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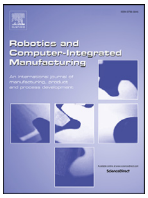

Iterative learning based trajectory generation for machine tool feed drive systems

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ABSTRACT

In machine tool performance, a fundamental factor is an axial movement which is driven to track a desired trajectory. Not only tracking errors in each drive axis but also contour errors, which are directly related to the machined shape of a workpiece, should be considered. Although most existing contouring controllers are based on feedback control, this paper proposes an embedded iterative learning contouring controller (EILCC) by considering both tracking and contour errors. The proposed control iteratively modifies the reference trajectory of each drive axis to reduce the contour error. The proposed controller can be directly applied to commercial machines currently in use without any modification of their original controllers. The proposed method has been experimentally verified through a biaxial feed drive system on a sharp-corner trajectory which normally leads to a large contour error around the corner due to the discontinuity. Comparison with a conventional iterative learning contouring controller (CILCC) was done so as to evaluate its performance. Experimental results have shown that the contour error converges within a few iterations, and the maximum contour error can be reduced by about 49.2% as compared to the CILCC.

1. Introduction

Feed drive systems such as biaxial feed drive systems are commonly applied in commercial industrial machines such as water jet machines, laser cutting machines, CNC punching machines, EDM wire cutting machines, etc. All have a fundamental movement based on X-Y axis movement which is driven to track a particular desired trajectory. The tracking ability is generally not so perfect that it may result in position errors [1]. However, the error has to comply with an allowable tolerance for producing required products. Achieving high precision in machining highly depends on control performance of each axis as well [2]. The common approach is to design an independent controller for each drive axis based on feedback control of the tracking error. However, the motion contour to achieve the desired shape of the workpiece is normally complex, whereby drive axes have to move in a synchronous manner with one another to obtain the desired contour. Under independent axial controllers, load disturbance or performance variance of either axis causes contour error [3]. Many control techniques have been developed in the past few decades to reduce both the tracking and contour errors.

Many cross-coupled methods are improved to control the contouring performance by coupling the individual axis error under high-feed-rate such as cross-coupled adaptive feed rate, and a cross-coupled iterative learning control (ILC) [4–9]. Moreover, the optimal contouring control deals with the evaluation of a cross-coupled compensator aimed specifically at improving the contouring accuracy in multi-axial feed drives by minimizing the weights of the contour error explicitly [10] and a novel cross-coupling control design by adjusting reference trajectory [11]. By applying an ILC, the convergence of the output error is guaranteed under certain conditions even when the system parameters are not known exactly or under the existence of bounded unknown external disturbances [12,13]. Furthermore, an iterative contouring controller minimizes the contour error through an iterative estimation of the instantaneous curvature of the reference trajectory and coordinates transformation [14]. In addition, the contour error can be significantly reduced by an ILC which considers both the tracking and contour errors [15]. All of the above mentioned and other ILC methods consider conventional iterative learning control (CILC) which assumes to have full access to the concerned system controller [16–21]. Normally, commercial systems do not provide full access to the controller except the adjustment of con-

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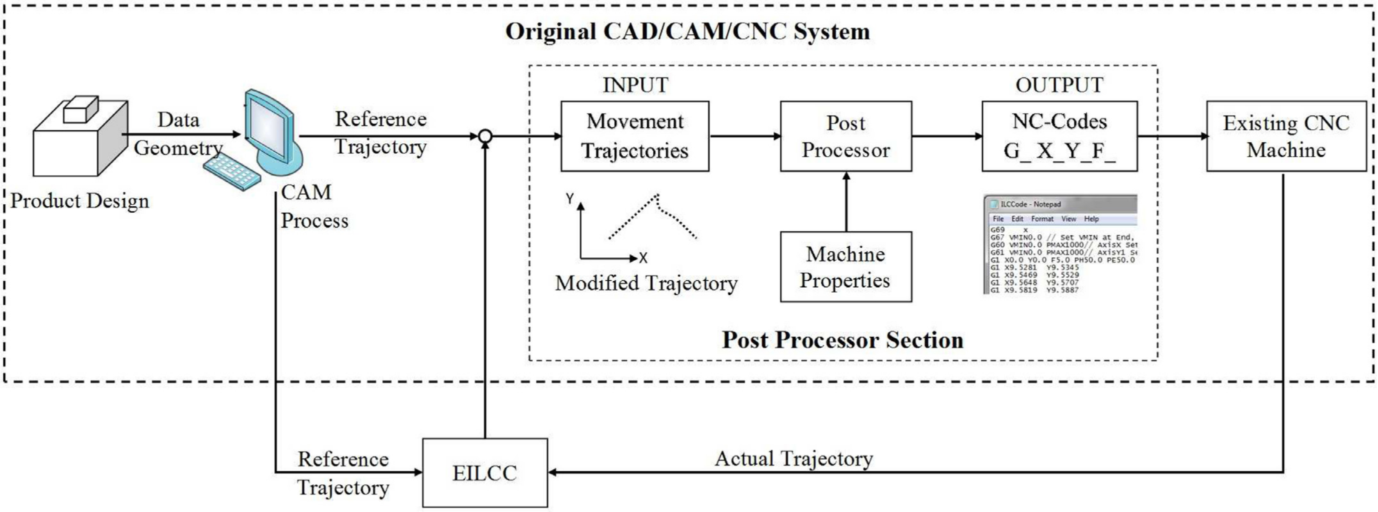

```
G69    X
G67 VMIN0.0 // Set VMIN at End,
G60 VMIN0.0 PMAX1000// AxisX Set
G61 VMIN0.0 PMAX1000// AxisY1 Se
G1 X0.0 Y0.0 F5.0 PH50.0 PE50.0
G1 X9.5281  Y9.5345
G1 X9.5469  Y9.5529
G1 X9.5648  Y9.5707
G1 X9.5819  Y9.5887
```

