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A chord error conforming tool path B-spline fitting method for NC machining based on energy minimization and LSPIA

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Abstract

Piecewise linear (G01-based) tool paths generated by CAM systems lack G^1 and G^2 continuity. The discontinuity causes vibration and unnecessary hesitation during machining. To ensure efficient high-speed machining, a method to improve the continuity of the tool paths is required, such as B-spline fitting that approximates G01 paths with B-spline curves. Conventional B-spline fitting approaches cannot be directly used for tool path B-spline fitting, because they have shortages such as numerical instability, lack of chord error constraint, and lack of assurance of a usable result. Progressive and Iterative Approximation for Least Squares (LSPIA) is an efficient method for data fitting that solves the numerical instability problem. However, it does not consider chord errors and needs more work to ensure ironclad results for commercial applications. In this paper, we use LSPIA method incorporating Energy term (ELSPIA) to avoid the numerical instability, and lower chord errors by using stretching energy term. We implement several algorithm improvements, including (1) an improved technique for initial control point determination over Dominant Point Method, (2) an algorithm that updates foot point parameters as needed, (3) analysis of the degrees of freedom of control points to insert new control points only when needed, (4) chord error refinement using a similar ELSPIA method with the above enhancements. The proposed approach can generate a shape-preserving B-spline curve. Experiments with data analysis and machining tests are presented for verification of quality and efficiency. Comparisons with other known solutions are included to evaluate the worthiness of the proposed solution.
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Keywords: CNC machining; G-code; B-Spline fitting; Progressive iterative approximation; Energy minimization

1. Introduction

G-code commands generated by CAM systems play an important role in CNC machining. Among them piecewise linear (G01-based) tool paths are widely used. The lack of G^1 and G^2 continuity of G01-based paths cause unwanted vibrations and slow-downs during machining. To ensure efficient high-speed machining, a method such as B-spline fitting to improve the continuity of tool path is required.

Tool path B-spline curve fitting is often required to fulfill more constraints than conventional B-spline curve fitting in shape and performance [1], such as approximation of the G01 points within a given tolerance, chord error constraint, shape preservation, G^2 continuity, and minimal number of control points. In addition, computation must be fast and accurate even for large size tool paths to use the solution in actual NC machining.

The conventional B-spline fitting approaches are often solved by minimizing Least Square Fitting (LSF) error or energy functions within a given tolerance [2–8]. LSF involves solving a very large system of linear equations. It is not suitable for industrial solutions because of numerical instability and lack of assurance of a usable result.

Instead of solving linear equation, Progressive and Iterative Approximation (PIA) proposed by Qi et al. [9] and de Boor [10] is a new and effective method for data fitting that eliminates the numerical instability of solving inverse matrices. PIA constructs a series of fitting curves by adjusting control points iteratively[11–15]. Deng et al. [4] reported a method of

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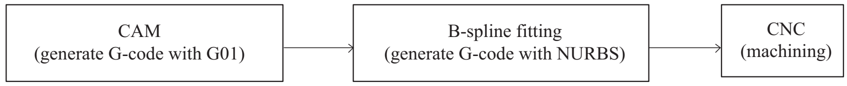

Fig. 1. Flowchart of the relationship between CAM, B-spline fitting, and CNC machining.

Progressive and Iterative Approximation for Least Squares (LSPIA) with the ability to handle point set of large size with less control points than PIA. Nevertheless the LSPIA method cannot be directly used in industrial applications of NC machining due to the following reasons: first, LSPIA does not consider chord error requirement, second, the data points of empirical examples distributed evenly, but actual NC tool paths have more complex and unpredictable shapes and non-uniform data point distribution.

Parameter values of data points and knot vector are critical to the quality of fitting curve. Piegl and Tiller [5, 16] suggested using averaging technique (AVG) and knot placement technique (KTP). Razdan [17] and Li et al. [18] suggested using shape information to determine knot vectors. Park et al. [3] devised a new B-spline curve fitting method based on adaptive curve refinement using dominant points. Their knots were determined by averaging the parameter values of the dominant points.

