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Improvement of Contour Following Control Using Cross Coupled Control and Adaptive Disturbance Compensation

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Abstract – Contour following motions are commonly seen in industrial manufacturing, in which the quality of manufacturing/product closely depends on the accuracy of contour following motions. In general, contour following accuracy will be affected by factors such as dynamics incompatibility among different axes and external disturbances. In order to cope with this problem, this paper proposes a new motion control scheme that consists of a well-known cross-coupled controller (CCC) and an adaptive disturbance compensator (ADC). In particular, the proposed motion control scheme is mainly used to suppress external disturbance and also cope with the problems of modeling uncertainty and dynamics incompatibility among different axes. Moreover, in order to further enhance the effectiveness of the proposed motion control scheme, the parameter-based contour error estimation algorithm is employed in this paper to provide accurate contour error information to the cross-coupled controller. Several contour following experiments conducted on a two-axis motion stage are used to assess the effectiveness of the proposed control scheme.

Keywords**:** Cross-Coupled Control (CCC), Adaptive Disturbance Compensator (ADC), Contour Error Estimation

1. Introduction

Many industrial manufacturing processes are required to perform contour following motions [1-6]. Generally speaking, tracking error and contour error are two of the commonly used performance indices for assessing contour following accuracy. The contour error is defined to be the shortest distance between the current position and the entire reference trajectory, while tracking error is the distance between the current position and the current position command. Since the accuracy of contour following significantly affects the quality of product, it is not surprising that many existing studies have been devoted to developing control schemes that can reduce tracking error and/or contour error so as to improve contour following accuracy [1]. Many existing literatures have pointed out that friction, external disturbance, and dynamics incompatibility among different axes are three of the major factors that may lead to deterioration in contour following accuracy for multi-axis motion stages [2]. Note that friction and dynamics incompatibility among different axes generally come from the mechanism design and material of the motion stage. One of the most effective ways to cope with the adverse effect caused by friction is the model based approach. That is, a suitable amount of compensation is determined based on an identified friction model. In addition, without properly dealing with the problem of dynamics incompatibility among different axes, significant contour error may occur. One of the most popular approaches for reducing contour error in a contour following task conducted on a biaxial motion stage is the cross-coupled controller (CCC) [3]. The original CCC proposed by Koren 1980 is only suitable for the case of straight line reference trajectory and its effectiveness closely depends on the contour error information. The calculation of contour error is routine for a straight line trajectory. However, it is not the case if one wants to apply the CCC to other types of reference trajectories. As a matter of fact, an accurate contour error estimation algorithm is essential when applying CCC to a parametric curve (not straight curve) following task. As for the suppression of external disturbance, many of the previous approaches preferred the disturbance observer based approach.

In order to cope with the problem of contour following accuracy being affected by factors such as dynamics incompatibility among different axes and external disturbances, this paper proposes a new motion control scheme that consists of a well-known cross-coupled controller (CCC) and an adaptive disturbance compensator (ADC). In addition, in this paper, a friction compensation term based on the renowned LuGre friction model [7] is used to compensate for friction. Moreover, in order to further enhance the effectiveness of the proposed control scheme, the parameter-based contour error estimation algorithm proposed in [8] is employed in this paper to provide accurate contour error information to the cross-coupled controller. Several contour following experiments conducted on a two-axis motion stage are used to assess the effectiveness of the proposed control scheme.

The remainder of the paper is organized as follows. Section 2 briefly reviews CCC and ADC. The proposed motion control scheme that consists of a CCC and an ADC is introduced in Section 3. Experimental results and conclusions are given in Section 4 and Section 5, respectively.

2. Brief Review on CCC and ADC

2.1. Brief Review on CCC (Cross-Coupled Controller)

As mentioned previously, the original CCC proposed by Koren is only suitable for the case of straight line reference trajectories. The idea of CCC is to calculate a proper compensation term based on contour error information so that the contour error due to dynamics incompatibility among different axes can be effectively reduced. Fig. 1 illustrates a typical block diagram of a modified CCC for a bi-axial motion control system, where $E_c^{'}$ is the estimated contour error obtained from a real-time contour error estimation algorithm. A suitable amount of compensation is sent to each axis after going through the cross-coupled controller K_c and the cross-coupled gains Cx, C_y described by (1) and (2).

$$C_x = -\sin\phi \tag{1}$$

$$C_y = \cos\phi \tag{2}$$

where ϕ is the angle between the straight line reference trajectory and x-axis.

