the surface. Shoulders left from the roughing stage by large machine tools are removed in semi-finish to yield a continuous offset surface for finishing [4]. At the finishing stage, the rough surface is transformed into the exact shape. Another method classified the stages as rough, finish and clean-up [5]. In this review, we use the 3-stage scheme throughout the paper. During clean-up machining, the uncut volumes that have not been machined in the finishing stage due to the use of larger cutters are removed. Thus clean-up regions play an important role in reducing the machining time of complex surfaces [5].

The concept of tolerance is used to measure quality of freeform surface machining. An upper bound and a lower bound should be considered for a designed freeform surface. The former controls the maximum scallop height while the latter corresponds to gouging. For a surface to be machined within the designed tolerance, the scallop height should not exceed the maximum allowed tolerance and the surface should be gouge free.

Gouges are classified into 3 categories: local, rear and global gouges as shown in Fig. 1. A local gouge occurs when the effective radius of curvature of the tool in the cutter contact (CC) point is larger than that of the surface. A rear gouge happens when the bottom of the tool interferes with the surface in the points other than the CC point. Local and rear gouging happens in saddle and concave surfaces [6]. Global gouging (or collision) results from the interference between the part’s surface and the non-cutting areas of the tool such as the tool shaft or tool holder. In the presence of a gouge, the surface accuracy and texture specifications are not satisfied and/or serious damage may happen to the part’s surface and machine tool.

Several techniques have been developed for gouging avoidance. For local gouging, methods based on matching the curvature of the surface at the CC point and the effective tool curvature have been most widely used [7–13]. Methods for proper tool orientation [14–18] have mostly addressed rear gouge avoidance. Among the methods for the identification of global gouging (or collision), feasibility cone checking method [19] and configuration space method [18,20–22] demonstrated effectiveness. A comprehensive review on most recent gouge detection and avoidance methods can be found in [23].

To machine a freeform surface with a 5-axis CNC machine, cutter location (CL) points generated by tool path planning, tool orientation at each point, tool shape and size, spindle speeds, and the traveling velocity of the CL points need to be considered. This state-of-the-art review focuses on the three most important issues: tool path generation, tool orientation identification, and tool geometry selection. These issues are related to each other [24]. However in 5-axis machining, because of the complex nature of the problem, it is difficult to solve the whole problem considering the optimality of all relevant aspects such as path pattern, path length, path parameters, tool orientation, smooth orientation changes, tool size, scheduling of the feedrates as well as other objectives to avoid gouging [15]. As a result, many researchers try to solve these problems separately.

It should be noted that three major reviews on freeform machining have been observed by the authors [25–27] that cover the research issues up to 1997. The review of the present paper, however, focuses on recent developments from 1997 up to 2008.

The rest of this paper is organized as follows. The three main aspects in freeform machining, including tool path generation, tool orientation identification, and tool geometry selection, are discussed in Sections 2–4, respectively. For each aspect, first concepts, requirements and fundamental research methods are briefly introduced. The major research methodologies developed in the past decade in each aspect are presented with details. Problems and future research directions are also briefly provided in each section.

2. Tool path generation

2.1. Overview

Tool path planning is a critical task in the machining of freeform surfaces. Specific constraints are applied in path planning for different machining stages to achieve the optimal time and quality. For example in finish machining, the machining time should be minimized while the scallop height must be maintained below the specified level. An ideal tool path should generate uniformly distributed scallops across the whole surface [28]. Smaller scallop size does not necessarily mean a better tool path, since it is achieved at the cost of increased machining time. On the other hand, the minimum machining time will be achieved when the scallop height is set to the maximum allowable measure. Tool path planning is composed of 2 aspects: path topology and path parameters. The former is defined by the pattern that the cutter moves to produce the surface, and the latter is modeled by the tool side step between successive paths and the tool’s forward step in each path. Many researches have been carried out on the optimization of the tool path in these two areas.

Hence the tool path generation problem will be converted into the following sub-problems: with a defined cutting tool, (1) specify path pattern and the linking strategy (path direction), (2) specify points on the surface that the tool should track, and, (3) check tool local and global interferences.
2.1.1. Path topology and parameters

Each tool path generation is conducted by selection of path topology and path parameters [29]. For machining, the cutter traces a sequence of CC points to approximate the freeform surface, and the pattern of tracing is called tool path topology. Path topology and the method of linking the generated paths directly affect the machining time [30]. A proper topology can result in the minimum path length, the minimum number of tool retraction, and the flexibility of being locally refined to match the surface’s geometric properties. Many researches have focused on minimizing the total path length and the number of tool retraction [30–33]. For milling of freeform areas, contour parallel and direction parallel paths are most widely used. Strip normal and parallel paths are suitable in the machining of clean-up areas [5,34]. It has been shown that a strip parallel pattern generates tool paths with the minimum number of retractions for clean-up machining [34].

In a direction parallel path, path segments are parallel with a predefined line (Fig. 2(a)). This line could be parallel or normal to the surface boundary or parallel with the axis of a specified coordinate system. Proper selection of the reference line directly affects the generated path length [36]. Specifically, the optimum path direction will result in longer individual paths and the minimum non-cutting movements of the cutting tool. A specific case of direction parallel path, zigzag path, is commonly used in commercial CAM systems for roughing [8,37].

A contour parallel path is constructed by the boundary curves of the surface [38]. Each path is an offset of the boundary of the surface. Voronoi diagram, pair-wise offsetting and pixel based approaches are used to generate the 2D offsets in contour parallel paths [31,33,39]. These methods may be computationally expensive [40]. The paths in the pattern could be spirally connected or each path could be independently an offset of the boundary (Fig. 2(b)). Kim and Choi [30] and El-Midany et al. [41] compared the machining time for direction- and contour-parallel paths by considering the feedrate acceleration and deceleration. In both researches, the machining times for different direction- and contour-parallel paths were compared by using a linear feedrate acceleration/deceleration model. El-Midany et al. [41] concluded that the selection of the optimal path topology depends on the geometry of the surface’s boundary and the cutting conditions. Kim and Choi [30] mentioned that although pure zigzag path (with sharp corners) results in a longer machining time compared to contour parallel path, it is practically preferred to contour parallel in and mold machining because of enhanced constant cutting loads. An investigation of optimal path pattern selection for layer-by-layer rough cutting has been carried out by Li et al. [42]. In this method, the optimal path topology for each layer was selected by fuzzy pattern analysis among a variety of topologies in a path topology database. So for each roughing process, more than one pattern could be selected to machine all layers based on the geometry of these layers.

