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A double-iterative learning and cross-coupling control design for high-precision motion control

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Abstract: In multi-axis motion control systems, the tracking errors of single axis load and the contour errors caused by the mismatch of dynamic characteristics between the moving axes will affect the accuracy of the motion control system. To solve this issue, a biaxial motion control strategy based on double-iterative learning and cross-coupling control is proposed. The proposed control method improves the accuracy of the motion control system by improving individual axis tracking performance and contour tracking performance. On this basis, a rapid control prototype (RCP) is designed, and the experiment is verified by the hardware and software platforms, LabVIEW and Compact RIO. The whole design shows enhancement in the precision of the motion control of the multi-axis system. The performance in individual axis tracking and contour tracking is greatly improved.

Key words: iterative learning control, cross-coupled control, contour tracking performance, double-iterative learning and cross coupling

1. Introduction

With the fast development of computerized numerical control (CNC) in manufacturing systems, modern manufacturing technology is more and more demanding on the precision of NC machine tool movement and the movement precision of CNC systems depends on the single-axis tracking performance and the contour tracking performance [1]. Among most multi-axis systems, the controllers are individually designed for each motion axis. In order to improve individual axis tracking accuracy, various control methods, such as sliding mode controllers [2], iterative learning controls [3], Discrete Loop Shaping Controllers [4], and zero phase error tracking algorithms [5], have been developed. But the improvement of the single axis tracking performance does not solve the problem of reduced tracking accuracy when the synchronization between the motion axes is poor [6].

In order to reduce the contour tracking error, a contour control method must be introduced into high-precision multi-axis motion. Results show that the cross-coupling controller (CCC) is an effective method to improve the accuracy of the system [7].

The first CCC and variable-gain CCC were proposed by Koren [8, 9]. Subsequently, cross-coupling control and modern control techniques were integrated by some scholars to further reduce the contour error. Li-Mei, Wang, and S. Lu designed the ILC controllers based on the robust condition of the direct-driven system with uncertainty and the robust convergence condition of the ILC in L_2 norm sense, which improved the tracking and contour performances [10]. Yang Lidong, Y. Liu, and H. Han presented a variable-weight position synchronous error, which can reduce the influence of dynamic nonlinearity through adjusting the error of each axis according to robot's inertia distribution [11]. Po Ray Chen, Y.P. Yang, and J.J. Chou proposed a time-optimal path-tracking strategy of cross-coupling control for a wheelchair driven by dual power wheels, which is robust to driver's weight and road disturbances [12]. Li Baoren *et al.* proposed cross-coupled synchronization fuzzy control based on the synchronization error of a double valve to solve the asynchronization problem during the working process [13]. Long Li proposed an adaptive zero phase error tracking controller (ZPETC), which could effectively improve the tracking accuracy and the contour accuracy combined with internal model control (IMC) control strategy [14]. Wu and Barton proposed the use of iterative learning control and cross-coupled control to design a cross-coupled iterative learning controller that can effectively improve contour performance in the case of stable convergence [15, 16]. Zhao Xi-Mei proposed zero phase adaptive robust cross-coupling control, combined with a phase error tracking controller (ZPETC), an adaptive robust controller (ARC), and a cross-coupled controller (CCC) [17]. Ouyang *et al.* proposed a position-domain cross-coupling control to improve contour tracking performance and to reduce the dependency on coupling operator accuracy compared to time-domain cross-coupled controllers [18, 19]. Li Xiang Fei *et al.* proposed a contour error compensation method based on the precise calculation of the contour error that the accuracy of the contour control can be improved by increasing the matching degree of the dynamic characteristics of the servo axes [20]. All of these methods can effectively improve the tracking performance of the system, but cannot effectively reduce the tracking error of a single axis. Therefore, there is a need for a method to improve the motion accuracy of the multi-axis system by combining the individual axis tracking accuracy and contour tracking performance.

In this paper, because mechanical parts in the processing industry usually undergo a repetitive processing movement, a control method combining iterative learning control and cross-coupled control was designed. The tracking performance of the single axis was improved by iterative learning control of the single axis, therefore the single axis tracking errors were decreased. The dual axis cross-coupled control was used to increase the matched degree among axes, thus the contour errors were reduced.

The iterative learning control of contour errors could further increase contour tracking performance. In this way, the system is designed to improve the individual axis tracking accuracy and contour tracking performance.