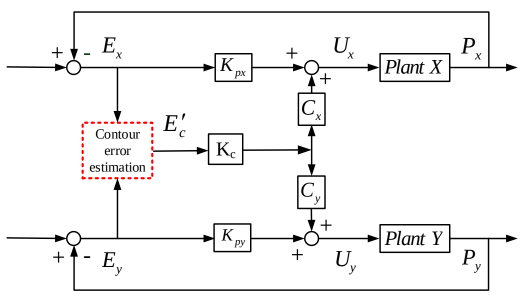

Fig. 1: Typical block diagram of a modified CCC for a bi-axial motion control system [4].

2.2. Brief Review on ADC (Adaptive Disturbance Compensator)

As mentioned previously, one of the most popular approaches for suppressing external disturbance is based on disturbance observers [5]. Among the disturbance observer based approaches, adaptive disturbance compensators (ADC) have been extensively adopted due to their gain tuning ability. Fig. 2 shows the block diagram of a motion control system consisting of a feedback controller and an ADC that is used to suppress external disturbance. In particular, the Adaptive Virtual Plant Disturbance Compensation scheme proposed by Chen *et. al.* [6] is adopted as the ADC in this paper. In order to implement the ADC, a virtual plant model needs to be identified first. An adaptive law is used to tune the gains of the disturbance observer so as to adjust the amount of disturbance compensation.

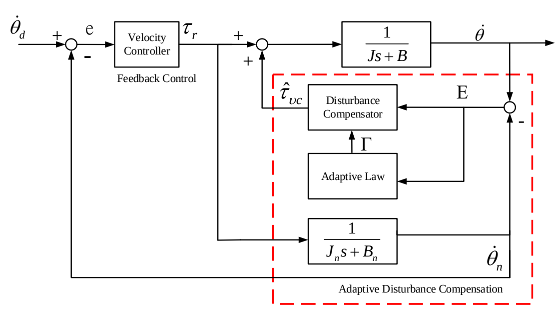

Fig. 2: Block diagram of a motion control system consisting of a feedback controller and an ADC that is used to suppress external disturbance [6].

3. Contour Following Control Using CCC and ADC

The block diagram of the proposed motion control scheme is illustrated in Fig. 3. As shown in Fig. 3, the outer position loop controller consists of a P type feedback controller, a velocity command feedforward term, and a modified CCC. In particular, the velocity command feedforward term is used to reduce tracking error, while the modified CCC is employed to overcome the problem of dynamics incompatibility among different axes. Note that the reason why a P type controller rather than a PI type controller is used in the outer position loop is that for contour following tasks of CNC machine tools, overcutting is prohibited. That is, overshoot in the position output should be avoided. As a result, the PI type position loop controller is not considered in contour following tasks in this paper. In contrast, the inner loop is composed of a PI type feedback controller, an ADC and a LuGre friction model based compensation term, in which the ADC is used to suppress external disturbance and the LuGre friction model based compensation term is employed to deal with adverse effects due to friction.

According to Fig. 3, the output of the outer loop for the *x*-axis and *y*-axis can be described as

$$\omega_{cx} = V_{ffx} + U_{fbx} + U_{cccx} \tag{3}$$

$$\omega_{cy} = V_{ffy} + U_{fby} + U_{cccy} \tag{4}$$

In (3), V_{ffx}, U_{fbx}, and U_{cccx} are the output of the velocity command feedforward term, the output of the feedback controller, and the output of the modified cross-coupled controller for the *x*-axis, respectively. In (4), V_{ffy}, U_{fby}, and U_{cccy} are the output of the velocity command feedforward term, the output of the position feedback controller, and the output of the modified cross-coupled controller for the *y*-axis, respectively. In order to enhance the performance of the CCC, as mentioned previously, accurate contour error information is essential. In this paper, the modified parameter-based contour error estimation algorithm proposed in [8] is used to provide accurate contour error information to the CCC in real-time.
Based on Fig. 3, the outputs of the cross-coupled controllers for the *x*-axis and *y*-axis are described by