Cox et al. [43] introduced the space filling curves (SFCs) for finish tool path generation of freeform surfaces considering that parallel or spiral line pattern is not the best way of traversing the tool in an area. They used truncated Palmer’s and Moore’s curves to avoid overlapping and crossing points in the generated tool paths. However, this truncation method doubles the number of lines to be traversed and sharp edges still remain in the tool paths. Marshall and Griffiths [38] mentioned that extensive changes in path direction decrease a tool’s life when using space filling curves. They used Hilbert’s curve to avoid this problem. The order of the curve can be locally adjusted for the areas that need finer cuts. However, this increases the number of lines in the whole refined areas by a factor of 2 that causes the efficiency problem. Furthermore, sharp corners are rounded by Bezier curves, thus improving the machine’s dynamic behavior [37]. SFCs method is not popular in 5-axis machining due to the path convolution, frequent changes in path direction and the computational difficulties.

SFCs have also been generated based on local optimal cutting direction to produce a shorter tool path [35,44]. The process is composed of three steps: grid construction, SFCs generation, and correction of generated SFCs. The curvilinear space filling curves introduced by Anotaipaiboon and Makhanov [35] can improve local adaptation and decrease frequent changes in machining directions usually observed in SFCs. In this work, the space filling curve was developed based on the rectangular grid generated from locally adaptable parametric curves in 2 directions (Fig. 2(c)). The rectangular grid is the result of an expensive numerical optimization with tolerance constraints. Optimal grid connection (path linking) is modeled as a traveling salesman problem. The generated tool path is locally adjustable, and the optimization tries to find the minimum tool path length, with the minimum tool retractions and sharp corners.

Based on the strengths and limitations of different path patterns investigated above, the direction parallel and contour parallel paths are considered the most widely used ones due to their simplicity and adaptability in engineering applications. Although space filling curves have found different applications such as in automatic polishing [45] and shape representation, they are not popular in 5-axis machining due to the path’s complexity, frequent changes in cutting direction, and the machine tool’s dynamic problems [46].

In addition to the path pattern, the tool path should include path parameters which are defined by side step and forward step. The resulting machining error is closely related to these parameters. As mentioned above, the cutter traces a sequence of CC points along the path pattern to machine the surface. The distance between consecutive CC points is called forward step denoted by f in Fig. 2. The distance between 2 adjacent paths is called path interval (also side step or stepover) denoted by w in Fig. 2.

Two methods are often used to calculate the forward step parameters: circular arc approximation [8,47] and maximum chordal deviation [6,8,48]. Although in most of the tool path generation methods, line segments are used to define the lengths of the forward steps, interpolation of the generated tool paths with polynomial curves has also been carried out [49–52]. This will
reduce machining time when the tool path is transformed to machine axis movements by the NC unit, and decrease the size of memory required inside the CNC controller (which is large when the tool path is represented by line segments). Path interval is determined by scallop height, cutter geometry and surface geometry information. The number of CC points is related to side and forward steps. In general with the larger numbers of CC points, the surface will appear more precise and with smaller scallops. But on the other hand, CPU time, memory usage and the machining time will increase with the large numbers of CC points.

2.1.2. Requirements

Based on the above discussions, a tool path is developed by selecting the path's topology and parameters considering the accuracy and time constraints. Hence a generated tool path can be evaluated by the following 3 criteria [38,53]:

- **Quality**: The generated tool path must be gouge free and the scallop height should be within the specified tolerance. These requirements are controlled by path parameters.
- **Efficiency**: Two types of efficiency measures need to be considered: (1) efficiency in simulation based on CPU time and memory usage, and (2) efficiency in the actual machining time. Efficiency is achieved by the system through generating and simulating different path topologies and parameters and identifying the optimal one.
- **Robustness**: We consider robustness as an adaptation capability with the different surfaces and machines. A robust system should be able to work with multi-patch surfaces and their continuity conditions. It should work for both parametric models and tessellated models. A robust system should allow for selecting among a variety of tool paths with different topologies and parameters. The machine's kinematic limitations should also be taken into consideration.

2.1.3. Traditional methods

Traditionally iso-parametric and iso-planar methods have been used for the tool path generation [10,48,54-56]. The iso-parametric paths have first been addressed by Loney and Ozsoy [57]. In this method by keeping one of the two parameters constant, CC points are generated along the other parameter of a parametric surface \(S(u,v)\). The iso-parametric method is popular for freeform surface machining, because the surface data are directly utilized in the tool path generation [48]. However the path interval (i.e., the constant parameter increment) is controlled by the scallop height constraint. Since a line in the parametric domain is usually mapped nonlinearly to the Euclidean space, a constant step in the parametric domain results in unequal path intervals between adjacent paths [8]. This leads to non-uniform distribution of scallops across the surface and affects machining efficiency [53,58,59]. Besides it is difficult to generate tool paths by the iso-parametric method in surfaces consisting of several trimmed surfaces [60].

An iso-planar tool path is developed by intersecting the surface with parallel planes in Cartesian space. The side step (i.e., the distance between the parallel planes) is decided based on the scallop height constraint. This method is very robust and widely used in commercial CAM systems [46]. Unlike the iso-parametric method, the iso-planar method can be used for compound and trimmed surfaces [61] and triangular meshed models. However proper selection of the intersecting planes in this method greatly affects the path length and machining time.

It is evident that both the iso-parametric method and the iso-planar method lead to conservative path intervals in an attempt to control the scallop height [10,58,61]. Only at certain points of the surface, scallop heights are close to the design constraint, and in other areas unnecessary high surface quality is achieved which leads to non-optimal machining time. Iso-scallop machining was introduced by Suresh and Yang [47] and Lin and Koren [62]. The iso-scallop height method is an improved version of the iso-parametric and iso-planar methods. Based on this method, scallop heights are the same everywhere in the surface. Most of the recent methods have focused on the development of iso-scallop tool paths.

