Computer-Aided Design 45 (2013) 1459–1468

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Iso-parametric tool-path planning for point clouds

Qiang Zou [a,b], Jibin Zhao [a,*]

[a] Shenyang Institute of Automation, Chinese Academy of Sciences, Liaoning, 110016, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China

HIGHLIGHTS

- A point-based iso-parametric tool-path planning method was proposed.
- The formulas for computing forward and side step were simplified significantly.
- Boundary conformed tool-path was generated for point clouds.

ARTICLE INFO

Article history:
Received 16 January 2013
Accepted 5 July 2013

Keywords:
Tool path
Point cloud
Meshless
Conformal parameterization
Linear interpolation

ABSTRACT

Due to the compute-intensiveness and the lack of robustness of the algorithms for reconstruction of meshes and spline surfaces from point clouds, there is a need for further research in the topic of direct tool-path planning based on point clouds. In this paper, a novel approach for planning iso-parametric tool-path from a point cloud is presented. Since such planning falls into the iso-parametric category, it intrinsically depends on the parameterization of point clouds. Accordingly, a point-based conformal map is employed to build the parameterization. Based on it, formulas of computing path parameters are derived, which are much simpler than the conventional ones. By regularizing parameter domain and on the basis of the previous formulas, boundary conformed tool-path can be generated with forward and side step calculated against specified chord deviation and scallop height, respectively. Experimental results are given to illustrate the effectiveness of the proposed methods.

1. Introduction

Free-form surfaces (e.g., aero-parts and molds) are widely used in manufacturing industries. They are often machined by computer numerical control (CNC) machine tools that move cutter or table along a specified trajectory. In the most common cases, this trajectory is so-called tool-path which constitutes the core of computer-aided manufacturing (CAM). The automatic generation of tool-path for free-form surfaces is a fundamental issue in modern CAD/CAM systems.

Planning tool-path is a compromising between precision and efficiency, which mainly involves two aspects, path pattern and path parameters. The former is about which shape the tool-path is. More specifically, there are three path patterns so far: direction parallel, contour parallel and spiral. The latter concerns geometric parameters of tool-path, i.e., forward step and side step bounding chord deviation and scallop height, respectively. In this paper, we shall use the terminology interval to refer to offsetting distance on surfaces and the step is used to refer to parametric offsetting distance. Fig. 1 shows the three path patterns and Fig. 2 describes the two path parameters. The basis of tool-path planning was laid in the 1990s. For instance, iso-parametric method [1], iso-planar method [2] and iso-scallop method [3–5] are some typical approaches. Several developments are, e.g., iso-phote [6] and C-space [7] methods with planning tool orientation taken into account. The former in fact proposed another method of parameterization and the latter introduced the classical C-space method for robotics into tool-path planning. What should be noted is the work [8] by G. W. Vickers et al. providing a mathematical method to determine the interval between the consecutive paths. And [2] presented a true machining error calculation method with which accurate forward step can be determined. Based on these pioneering and fundamental works, some recent developments are iso-scallop [9], boundary conformed [10,11], curvilinear [12], iso-conic [13], steepest ascent approach [14] and multiresolution method [15], to name a few. Surveys of much more work about tool-path planning research can be referred in [16,17].

Tool-path planning on a surface is closely related to its representations among which the point cloud, as a direct description of surfaces, has been receiving a growing attention since the pioneering work of Marc Alexa et al. [18]. In fact, a considerable part of meshes and spline surfaces encountered in CAD/CAM are reconstructed from point clouds through approximation. However, this kind of process is complicated and compute-intensive. What

* Corresponding author. Tel.: +86 13938809239.
E-mail addresses: 619499976@qq.com, jbzhao@sia.cn (J. Zhao).

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http://dx.doi.org/10.1016/j.cad.2013.07.001

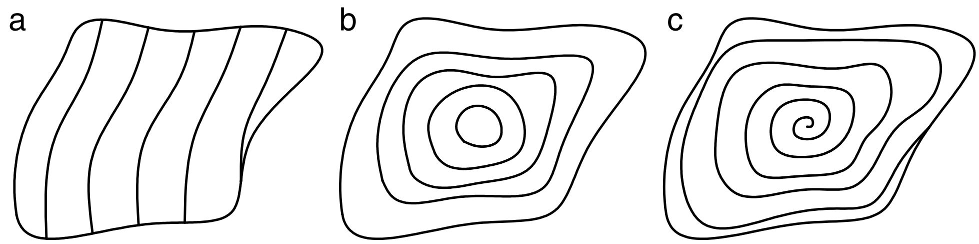

Fig. 1. Illustrations of tool-path patterns. (a) direction parallel tool-path; (b) contour parallel tool-path; (c) spiral tool-path.