Fig. 1. Proposed EILCC concept.

trol gains. In addition, a few existing methods based CILC consider either tracking or contour error [22,23].

EILCC method is proposed by considering both the tracking and contour errors for machine tool feed drive system. The contour error is estimated from the tracking error and a rotational matrix. Then, the original reference trajectory is iteratively modified by the EILCC through a learning compensator. The modified trajectory is executed by CNC machine for better performance than that under the original trajectory. The process is done iteratively until when no significant reduction of the contour error is observed. Referring to controller proposed in [15], the conventional iterative learning contouring controller (CILCC) is used as baseline for comparison, and the EILCC was proven to provide better performance than the CILCC by simulation [24]. This paper is an extension of the previous work through addition of convergence analysis using the contour error and experimental verification on a biaxial feed drive system. The proposed controller can be directly applied to commercial machines currently in use by modifying NC codes without modification of the embedded controllers as shown in Fig. 1. Furthermore, by using this new controller, the contour error, directly controlled and reduced.

The rest of this paper is arranged as follows: Section 2 gives a brief description of the dynamics of machine tool feed drive systems, tracking error and contour error definition, the design of the proposed controller, and convergence analysis. Simulation results which compare the proposed and conventional methods are described in Section 3. Experimental results and discussion are given in Section 4 followed by concluding remarks in Section 5.

2. EILCC for biaxial feedrive system

2.1. Dynamic model of feed drive system

The dynamics of a biaxial feed drive system is represented as follows:

$$
\begin{aligned}
&M\ddot{q} + C\dot{q} = u,\\
&M = \mathrm{diag}\{m_i\},\ C = \mathrm{diag}\{c_i\}, \quad i = x,\ y, \qquad (1)\\
&q = [q_x,\ q_y]^{\mathrm{T}},\ u = [u_x,\ u_y]^{\mathrm{T}},
\end{aligned}
$$

where m_i, c_i, q_i, and u_i are the inertia, viscous friction coefficient, actual position, control voltage for the axis i, respectively.

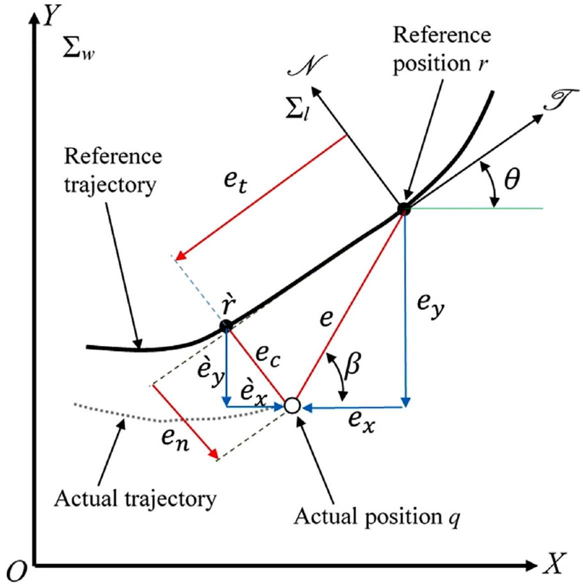

Fig. 2. Tracking and contour errors.

2.2. Error definition

The tracking error in each axis is defined as the difference between the desired and actual positions, while the contour error is the error components orthogonal to the desired contour curves [25]. The description of both the tracking and contour errors is shown in Fig. 2. The desired position of the feed drive system at time t in the coordinate frame Σ_w are denoted as r, while the actual position is denoted as q. The closest position of the desired contour to q is denoted by $\grave{r}$. The tracking error in each feed drive axis is defined as

$$e_w = [e_x,\ e_y]^{\mathrm{T}} = q - r. \tag{2}$$

$$e = \|e_w\| \tag{3}$$

The tracking error vector $e_l(t)$ with respect to Σ_l can be expressed as

$$e_l = [e_t,\ e_n]^{\mathrm{T}} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} e_w, \tag{4}$$