In iso-scallop tool paths, a master path can be selected from one of the surface boundary curves from which the other paths are constructed [7,47,62,63]. Each CC point in the next cutter path \(P_{j+1}\) is calculated from the CC point of the current path \(P_j\), so that the scallop height remains the same (or the maximum allowable tolerance) all over the surface. The direction of side step at each CC point is normal to the cutting direction at that CC point. The newly generated CC points form the new cutter path which can be fitted to a cubic spline on which new cutter points are determined by forward stepping. This secondary path is then used as a master path for generating another path. Although this method works for every kind of surface and significantly reduces the number of CC points and the path length, it suffers from its computational complexity. Another issue is the accumulation of errors due to the numerical fitting of cubic splines from the master path to the last one.

With the same scallop height, the path interval in concave areas was found to be larger than that of convex areas [62]. By utilizing this result, Giri et al. [63] suggested that the direction of the maximum convex (or the minimum concave) curvature should be selected as the initial cutter path for iso-scallop machining. The *machining potential field approach* developed by Chiou and Lee [64]...
is another method for the selection of the master cutter path based on the maximum material removal rate in the first path. Kim and Sarma [65,66] suggested the selection of the maximum kinematic performance (i.e., fastest path according to machine's structure) along with the maximum material removal rate for the first cut path. They defined the machining time as a function of cutting speed, cutting direction and side step which should be minimized in presence of a few machine and surface constraints. However the developed method is not generic and needs structural information of the specific machine tool [67].

2.2. Recent developments

Many new tool path generation techniques have been developed in recent years to solve different problems in 5-axis machining. Some of the typical problems include how to reduce simulation and actual machining time, machining of compound surfaces and non-parametric surfaces, innovative techniques leading to decreased machining and investment cost, etc. Our classification is based on an extensive study of the large body of literature on tool path generation techniques. For most of the methods, path topology and parameters, gouge detection techniques, as well as the improvement compared to the traditional methods, will be discussed.

2.2.1. Curvature matched machining

Curvature matched machining is a tool path generation and tool positioning method based on matching the curvatures between the cutting tool and the workpiece surface at the cutting point. Isoscallop gouge free tool paths can be generated for parametric or triangular meshed surfaces. Based on this method, the effective curvature of the tool should be smaller than or equal to that of the surface at the CC point. As a result of this assumption, local gouging is automatically avoided in the generated tool path. Two methods have been presented by Jensen [68] for curvature matching: the instantaneous approach and the swept silhouette approach. The instantaneous approach analyzes the cutter's movement at each CC point, while the silhouette approach considers the volume swept by the cutter during movement between two CC points.

In a 5-axis machine, the cutter can be tilted towards the feed direction to match the surface curvature at CC point. Fig. 3 shows tool coordinate system (x, y, z), surface coordinate system (x, y, z), local coordinate system (xL, yL, zL), and the global machine coordinate system (xG, yG, zG). z axis is along the direction of surface normal at the CC point in the 3 coordinate systems. x and y in the surface and tool coordinate systems are along the principal directions, and yL is the feed direction at CC point. xL is the cross product of yL and zL, α is the tilt angle, and β and δ are the angles between xL and the surface and tool principal direction respectively. When θ = 0, the cutting direction aligns with the tool's principal direction and the tool has the largest effective curvature. When λ and β are equal to zeros, tool and surface principal directions overlap each other and with xL. In this situation, the maximum machining strip width and path interval are achievable. However to avoid gouges, especially to avoid global gouges, it is not possible to set θ equal to zero. It should be noted that throughout this paper, ω (tool rotation about surface normal zL) is considered as inclination angle. The fillet end tool surface at the CC point in the tool's coordinate system is given by [8]:

\[ z_t = \frac{1}{2} (\kappa_1 x_t^2 + \kappa_2 y_t^2) \]

where \( \kappa_1 \) and \( \kappa_2 \) are principal curvatures of the cutting tool. By using Eq. (1) and the transformation, the tool projection in the plane with the same normal to feed direction (i.e., xLzL) in the local coordinate system can be derived. The same procedure can be applied for the part's surface. The effective tool and surface shape are used to estimate the machining strip width and tool path interval for iso-scallop tool paths (Fig. 4). It should be noted that these calculations for matching the tool and surface projected curvatures are only required for concave and saddle areas. For convex or flat areas, the tilt angle (α) should be selected as zero or near zero [69]. The projected shape for a generalized cutter has been studied by Chiu and Lee [9,64]. The effective curvatures of the cutter and workpiece surfaces can be calculated and compared in the local coordinate system.

In a similar manner, Lee and Ji [70], and Lee [7] used the effective cutting shape in the instantaneous cutting plane to find its intersection with the projected surface offset. The left and right machining strip widths found in each CC point are then used to calculate the path interval for the points in adjacent paths. However in both methods, the numbers of CC points in all the consecutive paths are the same. To overcome this problem, Lee [7] suggested selecting the longest surface of the boundary as the initial path and checking and bisecting the path segments that are out of the tolerance zone. Another method is to pass a spline through a set of all the newly generated points and find forward steps for the new curve [63]. Yoon et al. [12] developed an accurate mathematical solution to calculate the machining strip width and interaction between the part's surface and cutter at CC point based on the curvature matching.

Master cutter path for iso-scallop machining could be identified by curvature matching concept. Machining potential field approach developed by Chiu and Lee [64] defines the path with the maximum average machining strip width as the starting path amongst the potential paths across the surface. Maximum averaged machining strip width is the total swept area of a cutting tool divided by the total path length.