Tool path B-spline fitting method is often used to improve the machining efficiency within the precision to achieve high-speed and high-precision CNC machining. Yang and Chen [19] proposed a new high precision fitting approach which used roughly fit and fine fit for NURBS generation, and Newton–Raphson method is used to solve the optimization problem, but the authors did not give a method to solve chord error refinement, and Newton–Raphson method cannot ensure a solution that satisfies the accuracy requirement. Syh-ShiuhYeh and Hsin-Chuan Su [20] developed a method for implementing an online non-uniform rational B-spline (NURBS) curve fitting process on CNC machines for improving the quality and efficiency of machining. He fitted the data points using optimal search method and used least square fitting method to solve the optimization problem without considering chord error and numerical instability. If the fitting process fails, he just used stored data points as the motion commands for ensuring the continuous motion of CNC machines. Zhang et al. [21] proposed a method of curve fitting for velocity planning on CNC machines based on quadratic B-splines. The fitting curve was obtained by interpolating feature points. Chasing method was used to compute control points. This method also has shortage of the numerical instability of solving inverse matrices.

The goal of this study is to design and implement an algorithm that is capable of satisfying all of the requirements. Conventional LSF method is not considered for industrial-strength applications because of numerical instability. LSPIA method cannot be directly used for tool path B-spline fitting because it does not consider chord error requirement. Moreover, both the conventional LSF method and LSPIA lack actual machining experiments to validate the usability.

A number of commercial CAD/CAM software systems can generate NURBS tool paths, such as NX, CATIA, Delcam, PowerMILL, SINUMERIK 840D compressor etc. The NX solution delivers favorable results but from data analysis we found that NX solution has some limitations. It cannot ensure G^1 continuity between two B-splines and determine the feature points of the tool paths automatically – the feature points are determined by a user-provided angle. Our previous work [1] can identify the feature points, which are called “Hard Break Points (HBP)”, automatically. The goal is to ensure G^1 continuity between two B-splines, and G01 and B-spline, except at HBP locations. HBP identify algorithm [1] is not the key discussion point in this paper but is the prerequisite of the tool path B-spline fitting.

Data points in this paper are generated by CAM software, and our fitting results are used for 3-axis actual machining after B-spline fitting. Fig. 1 is a systematic flowchart of the relationship between CAM, B-spline fitting, and CNC machining. Tool path B-spline fitting is an optimize step for tool paths generated by CAM software, and after tool path B-spline fitting, the tool paths have better continuity and smoother than the original G01. It can generate better machining surface and save internal storage.

In this study, we propose to use LSPIA method incorporating an energy term (ELSPIA) to improve the performance and lower the chord errors. We select initial control points which can demonstrate the feature of data points and are uniformly distributed. We design an iterative algorithm such that the foot point parameters are updated strategically; then we analyze the required degrees of freedom of control points to insert new control points effectively; furthermore we apply chord error refinement with ELSPIA method if the chord error requirement is not satisfied.

This paper is organized as follows. In Section 2, we state the requirements and high-level algorithm of tool path B-spline fitting. In Section 3, we introduce the algorithm of LSPIA. In Section 4, we explain our improvement of LSPIA in four aspects. Section 5 is the implementation of data fitting and chord error refinement with ELSPIA. Section 6 presents some numerical validation and Section 7 presents machining experiments. The last Section 8 concludes this paper. Moreover, Appendix supplements some detailed algorithm of this paper.

2. Overview of tool path B-spline fitting algorithm

To obtain smooth, shape preserving, and tolerance banded cubic B-Spline tool paths, first the original data points need to be processed to remove noise points, determine HBPs, and identify long segments, then data points of tool path must be grouped by “breaks”, which should be identified by data analysis [1]. Thus the generated new point sequences are more suitable for further fitting.

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