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A fine-interpolation-based parametric interpolation method with a novel real-time look-ahead algorithm

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HIGHLIGHTS

- Optimization in both of the two interpolation stages.
- Full consideration of various kinematical constraints.
- Methodology of parameters adjustments in fine interpolation.
- Application of a novel look-ahead algorithm in rough interpolation.
- Application in open architecture CNC.

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ABSTRACT

Parametric interpolation is presently supported by majority of CNC systems because of its various advantages over traditional linear/circular interpolation. Two stages (i.e. rough interpolation and fine interpolation) involved in parametric interpolation are complementary to each other in terms of affecting machining quality significantly. So far much work has been conducted to improve the machining process with various rough interpolation adjustments, while with little research on fine interpolation. To further alleviate the feedrate jump between two adjacent rough interpolation periods, a fine interpolating strategy implemented within one rough interpolation period can be utilized to make the feedrate alteration comparatively smooth. Meanwhile, an arc is adopted to substitute the linear path to reduce the chord errors caused by rough interpolation. Besides, as one of the major difficulties of parametric interpolation is the feedrate determination concerning a wide variety of technical parameters, a real-time look-ahead feedrate generation method which can determine the decelerating position rapidly and accurately is proposed in this paper. The look-ahead approach can generate the feedrate profile to satisfy the geometrical constraints and kinematical characteristics determined by machine tools. Finally, the proposed parametric interpolation method is performed in an open architecture CNC platform to machine parametric curves. The results are satisfactory and are able to verify the robustness and effectiveness of the proposed algorithm.

1. Introduction

1.1. Parametric interpolation

CNC machining has become a significant part in the manufacturing industry for ever growing demands for high-precision and high-efficiency machining. Since the goal for machining is to obtain more satisfying machined parts within a shorter period, quality and efficiency are basically two pursuits for research and efforts in this field. As for the interpolation stage of machining, high-accuracy requires errors induced by the approximation with a large amount of segments are limited to a tolerant range, while high-speed needs a smooth feedrate profile that keeps machining fast and accurate. Parametric interpolation owns many merits over the traditional linear and circular interpolation in terms of the model representation, feedrate smoothness and application range [1–4].

(a) The geometrical information of the machining contours can be totally as well as accurately transferred to the CNC systems without any approximation errors and data loss that may occur in the linear and circular interpolation.
(b) Parametric interpolator only needs some critical parameters of the machining contours (i.e. control points, knot vectors,

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weights), such a transmission mechanism can guarantee the efficiency of interaction between the host and the slave.

(c) Feedrate continuity is achieved effectively as the junctions between tiny segments in traditional interpolation methods which require repeated acceleration–deceleration processes are avoided.

(d) Parametric interpolation can still be used in the conventional CNC systems after some developments of the machining segments, such as approximating tiny parts into curves or transitional optimization with parametric curves between them.

In order to realize parametric interpolation, researchers developed a wide variety of methods to achieve better machining qualities. The initial approaches for interpolating parametric curves were based on Taylor's expansion [5–8]. The first-order and the second-order approximations of Taylor's expansion were the representative methods to determine the feedrate based on a certain value of chord error. To alleviate the feedrate fluctuation during machining, other algorithms had been introduced, specifically, optimizing feedrate profiles considering acceleration/deceleration (ACC/DEC) processes was feasible in this respect. Du et al. [9] presented an adaptive NURBS interpolator with the consideration of ACC/DEC control. A real-time flexible ACC/DEC control scheme was introduced to solve the sudden feedrate change around the corners with large curvature in their method. Lin and Tsai [8] proposed a real-time look-ahead NURBS interpolator using a servo dynamic feedrate modification technique to generate a jerk-limited feedrate profile. Heng and Erkorkmaz [10] presented a robust and numerically efficient NURBS interpolation strategy which applied an adaptive manner to avoid unwanted feed fluctuations and round-off errors, and a feedrate modulation strategy based on the trapezoidal ACC/DEC profile was developed to guarantee the final trajectory was jerk limited in all axis and the kinematic continuity.