2.2.2. Isophote based methods

Isophotes are points on a surface with the same light intensities [46]. An isophote is a region on the surface where the normal direction
vectors \( n \) in all the points of the region are equal to a reference vector \( V \) (usually \( z \) axis) by a predefined tolerance called the inclination range (Fig. 5). In iso-inclination partitioning, the surface is segmented into regions which have the same normal, and hence the same path interval is required to machine the points on the surface. This method has been mainly applied in 3-axis machining. The iso-inclination angle \( \theta \) for a point \( P(u_i, v_j) \) on the parametric surface with reference vector \( V \) is given by:

\[
\theta = \cos^{-1}\left(\frac{\nabla P_{u(i,j)} \times \nabla P_{v(i,j)}}{|\nabla P_{u(i,j)}| \times |\nabla P_{v(i,j)}|}\right) \cdot V. \tag{2}
\]

In the method developed by Han and Yang [46], the free form surface is first segmented into iso-inclination regions. Then for tool path generation after partitioning, the iso-inclination curves of the boundaries are projected to a plane perpendicular to the reference vector. Paths are generated in this plane and then projected back to the 3D surface. The path interval is considered to be the same all over the projected 2D plane and calculated as follows:

\[
w = D \cos(\theta_{i+1}) \tag{3}
\]

where \( D \) is the approximation of path interval in 3D space for the iso-inclination curve with the minimum inclination angle, and \( \theta_{i+1} \) is the upper boundary of the inclination range as shown in Fig. 5. This ensures that the design tolerance is satisfied. However, the scallops are not constant in the iso-inclination anymore. To address this problem, an allowable variation for scallop heights can be specified with which the inclination range is defined for the surface’s partitioning.

In the research by Han et al. [6], a freeform surface was approximated by a ruled surface based on the isoplane method. Iso-inclination curves were used as generators for the ruled surface and also as the boundary curves for the tool path generation. An adaptive iso-planar method was used by Ding et al. [61] for the tool path generation after iso-inclination partitioning of freeform surfaces. It should be noted that in surfaces connected with \( C^0 \) continuity, iso-inclination curves break at the edge of the junction and do not form a closed loop [61]. Decision on uniting or separating these regions is not an obvious choice. In the global-local path planning strategy by Ding et al. [61], first a global iso-planar path is developed for all the surface regions. Then the path is locally adjusted for the regions with higher inclination ranges to satisfy the scallop height constraints. Yang and Han [71], Yin [72], and Yin and Jiang [73] have also reported applications of this method in generating tool paths.

Currently developed tool path generation methods based on iso-plane partitioning are fairly accurate, simple, and computationally inexpensive. However further improvements still need to be carried out. More accurate calculation of path interval with iso-scallop point-by-point strategy for each iso-plane region could be conducted. Since the shortest path length and the minimum number of tool retractions are often used as criteria to evaluate cutting paths, the optimum path linking strategy could be investigated for linking the generated paths for the regions.

2.2.3. Configuration space methods (C-space methods)

Choi et al. [20] and Morishige et al. [21] employed the configuration space (C-space) technique in tool path generation. The configuration space (C-space) of a rigid object with a certain degrees of freedom is defined as the space of the parameters corresponding to the degrees of freedom. Each point in the C-space represents one configuration. By considering the design tolerance and mapping the obstacles corresponding to the local and global gouges in the C-space, the problem of tool path planning can be converted into the problem of planning the movements of a point in the C-space [20,22]. The 2D C-space of the tool at the CC point is constructed by only considering two orientation parameters of the tool (\( \alpha \) and \( \omega \) in Fig. 2) and removing the configurations with collision from the available space [21]. Then the optimal parameters are selected in the C-space based on the maximum machining efficiency.

The 3D C-space is constructed by adding the tool motion parameters to the 2D C-space. Morishige et al. [22] and Lu et al. [18] developed different approaches for building 3D C-spaces. In the research by Morishige et al. [22], the aim is to find a 3D curve that describes the evolution of tool postures through CC points. The method by Lu et al. [18] first constructs the C-space by finding the upper and lower surface boundaries corresponding to scallop and gouge in each orientation set at the CC point. Then the optimal 3D set for a tool path is constructed by minimizing the motion distance between 2 neighbor C-space sets. Other objectives can be used as well. However searching for all the feasible configurations to identify the optimal tool trajectory in both 2D and 3D C-spaces can lead to computational perplexing problems. In this case, simplifying assumptions, such as neglecting the axis acceleration/deceleration [18], larger search increments, avoiding detailed kinematic analysis, or removing the unnecessary search space such as limiting the tilt angle range, may reduce the computational time.

2.2.4. Methods for polyhedral models and cloud of points

Polyhedral models (also called tessellated, faceted or triangular mesh models) have become popular in CAD/CAM systems. Because of the simplicity for data exchange and geometric computation [5,60], they are used as representation models for CAM and process planning purposes. These models are created either from a cloud of points [74,75] or from a parametric surface [53]. Polyhedral models facilitate the tool path generation for surfaces with multiple and large number of patches [16]. Apart from this, sometimes machining of non-parametric or non-implicit surfaces is inevitable, for example in cases that the design surface is created from a stylist prototype in an intermediate medium such as clay and converted into CAD data using contact or non-contact digitizers [55,76]. Fig. 6 shows the different input models and procedure for tool path generation.

The tessellation error during the generation of a polyhedral model may greatly affect the quality of the resulting tool paths [5,55,77]. Thus, grid density for sampling and triangulation should be selected with respect to the required accuracy and time efficiency. Estimation of differential geometric properties such as normal vector and curvature may also add another source of errors which makes it difficult to evaluate the generated tool paths against the surface finish requirements.

Based on this discussion, two new different trends are emerging in this area:
A method for the identification and machining of clean-up regions for tessellated surfaces, called the contraction tool method, has been developed by Ren et al. [5]. After identification of clean-up regions using gouging boundaries of the cutter on the tessellated model, virtual intermediate cutters, ranging from the finishing tool to a pencil cut in size, are calculated to trace the clean-up band in a strip parallel path pattern. For variable clean-up bands, the path interval and intermediate cutters are selected to satisfy the scallop constraint for the worst situation. Furthermore, the generation of pencil-cut and fillet-cut tool paths for polyhedral models has been introduced by Kim et al. [80].

For direct machining of cloud of points, the earlier methods rely on arrangement of a point pattern of the initial point cloud into a rectangular grid (Z-map model) and then selecting the line segments [81] or a cubic spline passing through the line segments of pattern rows [82] as the tool path. In the method developed by Lin and Liu [81], rough and finish paths were developed by slice-by-slice and height correction methods (to avoid gouging) respectively. A study on recent Z-map model slicing methods can be found in [78].

Methods based on construction of a parametric surface from measured data points such as those given by Yin [72], Yin and Jiang [73] and Sun et al. [83] are advantageous in the sense that machining of a parametric surface is straightforward and/or in some cases mechanical behaviors resulting from boundary conformed iso-parametric paths are improved. However these processes are less efficient because of the added parameterization errors and the inherent drawbacks of the iso-parametric methods presented in Section 2.2.

