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Cutter location path generation through an improved algorithm for machining triangular mesh[☆]

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ABSTRACT

Direct mesh machining has been an effective technique in rapid manufacturing. Currently, the cutter location path generation is an effective method for the direct mesh machining. However, this method may cause surface defects, such as the overcut-slot, the transit-pit, and the facet defects. Therefore, the application of this method is limited for the machining accuracy issue.

From the comprehensive analysis of cutter location path generation and the inspection of the machined parts by the mesh offset intersection (MOI) algorithm, the tessellation error of the offset mesh is the main factor causing the machining surface defects. To solve the problem, we propose an improved MOI algorithm to reduce the influence of tessellation error. Compared with the original surface, only the mesh vertices are considered as the points without tessellation error to the original surface. Therefore, we revise the algorithm through calculating the cutter location points only from the vertices and smoothing the tool-path in two perpendicular directions. This improved algorithm includes two sub-algorithms: a vertex-based cutter location point calculation sub-algorithm and a bi-directional spline interpolation sub-algorithm. To validate the effectiveness of the improved algorithm, the machining accuracy is investigated and verified through several testing parts. The experimental results show that the improved MOI algorithm can effectively improve the machining accuracy and avoid surface defects on the work-piece surfaces.

1. Introduction

Technology development has led to broad application of complex freeform surfaces in the aerospace, automobile, consumer products and die/mold industries [1]. Multi-axis numerical control (NC) machining has become an important manufacturing method of freeform surface parts [2,3]. Tool-path generation influences the accuracy and efficiency of the machining of freeform surfaces [4,5]. By using a commercial digital scanner, the mesh (a connected set of triangles) of a physical surface can be obtained, and saved as a stereo lithography (STL) model [6]. Direct mesh machining has been an effective technique in rapid manufacturing. This technique can also be used in the redesign and remanufacture of industrial products [7].

For the machining of the STL model, a feasible method is by reconstructing the mesh to obtain the original surface and generating the tool-path on the surface. Eck and Hoppe [8] presented an automatic B-spline surface reconstruction method for the 3D point cloud. Li et al. [9] reconstructed a work-piece surface from a set of surface points and presented a fast, practical, efficient, and priority-driven algorithm. Lin et al. [10] proposed an adaptive mesh-fitting algorithm, which fits the triangles with smooth patches.

Surface reconstruction can be used for NC machining of the mesh. However, the efficiency of the surface reconstruction is low, and a good quality is difficult to achieve. Direct mesh machining can obviously increase the efficiency. Koc and Lee [11] presented a method to generate the tool-path on adaptive ruled layers for rapid prototyping. This method can also be used in multi-axis machining for the mesh. By using the binary tree and real-time simulation, Mao and Liu et al. [12] achieved a three-axis NC milling of the mesh. Huertas-Talón et al. [13] used the non-deterministic techniques and spherical tool to obtain a spiral path for machining a mesh surface. In that work, the precision of machining a work-piece was tested using confocal microscopy and coordinate measuring machine (CMM). Choi et al. [14] presented a new approach to a three-axis NC tool-path generation and provided several distinctive features suitable for high-speed machining of dies and molds. Park [15] calculated the contours on the cutter location (CL) surface and generated the tool-path by linking the contours. Later,

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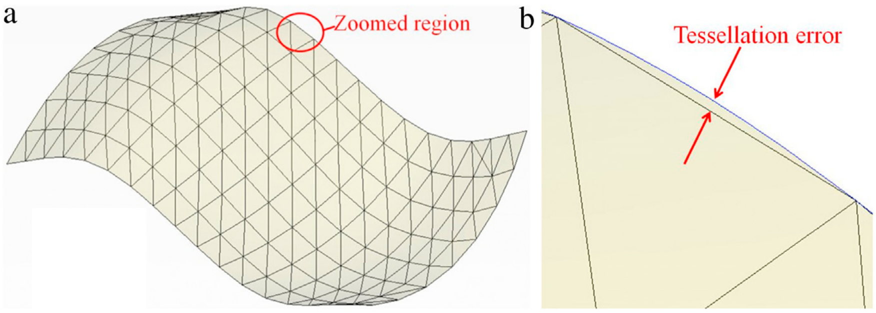

Fig. 1. Tessellation error. (a) Original surface and mesh. (b) Zoomed region.

Park [16] improved the method and generated the tool-path for the mesh. Chuang and Yau [17] presented a z-level contour tool-path generation algorithm for the mesh machining. This method can effectively calculate the tangent points but could only be used for fillet milling. Kout and Müller [18] obtained a tool-adaptive offset path for machining the work-piece surface of the mesh and considered the impact of a ball-end cutter.

