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A two-layered cross coupling control scheme for a three-dimensional motion control system

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ABSTRACT

A two-layered modeling and compensation scheme is proposed to reduce the contouring error of a three-dimensional motion control system. In the proposed scheme, the contouring error model of the three-dimensional motion control system is divided into two layers: the top layer and the bottom layer. The proposed multi-layered structure of the contouring error model presents more flexibility in the control system design because the cross coupling controllers in different layers can be designed separately. In this paper, a nonlinear PI controller and a position error compensator are designed in the bottom layer in order to achieve high contouring accuracy in the *XY* plane, while a unilateral compensator is designed in the top layer to further reduce contouring error in the three dimensional space. Finally, experiments are performed to verify the performance of the proposed two-layered modeling and compensation scheme. Experiment results show that the designed two-layered cross coupling controller can obtain higher contouring accuracy than traditional cross coupling controller both in the *XY* plane and in the *XYZ* space.

1. Introduction

Contouring error, which is defined as the shortest distance from the actual cutter location to the desired trajectory, is an important index in the contour following tasks such as CNC machining and welding. Although the tracking accuracy of an individual axis can be improved by applying various advanced control strategies such as sliding mode controller [1], feedforward controller [2] and so on, the tracking accuracy improvement of each individual axis cannot guarantee the reduction of the contouring error. The reason is that contouring error is not only affected by tracking errors of single drives, but also has tight relation with the synchronizing movements among them. The cross coupling controller (CCC), which considers the coupling effect between motion axes is regarded as one of the most effective methods to reduce the contouring error.

Most existing CCCs, especially early ones were mainly focused on bi-axis motion control systems. For example, Koren [3] firstly proposed the CCC based on a bi-axis platform in 1980, where the contouring errors were estimated as linear relationships with the drives' tracking errors and compensated to the velocity loop of each drive. Yang and Li [4] proposed a position loop-based CCC on a bi-axis motion control system. Meanwhile, many advanced controllers were also combined with CCC to improve the contouring performance of the bi-axis platform, such as the robust tracking controller (RTC) [5], the tangential-contouring controller (TCC) [6], the task polar coordinate frame controller (TPCFC) [7], and the hierarchical optimal contour controller [8]. Recently, Hu et al. [9] and Yao et al. [10] proposed a global task coordinate frame to improve the contouring accuracy of bi-axis systems, where the estimated contouring error is exactly the same as the first-order approximation of the actual contouring error, no matter how large the position tracking errors would be.

Although the above bi-axis CCCs [3–10] performed well on bi-axis motion control platforms, the kinematics relations between the axes needs to be considered when they were used in the motion control systems with more than three axes [11–16]. In [13], a traditional CCC method shown in Fig. 1 was introduced, which used the tracking error vectors to estimate the contouring error vector $\vec{\hat{\varepsilon}}_c$ and used a CCC to compensate the contouring error. In [16], crossing-coupling position command shaping controller was used to improve the contouring accuracy instead of a CCC. In most existing CCCs for multi-axis motion control systems, all axes were considered equally according to the topology of a machine tool. But in practice, the coupling relations between the axes are not equivalent and the requirements for the contouring accuracy in different planes are often different. For example, a general issue is often raised on how to achieve higher contouring accuracy in one of the planes while the contouring accuracy in the whole three-dimensional space is guaranteed.

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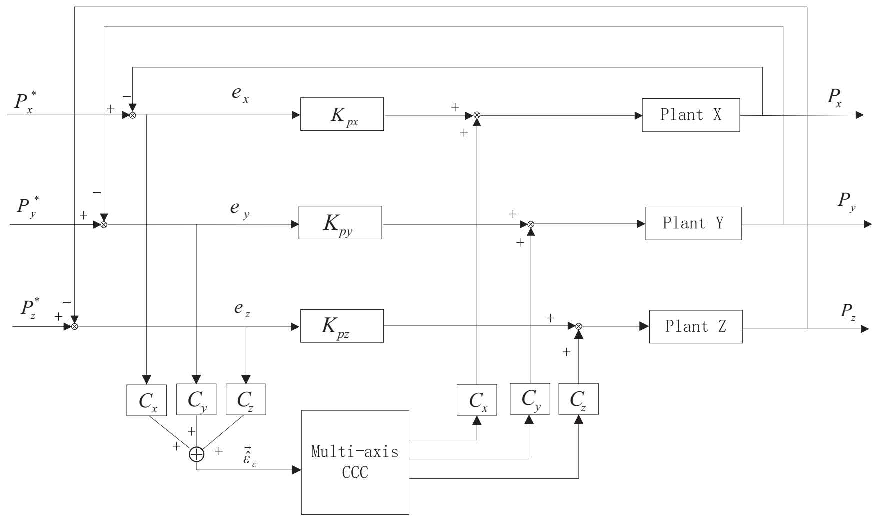

Fig. 1. The schematic diagram of a traditional multi-axis CCC [13].