In a similar way, Chui et al. [84] developed a method for 5-axis machining of cloud of points. CL data are approximated by 3D biarc fitting and the cutter’s orientation is calculated by the information of triangulated grid of points. However in all the methods discussed above, path parameters and the grid resolution have not been established based on the design tolerance. To ensure the finished quality, conservative path intervals and forward steps are often selected, thus resulting in significantly increased machining time.

In the method developed by Feng and Teng [55], side step and forward step are adaptively calculated by construction of the projected cutter location net (so called CL-net) using least squares plane fitting. The concept is similar to previous methods, except that machining error and maximum scallop height are considered in the grid spacing and selection of CL points in both directions of the grid. Although side and forward steps are adaptive to the geometry of point cloud, unnecessary dense path intervals still exist in the final tool path.

Rough and finish tool paths have also been generated from the measured data in the form of point sequence curves (PSC-map model) where each curve of the point sequence exists in a measuring plane of the physical object [40]. PSC-map model is basically a result at the data acquisition stage and eliminates the need for further processing of the point cloud for tool path generation.

From the above study of the literature on machining of polyhedral models and the cloud of points, it is evident that more research is still needed to improve machining quality and efficiency for producing these surfaces. Especially very little
work has been carried out in 5-axis machining of a cloud of points. The areas to be improved include the tessellation method, approximation of geometric characteristics, and exploration of advantages of 5-axis machining in tool path generation.

2.2.5. Region based tool path generation

Region based tool path generation methods are based on dividing the freeform surface into regions by identifying meaningful features. This process is also called segmentation, subdivision, partitioning, or feature extraction.

The isophote concept has been used for surface segmentation in the method developed by Han and Yang [46] and Han et al. [6]. The idea is to segment surface into regions based on similar normal vectors. Applications of isophote partitioning in tool path generation have been reported in [61,72,73]. Elber [85] divided the surface into 3-axis regions and 5-axis regions based on the surface curvatures to improve the machining productivity. Lee and Ji [70] used first and second fundamental forms of the surface [86] to extract different regions by classification of differential geometric characteristics of the surface. In the method by Chen et al. [2], surface segmentation was used to enhance 3.1 machining. First the freeform surface is divided into a number of regions, and then the part set-up is adjusted for machining each region by a tilt/rotary table. Hence each region is machined by 3-axis CNC tool paths. Although machining time is increased by using several setups, the machining cost is lower than 5-axis machining due to lower investment cost. Surface segmentation has been carried out based on surface shape category and machinability by a hierarchical data structure. Shape categories are determined by the signs of Gaussian and mean curvatures, and for machinability local and global gouging has been considered. To define the boundaries of the surface patches, a Voronoi diagram that is capable of sorting the discrete points based on their similarities has been used.

Tool paths can be generated for each region based on their similarities. This may lead to reduced tool path computation time and improved machine axis movement and machining efficiency. Machining cost will increase in region-by-region machining if only path length and machining time are considered as the cost factors. However the possibility of machining complex surfaces with 3- and 5.1.4-axis machines and decreased rate of orientation changes during 5-axis machining could be considered as some of the advantages of region based machining.

2.2.6. Compound surface machining

Compound surfaces are used in many products due to the complexity of the required shape. A compound surface may contain several distinct surface patches such as Coon’s patches, ruled surface patches, Bezier patches, or NURBS patches connected with C0 or higher continuity [87]. Depending on the situation, patch-by-patch strategy or the whole surface machining approach is applied for tool path generation. The iso-parametric patch-by-patch method is useful when different tolerances are required for different patches. It allows the selection of the optimal parameters for each individual patch. The iso-planar method can be applied to generate the tool path for the whole surface [48]. Compared to patch-by-patch machining, this method may result in a shorter path, but it takes longer to solve the nonlinear sets of equations for the plane intersection.

An issue in patch-by-patch machining is the proper linking of the paths between patches. Selection of the path start and end points in each patch and connecting the paths of different patches with each other are two coupled problems and affect the total machining time [48,88]. Veeramani and Gau [89] addressed the problem of optimal path linking in patch-by-patch machining. The problem was transformed into traveling salesman problem by graph models.

Inter-patch gouging may occur for CL based tool path generation when the tool removes material from the neighboring patch while cutting near the boundary of a patch. In this case, tool orientation adjustment along with proper trimming of the path (for paths normal to the boundary) and path interval adjustment (for paths parallel with the boundary) can be utilized to avoid gouges [87].

Generation of an iso-scallop path over the whole parametric patches has been developed by Sarma and Dutta [90]. Specifically they addressed identification of the CC points of the adjacent iso-scallop path in the situation where the current tool path passes through multiple parametric patches. The points of the adjacent paths were interpolated by a Hermite curve in the domains of each of the underlying patches. Then heuristics were employed for the connection of Hermite curves in the parametric surface to each other based on the type of discontinuity.

Tool path generation for multi-patch trimmed parametric surfaces is often required in aerospace and automotive industries. In these situations, the tool path should adapt to the boundaries of the surface for superior aerodynamic properties. Various reparameterization methods have been introduced by Yang et al. [91,92] that can be used to generate a new parametric surface and hence iso-parametric paths that conform to the boundary. These methods have the potential to be used for multiple trimmed surfaces. The geometric bisection method given by Li [93] works by successive partitioning of the surface patch by using its boundaries. This method has been used to generate boundary conformed tool paths for compound surfaces.

3. Tool orientation identification

3.1. Overview

As discussed in Section 2, in 5-axis machining the tool axes can have two rotational movements in addition to three translational movements. These two rotations are recognized by a tilt angle $\alpha$ about the $x_2$ axis and an inclination angle $\omega$ about the $z_3$ axis $(\alpha, \omega)$: $-\pi/2 \leq \alpha \leq \pi/2$, $0 \leq \omega \leq \pi$, as shown in Fig. 3. These rotations allow for the machining of areas where are inaccessible for 3-axis machining. Compared to ball end milling, by using fillet-or flat endmill, increased material removal rates are obtained [94] and lower spindle speeds are required. However the problem of finding the optimal tool orientation for 5-axis machining is much more complicated than the typical problems in 3-axis machining. The surface should be gouge free while the material removal rate is the maximal, and the orientation should change smoothly in successive CC points.

