International Journal of Machine Tools & Manufacture 65 (2013) 8–14

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

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

Short Communication

Sliding mode contouring control design using nonlinear sliding surface for three-dimensional machining

A. El Khalick M., Naoki Uchiyama *, Shigenori Sano

Department of Mechanical Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku, Toyohashi, Aichi 441-8580, Japan

ARTICLE INFO

Article history:
Received 1 December 2011
Received in revised form
11 July 2012
Accepted 13 July 2012
Available online 5 September 2012

Keywords:
Multi-axis feed drive system
Control
Contouring control
Sliding mode control
Nonlinear sliding surface

ABSTRACT

Machining accuracy as well as consumed energy saving are important issues in machining by multi-axis feed drive systems. The contour error, which is defined as the error component orthogonal to the desired contour curve, is a good indicator of machining precision. This paper presents a novel sliding mode contouring controller with nonlinear sliding surface to improve the machining accuracy for three-dimensional machining. Unlike the conventional sliding mode control design, the proposed nonlinear sliding surface depends on the output so that the damping ratio of the system changes from its initial low value to its final high value as the output changes from its initial value to the set point. Hence, the proposed algorithm allows a closed-loop system to simultaneously achieve low overshoot and settling time, resulting in a smaller error. Because the contour error is more important than the tracking error with respect to each feed drive, the contour error component is included in the proposed sliding surface. By using the proposed method, simulation and experimental results for a desktop three-axis machine show a significant performance improvement in terms of the contour error.

1. Introduction

High-precision machining and saving of the consumed energy are essential requirements for modern computerized numerical control (CNC) machines. For machining, error components orthogonal to the desired contour curve are called contour errors and represent good indicators of the machining precision. Tracking and contour errors are important aspects that significantly affect machining accuracy. Two main control approaches are used to improve contouring performance: the tracking control approach and the contouring control approach. Many existing approaches for reducing tracking errors in multi-axis feed drive systems have been developed to date [1–7].

The most significant factor in the performance of contouring systems is the accuracy of the overall system or the contour error of the system [8]. To reduce the contour error, researchers have developed a variety of alternative control approaches. By calculating the contour error from the tracking errors in biaxial contour-following tasks, Koren [9] proposed the cross-coupled controller (CCC), and Ho et al. decomposed the contour error into the normal tracking error and the advancing tangential error. A dynamic decoupling procedure is then applied to the system dynamics [10]. One disadvantage of the CCC methods is that both contour and tracking errors along the feed drive axes are used to calculate control inputs. This causes degradation in the contour tracking performance. To address this problem, Lo and Chung proposed a contouring control method for biaxial feed drive systems based on a coordinate transformation [11], in which tracking errors are transformed into errors with components that are orthogonal and tangential to the desired contour curves. Cheng and Lee proposed a real-time contour error estimation algorithm [12] and employed an integrated motion control scheme to improve the machining accuracy for a contour following tasks.

However, in all the above contouring algorithms, the case of three-dimensional contouring control is not considered. To reduce the contour error in three-axis machines, Lo proposed a three-axis contouring controller that operated in a trajectory coordinate basis that is moving along the tool path trajectory [13]. Other researchers such as Chiu and Tomizuka introduced transforming machine tool feed drive dynamics into a moving task coordinate frame attached to the desired contour, i.e., the task coordinate frame at the desired position of the feed drive system. The control system dynamics are then reformulated with respect to the new coordinate frame [14]. Uchiyama et al. established a contouring controller for three-dimensional machining based on a coordinate transformation [15]. In addition, they proposed a method to reduce the inherent contour error resulting from the coordinate transformation approach. Recently, Khalick and Uchiyama introduced a contouring controller for three-dimensional machining based on iterative contour error estimation and a coordinate transformation approach [16].

* Corresponding author.
E-mail address: uchiyama@tut.jp (N. Uchiyama).

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http://dx.doi.org/10.1016/j.ijmachtools.2012.07.004

Sliding mode control has received plenty of attention owing to its insensitivity to disturbances and parameter variations. The well-known sliding mode control is a particular type of variable structure control systems [17]. The conventional sliding mode controllers assume a linear sliding surface resulting in a constant damping ratio. The most important requirements of the modern control systems are fast response and small overshoot. However, quick response produces high overshoot, which causes tracking errors and also increases the consumed energy. On the other hand, low overshoot means slow response, which leads to tracking errors. Thus, it is very difficult to achieve small overshoot with a fast response using the conventional linear sliding mode control method. This particular problem can be solved by employing the composite nonlinear feedback (CNF) technique [18]. The nonlinear sliding surface consists of a linear term and a nonlinear term. The linear term comprises a gain matrix that has a very low damping ratio value, thereby facilitating a fast response [19]. The nonlinear term is introduced to accommodate a variable damping ratio in order to reduce the overshoot and settling time of the closed loop system as the output approaches the desired reference position.