Considering this condition, the traditional CCCs limit the flexibility of the compensation systems. For a traditional CCC shown in Fig. 1, the contouring error compensation mainly reduces the contouring error of the whole motion control system and cannot guarantee high contouring accuracy in one of the planes. In order to achieve the contour accuracies both in the required plane and the three-dimensional space, the multi-layered contouring error compensation is necessary which allows applying different control strategies for the different contouring error terms.

In the proposed two-layered CCC, the contouring error model is divided into two layers, i.e. the top and bottom layers. Different from the traditional multi-axis motion controller, the CCCs in different layers are designed separately. In order to reduce the contouring error in the bottom layer, an advanced CCC controller is adopted in the bottom layer. As a result, the designed two-layered CCC can reduce the overall contouring error and achieve high contouring accuracy in the bottom layer.

Although the two-layered CCC is a specific case, multi-layered CCCs with more layers can be similarly designed for machines with more complex topologies. Therefore, the contributions of the paper are

i. The proposed model builds contouring error controllers in several layers and every layer can be designed separately, which will result in more flexibility in the contouring error controller design. The multi-layered structure benefits applying different control strategies for the different contouring error terms.
ii. In the bottom layer, almost all advanced bi-axis CCCs can be used to compensate the contouring error, which can result in higher contour accuracy in the required planes.

The remaining of the paper is organized as follows. Section 2 describes the two-layered contour error model based on a three-dimensional motion control system. In Section 3, the two-layered CCC is designed. Experiment results are presented in Section 4. Finally, Section 5 draws the conclusions.

2. The two-layered error model of a three-dimensional contour

For a designed tool path, the contouring error is determined by the geometric relationship between the reference trajectory and the actual position. As shown in Fig. 2, P and R are the actual and reference positions, respectively. The tracking error vector $\vec{e}$ is divided into the tangential vector $\vec{\varepsilon}_t$ and the normal vector $\vec{\varepsilon}_n$, respectively.

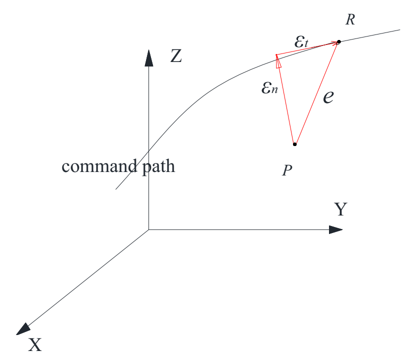

Fig. 2. Contour error estimation in the three-dimensional space.

Suppose that $\vec{e} = [e_x e_y e_z]^T$ is the tracking error vector of a three-dimensional contour, then the tangential and normal components of tracking error are respectively calculated as

$$\vec{\varepsilon}_t = \left\langle \vec{e}, \vec{t} \right\rangle \cdot \vec{t}, \ \vec{\varepsilon}_n = \left\langle \vec{e}, \vec{n} \right\rangle \cdot \vec{n} \tag{1}$$

where $\vec{t}$ and $\vec{n}$ are the unit tangential and unit normal vectors at the reference position R, respectively.

The contouring error can be estimated as the normal component of the tracking error [13].

$$\vec{\hat{\varepsilon}}_c \approx \vec{\varepsilon}_n = \left\langle \vec{e}, \vec{n} \right\rangle \cdot \vec{n} \tag{2}$$

From Fig. 2 it can be deduced that the estimated contouring error $\vec{\hat{\varepsilon}}_c$ approximates the contouring error well only when the tangential vector $\vec{\hat{\varepsilon}}_t$ is small. However, this disadvantage will be overcome by the position error compensator in Section 3.

In the proposed two-layered contouring error model shown in Fig. 3(a), the contouring error in the *XYZ* space is divided into two layers, i.e. the top and bottom layers, which are presented in Fig. 3 (b) and (c) respectively. Because the contouring error in the *XY* plane is mostly concerned, all points and paths are projected into the *XY* plane. After the contouring error is calculated in the *XY* plane, the tracking error in the *Z* direction is combined to achieve the contouring error in the *XYZ* space. The contouring error model in the *XY* plane is the bottom layer, and the two-dimensional contouring error model is considered to be the projection of the