Currently, the CL path generation method is an effective method to generate the tool-path of the mesh. The core idea of the cutter location path is to obtain the cutter location points on the offset mesh. In this paper, we define this type of method as the mesh offset intersection (MOI) algorithm. Jun et al. [19] offset the polyhedral model using a local-offsetting scheme and generated the three-axis NC tool-path. In that paper, the offsetting of the vertex was considered using different attributes of the geometric characteristics. Kim and Yang [20] illustrated that each triangle was offset to the CL surface using multiple normal vectors of a single vertex. The offset vector was computed according to the geometry of the cutter and the normal vector of a part surface. Later, Kim and Yang [21] improved the algorithm wherein the boundary edges and boundary vertices were offset using virtual multiple normal vectors of boundary vertices. Kim et al. [22] divided the mesh offset method into three types: offset of faces, edges, and vertices. For each method, the area of the offset mesh with gap was filled with a cylindrical or spherical surface, and the area of the offset mesh with overlap was trimmed. Koc and Lee [23] calculated the vertex vector by averaging the connecting facets vectors and offsetting each vertex along the averaged vector. Qu and Stucker [24] also used the connecting facets vectors to calculate the vertex vector. Instead of using the averaged vector, this paper presented that when the offset vector for each vertex is calculated, the weighted sum from the normal vectors of the connecting triangles is used, and the weights were derived from the equations yielded in a matrix form. Chen and Wu [25] presented a new set of weights from duality and gravity. Their method enhanced the accuracy of the vector calculation. With regard to the calculation of the intersection points (the offset mesh intersect with the drive plane), Qu and Stucker [26] classified them into four conditions. In this research, the intersection points can be directly used as the cutter location points and used to optimize the tool-path for the machining of the mesh.

For a STL model, the tessellation error exists between the mesh and the original surface. Chen and Shi [27] evaluated the tessellation error between the mesh and the surface patch. They presented that subdividing the mesh [28] can reduce the tessellation error to the allowed bound error. Lee et al. [29] presented a re-meshing algorithm using the recursive subdivision of irregular mesh with boundaries. Ma et al. [30] used a direct approach for fitting the subdivided surface from an irregular and dense mesh of an arbitrary topological type. Yang [31] interpolated the mesh surface through geometric subdivision. In that paper, two new nonlinear subdivision schemes were introduced for surface interpolation of the mesh. For the flattenable mesh surface, Wang [32] used nonlinear subdivision and reconstructed the mesh surface.

Among the current research works, the mesh offset intersection algorithm can achieve the direct NC machining of the mesh. The subdivision operation was adopted to reduce the tessellation error, but it will certainly use much more computational resources, increase the processing time, and affect its performance. Furthermore, the subdivision operation cannot eliminate the tessellation error, and the mesh machining quality will still be a problem. The MOI algorithm did not consider the smoothness and continuity in the tool-path generation, and it will result in a rough surface when machining with this method.

On the basis of our investigation, we studied the MOI algorithm for the direct mesh machining. Through the experimental tests on the MOI algorithm, we find that there are some surface defects on the machined work-piece surface. We classify these defects as overcut-slot, transit-pit, and facet defects. Through the detailed analysis, we found that these defects are caused by the tessellation error. To solve the problem, we proposed an improved MOI algorithm to reduce the influence of tessellation error. Compared with the original surface, only the mesh vertices are considered as the points without tessellation error to the original surface. Therefore, we revised the algorithm through calculating the cutter location points only from the vertices and smoothing the tool-path in two perpendicular directions. This improved algorithm includes two sub-algorithms: a vertex-based cutter location point calculation sub-algorithm and a bi-directional spline interpolation sub-algorithm. This improved algorithm was implemented with C++ programming, and the NC code for the direct mesh machining can be generated. With the improved algorithm, smooth work-piece surfaces can be obtained, and the quality of the work-piece surface can be guaranteed.

The main sections of this paper are presented as follows: Section 2 presents the problem and analyzes the causes. By observing the work-piece surface machined by the MOI algorithm, we found that defects occur on the machined work-piece surface. From the detailed analysis of the MOI algorithm, we found that the mesh tessellation error is the key element that causes the surface defects. Section 3 introduces the improved MOI algorithm. The vertex-based cutter location point calculation sub-algorithm and the bi-directional spline interpolation sub-algorithm are explained in detail, and the smooth tool-path can be generated for the direct mesh machining. In Section 4, the improved MOI algorithm is implemented and verified through experimental tests. Finally, Section 5 summarizes the conclusions of this paper.

2. Problems description and analysis

2.1. Mesh tessellation error

Through digital scanning, the mesh represented by a series of triangles can be obtained. The scanning error exists between the