To improve the contouring performance in machine tool feed drive systems, a nonlinear sliding mode contouring controller is designed based on iterative contour error estimation and a coordinate transformation approach. We propose a novel sliding surface, in which the normal and bi-normal error components are given more importance than the tangential component, to reduce the contour error. The aim of the proposed controller is to guarantee stability and enhance the contouring performance of three-axis feed drive systems. The main advantage of the proposed approach is that it achieves a quick response and a small overshoot, thereby providing improved performance in terms of contouring errors and consumed energy savings. To verify the effectiveness of the proposed approach, experiments have been conducted for a three-axis CNC machine. The experimental results show that by adjusting the parameters of the nonlinear term, the contour error can be significantly reduced.

2. Three-dimensional contour error estimation

This section briefly explains the iterative estimation method for contour errors in three-dimensional machining, presented by the first two authors [16]. The contour error is defined as the shortest distance between the actual contour and the desired one. The relationship between the contour error and the tracking error in each feed drive axis is shown in Fig. 1. The curve o is the desired contour curve of the point of a machined part driven by the feed drive system. The variable $r=[r_x,r_y,r_z]^T$ is the desired position of the point of the machined part at time t, and is defined in a fixed frame Σ_w, whose axes x, y, and z correspond to the feed drive axes. In addition, we assume that the first and second time derivatives, $\dot{r}$ and $\ddot{r}$, of the reference signal r are available. The actual position of the feed drive system is assumed to be $q=[q_x,q_y,q_z]^T$, which is also defined in the fixed frame Σ_w. The tracking errors in each feed drive axis, $e_w=[e_x, e_y, e_z]^T$, are defined as follows:

$$e_w=[e_x,e_y,e_z]^T=q-r. \tag{1}$$

The above errors are defined in the coordinate frame Σ_w. For a parametrically defined curve, the curvature at the desired position r is calculated as follows [20]:

$$\frac{1}{R}=\frac{\|\dot{r}\times\ddot{r}\|}{\|\dot{r}\|^3},\quad \dot{r}\neq 0. \tag{2}$$

The iterative algorithm can be summarized as follows:

(1) A local coordinate frame Σ_L is defined with origin at r and axes t, n, and b, as shown in Fig. 1. The t-axis is in the tangential direction of o at r, the n-axis is in the normal direction of o at r, and the b-axis is the bi-normal component normal to t and n. For the parametric trajectory, the tangential, normal, and bi-normal vectors, denoted as t, n, and b, respectively, are calculated at a time t as follows:

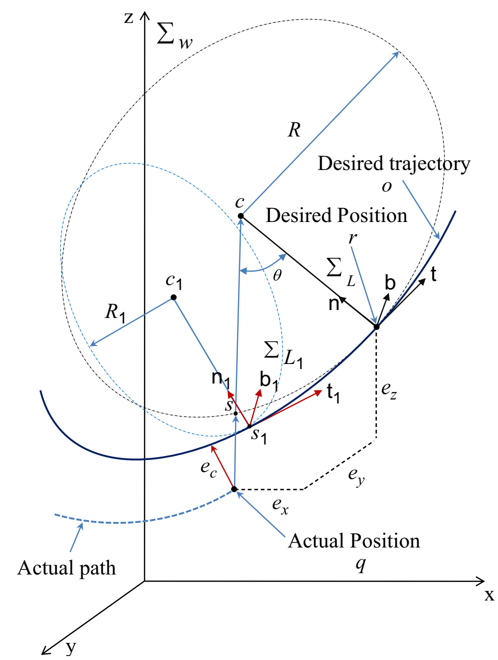

Fig. 1. Iterative approach for three-dimensional contour error estimation.

$$t=\frac{\dot{r}}{\|\dot{r}\|}, \tag{3}$$

$$n=\frac{\ddot{r}}{\|\ddot{r}\|}, \tag{4}$$

$$b=t\times n. \tag{5}$$

(2) The circle of curvature is located in the t–n plane and perpendicular to b. The center of the circle c can be estimated using a coordinate transformation between the fixed and the local coordinate frames:

$$c=[c_x,c_y,c_z]^T=r+L[0\;\;R\;\;0]^T,$$
$$L=[t\;\;n\;\;b]. \tag{6}$$

(3) The angle θ can be estimated as follows:

$$\theta=\cos^{-1}\frac{a\cdot n}{\|a\|\|n\|},$$

$$a=\frac{c-q}{\|c-q\|}. \tag{7}$$

(4) A new local coordinate frame Σ_{L_1} is defined at point $s_1=r(t_1)$, where the time t_1 can be estimated by assuming a constant velocity throughout the segment r–s equaling to the desired velocity at r. The time required to pass the segment r–s is the same as that required to pass the segment r–s_1 on the desired trajectory. The delayed time t_1 is calculated as follows:

$$t_1=t-t_d.$$

$$t_d=\frac{R\theta}{\|\dot{r}\|},\quad \dot{r}\neq 0. \tag{8}$$

(5) The three unit vector for the coordinate system Σ_{L_1} corresponding to the instantaneous reference position, s_1, are