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A tool path generation and contour error estimation method for four-axis serial machines

Jixiang Yang, Youping Chen, Yuanhao Chen, Dailin Zhang *

School of Mechanical Science and Engineering, State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China

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ABSTRACT

Although four-axis machines are widely used in welding, carving, and cutting revolving parts, much fewer four-axis tool path generation and contour error estimation researches have been studied when compared with five-axis ones. This paper proposes an off-line tool path generation and an on-line contour error estimation method for four-axis serial machines that are used for welding spatial intersecting curves on revolving parts. First, the kinematics module is derived, followed by proposing the tool path generation algorithm. The tool tip positions are represented by using a third order B-spline, while the tool orientations are represented by a third order polynomial-spline. Both splines, which form the C^2 continuous tool path, are fitted to the curve length parameter of the tool tip positions. When compared with existing multi-axis trajectory generation methods, the proposed method is greatly simplified by mapping the tool pose commands from the Cartesian coordinate frame to the cylindrical coordinate frame. In the proposed contour error estimation method, the tool tip position contour error is estimated at first, followed by calculating the relative tool orientation contour error which is synchronized with the tool tip position contour error to one same pose on the desired trajectory. The proposed tool path generation and contour error estimation methods are experimentally verified on a four-axis welding machine controlled by an in-house developed CNC system. Experiment results show that the desired trajectory can be tracked continuously and steadily. The contour error can be estimated with high accuracy and reduced by 50% after performing on-line compensation.

1. Introduction

Typical four-axis machines usually have one or two rotary axes. The increasing rotary axes make four-axis machines be able to flexibly adjust both positions and orientations of the tools relative to the workpieces. Consequently, four-axis machines have higher machining rate when compared with two or three-axis machines and are widely used in welding, carving and cutting revolving parts [1,2]. However, the increasing rotary axes make the four-axis tool path generation and contour error estimation complex because both the tool tip position and tool orientation affect machining accuracy. The kinematics configurations of a laser carving machine and welding machine are respectively shown in Fig. 1(a) and (b).

In multi-axis contour machining, CAM systems generate discrete tool poses by indicating the tool tip position coordinates and the tool orientation vectors in the workpiece system (P-system). Later, the tool tip positions and orientations are transformed into motion commands of the linear and rotary drives in the machine system (M-system) by using the kinematics model of the machine tool. After performing the inverse kinematics solution, the discrete data points along the tool paths are usually linearly interpolated by the CNC in order to obtain a continuous tool path. However, the velocity discontinuities at the linear segment junctions lead to high accelerations and poor trajectory tracking performance [3]. In order to obtain a continuous high order tool path, many researches have been studied on parameterized spline tool path generation for multi-axis machines. Fleisig and Spence [3] used C^2 continuous splines for tool tip position and tool orientation in generating five-axis tool paths. They used another C^2 continuous, re-parameterization spline to relate the tool tip position to the orientation splines. Liu et al. [4] improved on [3] by re-parameterizing the orientation parameter spline to the arc-length of the tool path, instead of the chord-length used in [3]. Langeron et al. [5] represented the tool path using two B-splines, each corresponding to the trajectory of two particular points on the tool axis. Zhang et al. [6], and Bi et al. [7] adopted dual quaternion as a mathematical tool and generated dual rational tool paths with equal distance. The dual splines synchronized the two curves that represent motions of two points on

* Corresponding author. Tel.: +86 2787543555.
E-mail addresses: jixiangyang@hust.edu.cn (J. Yang), mnizhang@hust.edu.cn (D. Zhang).

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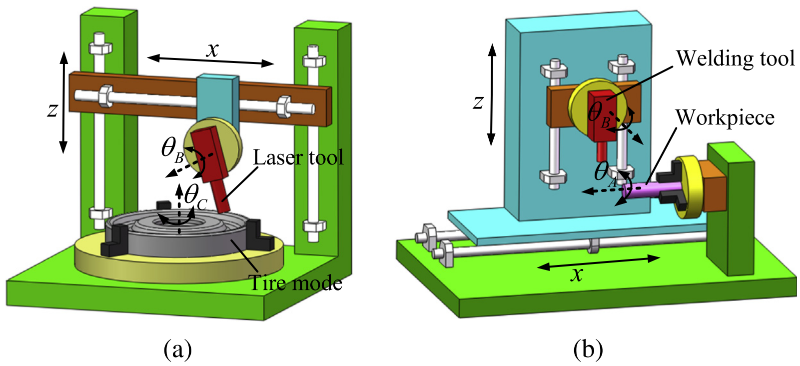

Fig. 1. Four-axis kinematics configuration: (a) laser carving machine; (b) welding machine.