Besides, Shen et al. [11] offered a new interpolation scheme for 2D NURBS curve which contained two steps: pre-processing and real-time interpolation. Besides the geometrical characteristics of the machining contours, the method also took the dynamic parameters limitations into consideration to achieve satisfied machining results. Lee et al. [12] proposed an off-line feedrate planning method of CNC machines constrained by chord error, acceleration and jerk limitations. The method adopted a pre-processor to process the machining NURBS in advance to release computation burden as well as to improve the feedrate profile. The feedrate profile out of their approach was suitable for CNC high-speed machining. Zhou et al. [13] presented a novel multiconstraints feedrate scheduling method for the parametric interpolation in five-axis machining. A feed optimization model was initially built with constrains of geometric error, the maximum feedrate and acceleration in their method. Then a linear programming algorithm was applied to achieve the optimal feedrate profile on the sampling positions. Beudaert et al. [14] put forward an algorithm to obtain an optimized feedrate profile to make the best use of kinematical characteristics of the machine. They pointed out the fundamental job of the feedrate interpolation which was limited by various kinematical parameters. Meanwhile, they proposed an iterative algorithm to compute the minimum time feedrate profile. Besides the full consideration of both tangential jerk and axis jerk, their algorithm could be applied to any articulated mechanical structures, which was quite meaningful. Sun et al. [15] proposed a novel adaptive feedrate interpolation method with drive constraints. They mainly adopted an iterative adjustment to generate a smooth feed profile. While Zhao et al. [16] introduced a feedback interpolator to eliminate the feedrate fluctuation. Besides all these researches, researchers mainly focused on the solution of feedrate determination or feedrate optimization with different kinds of algorithms, such as adaptive speed control algorithms and look-ahead algorithms by taking a wide range of kinematical and dynamical factors.

1.2. Look-ahead process

Look-ahead is a preprocessing on the contours before the real machining. Detecting the feedrate sensitive areas of the curve and determining the decelerating points to achieve a smooth feedrate profile are the main goals in the look-ahead process. Nam and Yang [17] developed a recursive trajectory generation method to estimate and determine the deceleration stage according to the distance left to travel; a look-ahead scheme with a jerk-limited acceleration was proposed for smoothing feedrate profile. Tsai et al. [18] applied a hybrid digital convolution technique to develop a look-ahead scheme that smoothed the feedrate between the joint of two curves. However, the algorithm was applied to multi-block NURBS curves, not to single NURBS curves. Tsai et al. [19] proposed an integrated look-ahead dynamics-based algorithm with the consideration of geometric and servo errors simultaneously. Emami and Arezoo [20] introduced a look-ahead trajectory generation to determine the acceleration stage according to the fast estimated arc length and the reverse interpolation of each curve for NURBS curves. Zhao et al. [2] presented a real-time look-ahead scheme which comprised of path-smoothing, bidirectional scanning and feedrate scheduling to acquire a feedrate profile with smooth acceleration. Based on the works referred above, look-ahead process is able to achieve the adaptive control of the feedrate according to the geometrical characteristics of the trajectory to be machined and assures that the contour errors of the interpolation trajectory are within the range of the appointed error [21].

There are two universal approaches for look-ahead strategy. One is off-line prediction, the other is on-line operation. Off-line strategy provides sufficient detection of the machining contours, and the feedrate profiles are obtained in a non-real-time process before machining procedure. Some complicated and comprehensive algorithms can be realized because the time-consuming computation can be accomplished in advance. On-line method is also called real-time look-ahead process, which requires predicting the following machining contours and determines the current feedrate within a limited time. Among majority of the research on look-ahead methods, the length of the tool path is known or can be calculated easily; however that is actually impractical for parametric curves because of an inaccurate mapping between the parametric u and the displacement S [6]. Besides, off-line look-ahead cannot be applied the to real-time systems effectively, so the expansibility of interpolation algorithms is limited. Hence, in this paper, a real-time look-ahead strategy for parametric interpolation which can enhance the effectiveness and efficiency of machining is presented.

1.3. Two stages of machining

To accomplish the machining of parametric curves, two stages are involved in the CNC interpolation process: rough interpolation and fine interpolation [22]. Rough interpolation generates tiny line segments for each rough interpolation period and sends them to the fine interpolator. The fine interpolator finishes the machining of these tiny parts with several sections based on the servo cycle. So, the rough interpolation period should be integral multiples of the fine interpolation period. A general architecture of the current parametric interpolation methods is shown in Fig. 1. Currently, most research which concentrates on the improvement of machining performance with various algorithms is implemented in the former stage, while quite a few works are involved with the fine interpolation stage that affects the machining results significantly. Therefore, some strategies are proposed in this paper to boost the machining accuracy and efficiency in the fine interpolation stage.

1.4. Research objective

This paper proposes a parametric interpolation method integrated to a novel real-time look-ahead algorithm as well as