3.1.1. Requirements

The main objective in tool orientation identification is to select the orientation parameters at each point such that the minimum machining time (the maximum material removal rate) can be achieved while the generated surface is gouge-free and within the profile tolerance with even quality across the surface. Some methods conduct extensive searching of the orientation area (C-space) to find the optimal smoothly varying gouge-free orientation while the others try to incrementally change the orientation to find the feasible one. Both methods have advantages and limitations which will be discussed later.

3.1.2. Traditional methods

Three methods have been widely used in tool orientation identification. The initial method for tool orientation was to consider a fixed tilt angle (i.e., Sturz angle) in the plane containing the feed direction and surface normal at CC point [14,95,96]. The tilt angle was chosen between $3^\circ$–$10^\circ$ [95]. This method obviously can improve material removal rate compared to 3-axis machining.
However a trial and error process was required to select the optimal angle. Smaller angles could result in rear gouging while larger angles reduced the material removal rate.

**Principal axis method (PAM)** [14,96,97] borrowed the concept of curvature matched machining. Ideally the tool is tilted towards the feed direction so that the minimum effective curvature of the tool is equal to the maximum effective curvature of the surface at the CC point. However practically this may not be possible because the cutting direction in iso-scallop machining cannot be exactly the same as the direction of the minimum principal curvature of the surface. Moreover to avoid rear and global gouging in 5-axis machining, the inclination angle \( \omega \) may not be always kept equal to zero at each CC point. However it should be noted that PAM only avoids rear gouging by incrementally tilting the tool away from the ideal situation, thus it is suitable for open face freeform areas [14,97].

Another method called **multi point machining** (MPM) [96, 98,99] searches for the second CC point while keeping the tool in contact at the first CC point. These two points are approximately symmetrical about the direction of the minimum surface curvature. This results in increased material removal rate and a controllable scallop shape. MPM has not been popular due to the mathematical complexity in finding the second CC point and the possibility of not converging to a solution [14].

### 3.2. Recent development

For optimization of tool orientation, many recent investigations focus on an improvement of the computational efficiency of finding a gouge-free orientation [14,17,23], while many others work on the improvement of machining quality and efficiency [15,18,67,100–102]. Classification of these methods in this review is based on their characteristics and algorithms to achieve the required objectives.

#### 3.2.1. C-space based tool orientation methods

As discussed in Section 2, the C-space method can be utilized for both tool path generation and tool orientation [18,20–22]. In tool orientation identification, the C-space will be the tool tilting and inclination parameter areas excluding the gouge prone orientations (Fig. 7). The sampling approach and the resolution of rotation parameters for sampling are critical for C-space computation efficiency and accuracy. After construction of the C-space, selection of the smaller tilt angles as well as the minimum changes of orientations in successive CC points can be objectives of the optimization process. As a result the optimal solution lies close to the boundaries of the C-space [15]. Morishige et al. [21] introduced the domain of admissible orientation for avoiding local and rear gouges. Jun et al. [15] introduced a tool orientation method based on local, rear and global gouge avoidance. The optimization goal is to maximize scallop height and minimize tilt and inclination angles. A complete gouge free 3D C-space method was developed by Lu et al. [18] based on minimizing the time travel distance to smooth the tool orientation changes. Although C-space is effective to monitor all the possible orientations, exhaustive computation may be required to reach the optimal solution in most of the above mentioned methods.

#### 3.2.2. RBM and AIM

**Rolling ball method** (RBM) and **arc intersect method** (AIM) are two powerful tool orientation techniques for local and rear gouge avoidance. Local gouging is avoided by the curvature matching concept. RBM takes into account the approximate curvature of the surface in the vicinity of the CC point. Generated tool paths are free of rear gouges. A rolling sphere is constructed based on the characteristics of the surface under the arbitrary tool shadow [14]. This shadow, called the shadow checking area, is divided into concentric grid of points and the pseudo radius of curvature is calculated at each grid point under the tool shadow as shown in Fig. 8. Calculation of the pseudo radius of curvature is similar to the calculation of an osculating plane for a point on 3D curves [103]. The tool should be positioned in the sphere constructed by the most concave radius of curvature such that it makes a circular line of contact with the sphere.

RBM only requires the surface normal at the CC point and the positions of grid points. However the equation of the surface is required to calculate the shadow grid area and points. This problem was addressed by graphic-assisted RBM [104] where the computer’s graphic hardware was used to enhance tool orientation computation for polyhedral models. In RBM the shadow checking area beneath the tool is oversized which may result in tilt angles larger than required and over computation.

In AIM the same shadow checking area and grid points in RBM are used, however instead of constructing rolling spheres for every grid point at each CC point, the surface under the tool shadow is rotated to intersect the surface [3,16]. The smallest resulting angle (equivalent to the largest tilt angle) is selected as the gouge free orientation. It should be noted that as a single independent tool orientation method, AIM and RBM are only applicable to machining of open faced freeform surfaces (which are assumed to be collision free). The methods can be used for both multi-patch triangular and parametric surfaces; however it is more complicated to check the points of adjacent patches. Like every other method used for polyhedral models, their accuracy is greatly related to the grid size.

![Fig. 7. C-space for orientation parameters. (a) Discretized 2-D orientation space (white area shows safe orientation space). (b) 3D C-space for one tool path [102].](image-url)
of triangulation. The computational efficiency of AIM is reported to be low due to the calculation of exact rotation angle at every grid point [17,105].