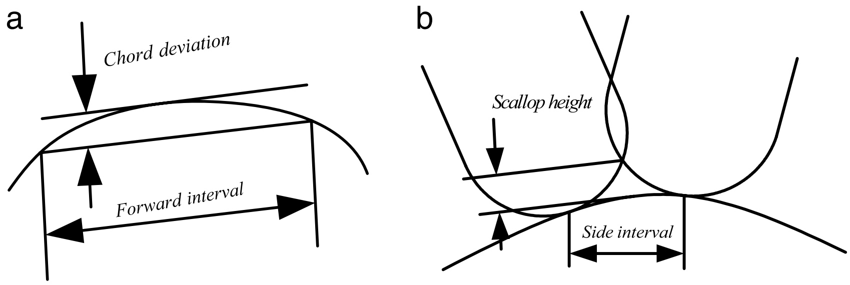

Fig. 2. Definition of tool-path parameters.

is worse, it is non-robust especially when the point cloud is a non-uniform sampling. Therefore, direct planning of tool-path for point clouds is of great significance. Compared with other representations, the lack of topological information simplifies the representation and storage of surfaces. Yet, when it comes to geometric processing, things become rather tough. That is why although there is enormous literature focusing on tool-path planning, those specified for point clouds are a few. The earlier methods of directly planning on point clouds resorted to resampling, which can be regarded as an extension of traditional iso-planar ones. Lin et al. [19] employed a uniform rectangular grid (i.e., the Z-map constructed from an original point cloud) to generate tool-path for milling surfaces slice-by-slice. Rows of the grid on each slice (or level) were picked out as tool-path for the slice. Another relevant method is the work [20] by Feng and Teng. They adaptively computed the forward and side step by constructing a so-called CL-net which in fact is a variant of the Z-map. The iso-scallop method [5] of spline surfaces was extended to point clouds by Wei et al. [21]. Apart from those, S. C. Park et al. [22] generated contour parallel tool-path for pocket milling from a data structure point of view (i.e., PSC-map). The preceding review is carried out regardless of those based on local or global surface reconstruction, which in fact steps backward. To review as far as we can, the extension of traditional iso-parametric tool-path planning method, which can avoid complicated surface–surface intersection and surface offsetting in iso-planar and iso-scallop methods, to point clouds seems to remain blank.

In this paper, a method of iso-parametric tool-path planning for point clouds is presented. Surface parameterization, closely related to machine learning and computer graphics [23,24], is crucial for planning tool-path iso-parametrically. Yang et al. [10] and Sun et al. [25] employed harmonic map to parameterize spline surfaces and meshes respectively, of which free-boundary property was exploited to plan boundary conformed paths. The property means that the boundary of parameter domain can be defined arbitrarily. Thus, by mapping spatial boundaries to regular planar boundaries (i.e., rectangles and circles), boundary conformed tool-path can be generated. These methods as well as their developments are heavily dependent on the topological information and hence unlikely to be applied to unstructured point clouds. By locally triangulating, Floater et al. [26] were able to extend their parameterization method to point clouds and this method has been extended to point clouds of spherical topology by Gotsman et al. [27]. In the meshless domain where topological reconstruction is excluded, conformal parameterization is based on the spectral theory. There are mainly two ways to construct point-based Laplacian, heat diffusion scheme [28] and optimal scheme [29]. For heat diffusion scheme, choosing a proper time parameter is non-trivial, and thus the optimal scheme is preferred. Once point-based Laplacian constructed, harmonic map can be exploited to parameterizing point clouds conformally. It is obvious that such parameterization method holds the free-boundary property too. Therefore, similar to the preceding mapping-based family of tool-path planning methods [10,25], boundary conformed tool-path can be generated. However, in addition to the free-boundary property, there is another more exciting property that their works did not cover, i.e., the conformal property. The advantage of conformal parameterization over conventional ones is the conformality (i.e., angle preserving) with which the computation of side and forward step can be simplified significantly. As known, a single path on a free-form surface is offset from a previous one along the direction orthogonal to forward direction. As the conformal parameterization is angle preserving, direction on a surface is consistent to that on its parameter domain. Therefore, for iso-parametric tool-path, its forward direction is the v-direction (or u-direction) and the offsetting direction is the u-direction (or v-direction). What is more, the step size calculation is avoided if the parameterization is conformal, since for any point on the surface, its local shape is similar to its parametric image, with respect to a factor. Namely, a small interval on the surface and its corresponding step in the parameter domain are proportional. In fact, these presented approaches can also be exploited to generate iso-scallop tool-path for point clouds as an extension of the works [3,4].

The remainder of this paper is organized as follows. Section 2 introduces the conformal parameterization of point clouds; in Section 3, we derive the formulas for calculating path parameters, which is a significant simplification of the conventional ones; Section 4 describes the proposed iso-parametric tool-path planning method; Section 5 shows the experimental results; Finally, we conclude the whole paper in Section 6.

2. Conformal point cloud parameterization

Surface parameterization is to find a bijective mapping between two surfaces with similar topology. If both surfaces are discretized