the tool axis directly by using only one parameter. However, the tool path with an abrupt angular change over a short displacement may bring oscillatory as pointed out by Yuen et al. [8]. In order to solve the shortages of the coupled trajectory generation method, Yuen et al. [8] used two fifth order B-splines to represent tool tip position and tool orientation vectors separately, and then fitted both B-splines to arc-length parameter in order to accomplish coordinated motion. Yang and Altintas [9] also proposed a decoupled five-axis tool path generation algorithm where singularities are detected and avoided by using local deformation method. However, most of the existing multi-axis tool path generation methods are desired for five-axis machines and very few researches have been done specially for four axis ones.The existing multi-axis tool orientation splines are more complex than the standard Cartesian splines because the orientation vectors along the whole trajectory need to be unit ones and sphere splines are usually needed to represent tool orientations [3,8,9]. Lü et al. [2] presented a four-axis interpolation algorithm for four-axis saddle curve automatic welding. However, the model in [2] is built based on the assumption that the saddle curve is the intersection line of two cylinders, which is not suitable to general conditions when the tool paths are intersection lines on common revolving parts.

While high order smooth multi-axis trajectory generation is a prerequisite for good tracking performance with low vibrations, multi-axis contour error is an important index of multi-axis machining quality because it directly affects the dimension accuracy of the parts. It is important to estimate contouring error accurately because it is the basis to effectively control and evaluate contour accuracy. For multi-axis machines with rotary axes, the machining accuracy is affected by both tool tip position and tool orientation. Consequently, unlike two or three-axis machines, multi-axis tool tip position and tool orientation should be simultaneously considered to minimize contouring errors [10]. According to the authors' knowledge, only a few researches on contour error estimations have been presented for multi-axis with rotary axes so far. Lo [11] estimated the arc-length lag along the desired trajectory by using the tangential projection of the tracking error in the five-axis workpiece frame, then the contour error are estimated through the 2nd order Taylor series expansion with respect to the arc-length. Sencer et al. [12] provided a five-axis contour error estimation method for tool tip position spline and tool orientation spline separately. The tool tip position contour error was estimated according to the tracking error by using a shifted Frenet frame, while the tool orientation contour error was estimated by projecting the tool orientation tracking error to the tangential direction of the tool orientation trajectory. Based on the research of Sencer et al. [12], El Khalick and Uchiyama [13] presented a new method to estimate tool orientation contour errors for five-axis machining, where the tool tip position errors and tool orientation errors are synchronized to one same tool pose on the desired trajectory. Khoshdarregi et al. [14] integrated an iterative method proposed by Erkorkmaz et al. [15] with a look-ahead function to estimate five-axis tool tip position contour error, while the tool orientation contour error was not covered. Yang and Altintas [16] proposed a generalized on-line contouring error estimation algorithm of five-axis CNC machine tools based on a generalized Jacobian function.

It can be seen that although there are existing researches which focus on the tool path generation and contouring error estimation for multi-axis machine tools with rotary axes, most of them are studied for five-axis machines and very few researches have been done on four-axis machines by considering their own kinematic characteristics. Four-axis machines normally contain one less translational freedom when compared with five-axis machines and are widely used to manufacture revolving parts as shown in Fig. 1. Because of the lacked translational freedom that could compensate tool tip displacement caused by tool orientation variance in some directions, the four-axis tool orientations are normally constrained in one plane that pass through the center axis of the revolving parts, rather than free directions in the 3-D space like five-axis machines. By considering this kinematics characteristic, four-axis tool orientations can be represented by planar splines, rather than unit sphere splines required by five-axis machines. Consequently, tool orientation generation process can be significantly simplified. The corresponding contouring error estimation algorithm, which tightly depends on the trajectory type, can also be simplified by considering four-axis kinematics characteristics.

This paper focus on developing a tool path generation and contour error estimation method for four-axis welding machines that are used for welding spatial intersecting curves on revolving parts. First, the kinematics module is derived, followed by proposing the tool path generation algorithm. The tool tip positions are represented by using a third order B-spline, while the tool orientations are represented by a third order polynomial-spline. Both splines, which form the C^2 continuous tool path, are fitted to the curve length parameter of the tool tip positions. When compared with existing multi-axis trajectory generation methods, the proposed method is greatly simplified by mapping the tool pose commands from the Cartesian coordinate frame to the cylindrical coordinate frame. In the proposed contour error estimation method, the tool tip position contour error is estimated at first, followed by calculating the relative tool orientation contour error which is synchronized with the tool tip position contour error to one same pose on the desired trajectory.

The rest of this paper is organized as follows: In Section 2, the kinematics module is built, followed by proposing the tool path generation algorithm. In Section 3, the four-axis contour error estimation method is proposed. Experiments are performed in Section 4. Finally, the paper is concluded in Section 5.

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