3.2.3. Tool orientation smoothing

Dramatic changes in tool orientation from point to point may increase machining time [76] and decrease its quality by leaving tool marks on the machined surface [67]. As a result recently considerable researches have focused on development of methods for smoothly varying tool orientation. Jun et al. [15] developed a tool orientation smoothing method by minimizing the C-distance between successive tool orientations. The forward scheme for C-distance calculation between \((\alpha_{i-1}, \omega_{i-1})\) and \((\alpha_i, \omega_i)\) is calculated as follows:

\[
(C_{-distance})_i = \min(\sqrt{(\alpha_{i-1} - \alpha_i)^2 + (\omega_{i-1} - \omega_i)^2}).
\]  

Both Morishige et al. [22] and Jun et al. [15] used forward and backward smoothing to reach the optimal solution. Lauwers and Lefebvre [106] applied a two-step iterative procedure for smoothing the variations of tilt angle. Tilt angles are smoothed by removal of one or two intermediate points that form a valley, while gouging is avoided by not allowing the tilt angle to decrease during the smoothing process. In the method by Ho et al. [100], first critical areas were manually assigned orientations. This can greatly improve the complexity and reduce computational time. Then smooth tool orientations were generated by using a vector interpolation algorithm called quaternion interpolation. Further collision checking was conducted after interpolation and the overall process was iterative. Wang and Tang [102] used the concept of discretized visibility map \((Vmap)\), which was introduced by Balasubramaniam et al. [107], to identify the set of valid orientations by inspecting the valid area with all the gouging constraints. Then a feasibility map \((Fmap)\) was defined at each CC point. The first Fmap is a single point in \(Vmap(C_1)\). Then the successive Fmaps for \(i > 1\) are defined recursively as follows:

\[
Fmap(C_{i}) = Vmap(C_{i}) \cap Fmap(C_{i-1}).
\]  

Please note that the \(Fmap(C_{i})\) for \(i > 1\) spreads in the discrete orientation domain and does not remain a single point. Then using the combination of Fmaps and an angular velocity change limit operator, they solved the problem of smooth orientation in a forward scheme. Castagnetti et al. [67] first developed the domain of admissible orientation [95] in the part coordinate system and transformed it to the machine's coordinate system. Then smoothly varying orientations were generated by minimizing two measures: (1) the angular difference between two successive CC points, and, (2) the curvature of tool axis orientation evolution. Their results showed that the optimization of tool orientation in the machine's coordinate system could reduce machining time. The iso-conic partitioning method developed by Wang and Tang [23] integrated optimal path generation with tool orientation smoothing. As can be seen these methods are similar in nature. The main objective in tool orientation smoothing is to limit the solution bound to reduce the variation level of tool orientation in successive points and also over haul the large body of required computation.

3.2.4. Other methods

Hosseinkhani et al. [17] developed a method called the penetration–elimination method (PEM) for rear gouging avoidance. Similar as RBM and AIM, the PEM is only applicable to open face collision-free areas. A new concept for gouge quantification was introduced based on radial and axial depths of gouge. If a point is inside the tool area, it is assigned a negative radial depth of gouge. The gouging intensity function is defined as the multiplication of radial and axial depths of gouge. Hence, a point in the gouge area has a negative gouge intensity value. The penetration–elimination is conducted by incremental checking of the tool shadow area and adjusting the tilt angle, while each time the points calculated with positive gouge intensity values are deleted from the checking seed points. Together with an optimized root finding method, this method greatly reduces the calculation time by dynamically removing the safe areas out of the calculation loop.

Optimization of tool orientation has also been conducted to reduce the kinematic error of 5-axis machining [108]. Analysis of kinematic error for 5-axis machining can be found in [50,109–111]. The errors addressed by Ye and Xiong [108] are the ones resulting from postprocessor of the CAM software system during the linearization process when it transforms the tool orientation data (and the CC points) into the machine axis movements. When the postprocessor controls the deviation of the generated axis movement with the original CC points, it transforms back the machine axis movements into CC points. This may result in over- or under-estimation of kinematic errors. Ye and Xiong [108] showed that the proper selection of tool orientation can reduce this type of error.

Approximation of rear gouging area by a quadric surface has been used by Fan and Ball [105] for the tool orientation in 5-axis machining. A major advantage is the computational efficiency of fitting and distance calculation and the applicability to implicit, polyhedral and point based surfaces. However, the required sample point patterns exaggerate the gouge prone area under the tool shadow, and hence increase the time of gouge checking. Another group of methods tends to locate the workpiece in a few setups by using tilt/rotary tables [2,112,113]. Note that this is different from 5-axis machining when the tool rotations are controlled by the machine table. In these methods, setups are generated based on partitioning the surfaces into a few areas and then machining by a multi-axis machine. This partitioning process has been conducted by the shape classification and machinability in [2], accessibility domain analysis in [112] and Gmap (Gaussian map) based area normal matching in [113]. Then tool orientation is adjusted in every setup by tilt/rotary table to machine with 3, 3 1 2, or 4 axis NC machine.

4. Tool geometry selection

4.1. Overview

The main objective for tool geometry selection in 5-axis machining is to reduce the machining cost. Machining cost is determined by the machining time and tool cost. Lee et al. [4] showed that the best way to minimize machining time is to choose the largest possible tool along with the minimum number of tool changes. Also a number of geometric constraints should be satisfied. The surface should be gouge free and within the bounds of assigned tolerances. The cutter should be selected for different stages of machining, i.e., roughing, semi-finishing, finishing and clean-ups. It should be noted that proper assignment of clean-up regions by selection of larger tools during the finishing process and then cleaning of sharp filleted areas may be a good strategy for reducing the total machining time.
Special cases of the generic tool. Selection of tool size includes the description is shown in planes and the cutter to minimize the machining time. A generic dynamic programming for the simultaneous selection of hunting surfaces is the layer-by-layer machining approach (machining a similar APT). In 5-axis machining, cutter selection is closely related to the tool's orientation, tool path topology and tool path parameters. The problem can be stated as follows:

Given a set of cutting tools, select the best cutter/cutter set that can traverse the entire surface in the minimum time without causing the three types of gauges and within the tolerances.

This formulation requires optimization of the tool orientation, tool path, and the tool geometry at the same time. Most of the current methods avoid modeling of this problem and assume that the tool has been selected before tool path generation \([122,123]\). For 3-axis machining, a big part of the problem, i.e., optimization of tool orientation, will not be considered. In this case, the tool selection is basically to calculate the minimum radius of curvature for the surface and match the largest possible tool with that \([71,87,114,124]\). However in 5-axis machining due to the variable orientation parameters, it is possible to select a tool with a radius larger than the smallest radius of curvature of the surface.