$$U_{cccx} = C_x U_{ccc} = -sin(\phi) U_{ccc} \tag{5}$$

$$U_{cccy} = C_y U_{ccc} = cos(\phi) U_{ccc} \tag{6}$$

According to Fig. 3, the output of the inner velocity loop for the *x*-axis and *y*-axis can be described as

$$T_{cx} = \omega_{fbx} + \omega_{frix} + \omega_{adcx} \tag{7}$$

$$T_{cy} = \omega_{fby} + \omega_{friy} + \omega_{adcy} \tag{8}$$

In (7), ω_{fbx}, ω_{frix}, and ω_{adcx} are the output of the feedback controller, the output of the LuGre friction model based compensation term, and the output of the ADC for the *x*-axis, respectively. In (8), ω_{fby}, ${}_f\omega_{friy}$, and ω_{adcy} are the output of the feedback controller, the output of the LuGre friction model based compensation term, and the output of the ADC for the *y*-axis, respectively.

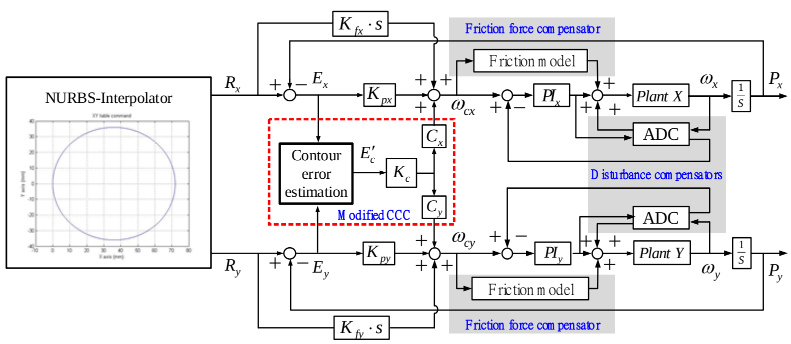

Fig. 3: Block diagram of the proposed motion control scheme.

4. Experimental Results

In order to assess the performance of the proposed motion control scheme, several contour following tasks are conducted on an X-Y table as shown in Fig. 4. Experimental results shown in Fig. 5-7 and Table 1 verify the effectiveness of the proposed motion control scheme.

Fig. 4: X-Y table used in the experiment.

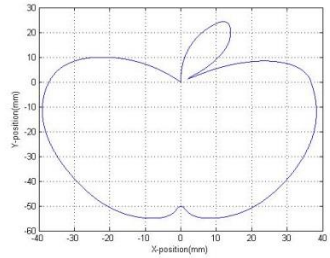

Fig. 5: Results of Apple-shaped contour following.

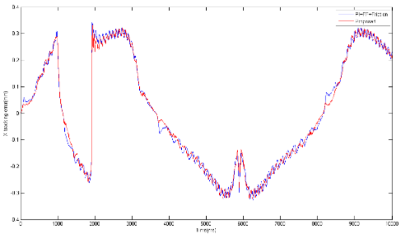

Fig. 6: Tracking error of X-axis.

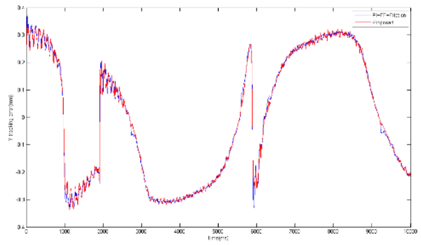

Fig. 7: Tracking error of Y-axis.

Table 1: Performance comparison of Apple contour following task.

	PI only	Proposed
Tracking error of X-axis		
RMS(mm)	0.2024	0.1993
Tracking error of Y-axis		
RMS(mm)	0.2328	0.2306
Contour error		
RMS(μm)	9.6	6.8

5. Conclusion

This paper proposes a new motion control scheme consisting of a CCC and an ADC to suppress external disturbance and also deal with the problem of dynamics incompatibility among different axes. In addition, a friction compensation term based on the LuGre friction model is used to compensate for friction. To further enhance the effectiveness of the proposed control scheme, the parameter-based contour error estimation algorithm is employed to provide accurate contour error information to the CCC. Results of contour following experiments indicate that the proposed motion control scheme performs much better than the conventional feedback controller.

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