Lee and Chang \([19]\) introduced a method for the identification of a feasible cutter at a CC point. At first the collision-free tilt and inclination angle limit at each CC point are determined by a feasibility zone. Then in samples of tilt and inclination angles, the effective radius of the tool and that of the surface are evaluated. To avoid local gouging, the effective radius of the tool should be smaller than that of the surface in different samples of tilt and inclination angles. The effective curvatures of tool and surface at a specific direction \((\nu_1)\) are given as follows (see Figs. 3 and 4):

\[\kappa_{1t} = \kappa_1 \cos^2(\theta) + \kappa_2 \sin^2(\theta)\]

\[\kappa_{1d} = \kappa_1 \cos^2(\lambda) + \kappa_2 \sin^2(\lambda)\]

where \(\kappa_1\) and \(\kappa_2\) are surface minimum and maximum curvatures, and \(\kappa_{1t}\) and \(\kappa_{1d}\) are those of the tool defined by:

\[\kappa_{1t} = \frac{\sin(\alpha)}{r_1 + r_f \sin(\alpha)} ; \quad \kappa_{1d} = \frac{1}{r_f}.\]

Thus all the possible cutter orientations can be checked for local gouging at different feed directions. Jensen et al. \([125]\) mentioned that because of the convex hull property, it is not required to check all the feasible orientation areas for tool selection. As mentioned in Section 3, the optimal orientation must lie in the boundaries of the feasible orientation area. Jensen et al. \([125]\) proposed the relative optimal cutter selection method to initialize with the largest available tool in the tool library and the following tilt and inclination angles:

\[\alpha = \sin^{-1} \left( \frac{r_f}{k_{s1} - r_1} \right) ; \quad \omega = 0\]
where \( r_f \) and \( r_1 \) are the cutter fillet radius and the cutter radius, and \( \kappa_s \) is the surface minimum principal curvature. Cutter size parameters (e.g., corner radius and shank radius) will change in cases where the interference constraint is not satisfied. Compared to the method by Lee and Chang [19], the method by Jensen et al. [125] requires less computation effort. A few good examples of different cutter parameter selection and the resulting machining time can be found in [125]. Tool selection developed by Li and Zhang [123] is based on accessibility analysis before the generation of tool path. Accessibility of a cutter has been defined as being oriented at a point without causing any of the three types of gouges. The largest cutter which is accessible all over the surface is then selected as the feasible cutter. Similarly in the research by Li and Zhang [122], it has been assumed that tool path pattern and direction are not decided at the cutter selection stage. The surface is decomposed into convex, concave and saddle regions and the sampling points for accessibility checking are only considered in concave and saddle regions. Although the methods by Li and Zhang [122, 123] give flexibility for the selection of any path pattern and direction for the selected cutter, the results are relatively conservative and computationally expensive compared with the methods by Lee and Chang [19] and Jensen et al. [125].

4.2.3. Tool selection for semi-finish and clean-up stages

Pencil-cut and fillet-cut methods are used for clean-up machining [80]. Few works have been carried out on the selection of appropriate clean-up and semi-finish cutters. In the method by Ren et al. [5], the clean-up area has been approximated by a V-shape to generate a tool path by the pencil-cut method. Then the number and size of ball endmills to clean the sharp filleted areas are calculated by considering intermediate virtual cutters ranging from the finishing tool to the clean-up tool. For semi-finishing, the cutter selection should be based on the geometric constraints and the thickness of the shoulders left from the roughing process [4, 114].

5. Summary and discussions

5.1. Summary

A review of the fundamental issues and new developments in CNC machining of freeform surfaces has been carried out in this work. Three major issues, tool path, tool orientation, and tool geometry, have been considered. Numerous researches in the last two decades have resulted in significant improvement in these aspects. Among different evaluation measures, quality and efficiency of machining are primarily used to study and compare these different developed methods.

- In tool path generation, iso-scallop tool paths along with the curvature matching method have significantly lead to the improved surface quality and reduced machining time. Many achievements have also been observed in the machining of polyhedral surfaces, point clouds and compound surfaces. Various surface segmentation techniques such as the isophote partitioning method, which leads to decreased machining time and/or reduced investment cost, have also been studied.
- Development of optimal tool orientation techniques for 5 axis machining has significantly improved machining productivity and quality. Methods for the tool orientation identification focus on either improvement of the computational efficiency of the existing methods or development of new methods. Tool orientation smoothing plays an important role to achieve a high quality of freeform surface machining.
- Tool selection methods for freeform surface machining have been developed for roughing, semi-finishing, clean-up and finishing stages. One of the critical issues is the selection of the optimal tool sequence for roughing stage in layer-by-layer machining. For 5 axis machining, the tool selection for finishing stage is closely related to tool orientation, tool path topology and path parameters. The majority of the developed methods combine different techniques with the curvature matching principle to identify the largest possible cutter for finishing of a freeform area.

5.2. Discussions

Some studies show that introduction of the freeform surface machining techniques has considerably reduced the time and cost in industry [28, 64]. Despite the progress, many challenges still need to be further addressed to improve the quality and efficiency of the freeform surface machining methods.

Computation time and machining time are the two major issues for further improvement of efficiency in freeform surfaces machining. As a core method, curvature matched machining has largely affected the recently developed techniques in tool path generation, tool orientation identification and tool selection. Employment of the curvature matched machining approach together with the iso-scallop method in these three areas can significantly reduce actual machining time while ensuring the quality of the final surface at the cost of increased computation time. However in some of the recently developed methods, it has been observed that surface quality has been overlooked in order to decrease either the machining time or the simulation time. The iso-scallop rule no longer applies to the resulting tool path in these methods.

The quality issue needs to be further investigated in the machining of polyhedral surfaces, cloud-of-points surfaces, and compound and trimmed surfaces. Many new techniques have been developed for the local and global gouge detection in machining of polyhedral surfaces which was previously assumed to be an error prone, time consuming and approximation based task. For machining of cloud-of-points surfaces, the developed methods are conservative for achieving the required quality. This is due to lack of a precise measure for determining path parameters for machining these surfaces as well as compensation for the approximation errors introduced by geometric modeling. For compound surfaces, more efficient methods for rear and global gouge detection in the boundary areas need to be developed.

In addition to the three major issues studied in this review considering the geometric aspect of freeform machining, other issues such as machining feedrate scheduling [126–129] and kinematics and dynamics of CNC mechanisms [130, 131] also affect the quality and efficiency of freeform surface machining. All these problems need to be further addressed to apply the developed freeform surface machining methods effectively in industry.

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