2. Double iterative learning and cross-coupling control

This section presents a contour error model of a motion trajectory, provides a brief review of cross-coupling control (CCC) and single axis iterative learning control (ILC), and proposed a double iterative learning and cross-coupling control (ILC and CCILC).

2.1. Contour error model of motion trajectory

In a multi-axis motion control system, mechanical error and control system error will affect the control accuracy of each axis, and the contour error caused by the uniaxial tracking hysteresis and the dynamic characteristic mismatch between the motion axes will reduce the accuracy of the motion control system. In a two-dimensional motion system, the contour trajectories are mainly linear and non-linear trajectories, and Yeh and Sun proposal the contour error model of two kinds of motion trajectories [21, 22]. The contour error is defined as the distance between the actual position point and the nearest point of the reference trajectories. At the same time, where P and $P*$ are the desired position and actual position.

As known from Fig. 1, the contour error of the linear trajectory is expressed as follows:

$$\varepsilon = E_y \cdot \cos\theta - E_x \cdot \sin\theta. \tag{1}$$

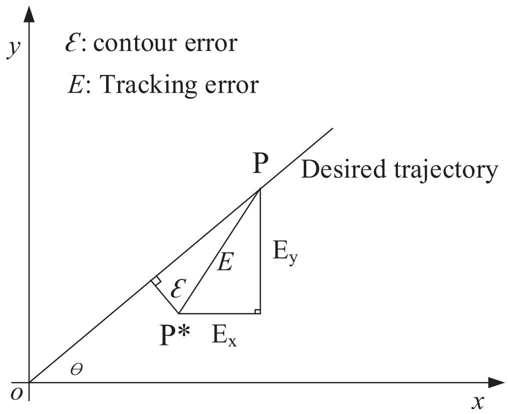


Fig. 1. Contour error model of linear trajectory

For non-linear contour trajectories, take any curve as an example. As known from Fig. 1, the contour error of the non-linear trajectory is expressed as follows:

$$\varepsilon = E_y \cdot \left(\cos\theta + \frac{E_y}{2\rho}\right) - E_x \cdot \left(\sin\theta - \frac{E_x}{2\rho}\right). \tag{2}$$

2.2. Cross-coupled control (CCC)

The cross-coupled control method is proposed to coordinate the motion of each axis to eliminate the contour error of the multi-axis motion system. The contour error is generated by the cross-coupling controller to generate a new control signal, and the new control signal is compensated to the coordinate axes by seeking and establishing the optimal compensation rate, so as to achieve the purpose of reducing the motion system contour error [23]. The establishment of the contour error model is the key of the cross-coupled controller. The contour error estimation model for linear trajectories and non-linear trajectories is shown in Eq. (1) and Eq. (2).

In Fig. 1, where $C_x = \sin\theta$, $C_y = \cos\theta$, θ is the angle between the x-axis and the desired linear motion. C_x and C_y are the coupling coefficients of linear trajectories in cross-coupling control. Similarly, in Fig. 2, where

$$C_x = \sin\theta - \frac{E_x}{2\rho}, \qquad C_y = \cos\theta + \frac{E_y}{2\rho},$$

θ is the angle between the tangent at the reference position and x-axis. C_x and C_y are the coupling coefficients of non-linear trajectories in cross-coupling control. Then Fig. 1 and Fig. 2 can be written as follows:

$$\varepsilon = -C_x e_x + C_y e_y \,. \tag{3}$$

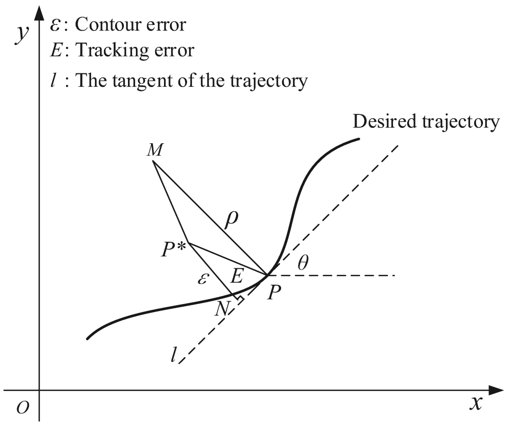


Fig. 2. Contour error model of non-linear trajectory

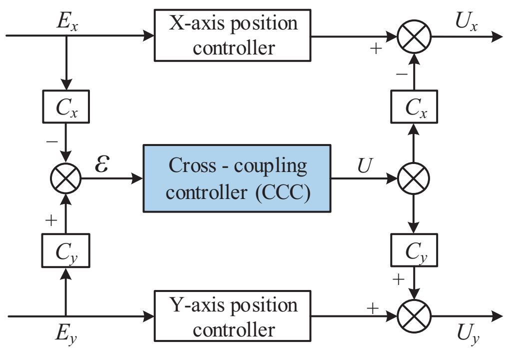


Fig. 3. The structure of the cross-coupling controller

The CCC consists of a contour error model and a contour error compensation strategy. The contour error compensation is determined by the weight gain coefficient. In this paper, the variable-gain CCC is used to coordinate the motion of each axis to eliminate the contour error of the multi-axis motion system. The block diagram of the variable-gain cross-coupling controller is illustrated in Fig. 3.

2.3. Cross-coupled iterative learning control (CCILC)

Cross-coupled iterative learning control is a control method that applies iterative learning directly to the contour error of the multi-axis control system. It can reduce the contour error of the system in finite time intervals. The contour of the motion system has a significant improvement, and the system block diagram of the cross-coupled iterative learning system is shown in Fig. 4.

The iterative learning law of a PD type system for the contour error can be expressed as follows:

$$u_{ccj+1}(t) = u_{ccj}(t) + L_{\varepsilon}(q^{-1})\varepsilon_j(t+1), \tag{4}$$

where $L_{\varepsilon}(q^{-1})$ is defined as the learning function of the contour, and ε_j is the contour error.

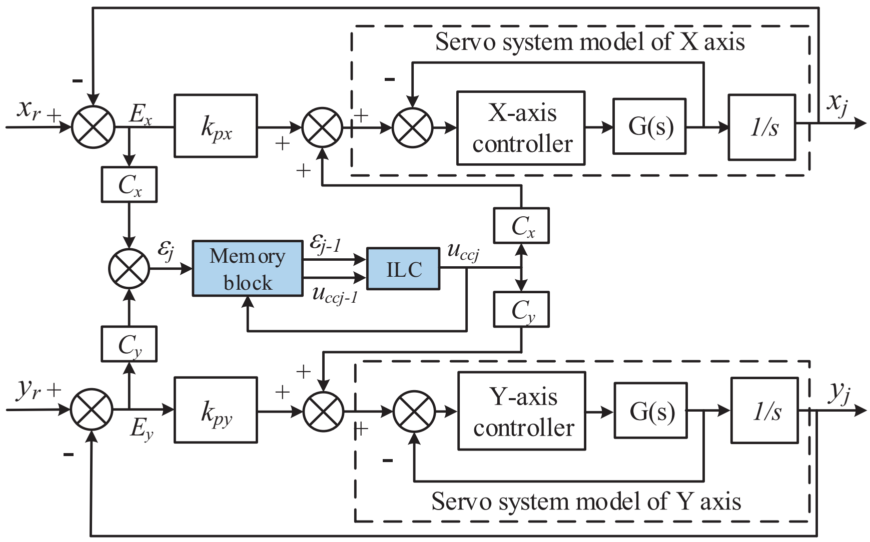


Fig. 4. Block diagram of the cross-coupled iterative learning control system

2.4. Double iterative learning and cross coupling control (ILC and CCILC)

Iterative learning control is a modeless integrated control method. The accuracy of the mathematical model and parameters of the motion system are not very strict. It does not need a lot of prior knowledge and computation, and can improve the tracking performance effectively. The cross-coupling controller is based on the contour error model, which can compensate the contour error of each axis effectively, and can improve the contour tracking ability of the multi-axis motion system to reduce the contour error. Cross-coupled iterative learning control applies the iterative learning control to the cross-coupled controller; it can improve the contour trajectory tracking performance of the system by studying the coupling error to modify the control signal, which can reduce the contour error to a certain extent. But it cannot improve single-axis tracking performance. Based on these characteristics, a double iterative learning and cross-coupling control method is proposed by combining the single axis iterative learning control and multi-axis cross-coupling iterative learning control. The system block diagram is shown in Fig. 5. Where x_r and y_r are the desired trajectories of the x-axis and y-axis. E_x and E_y are the tracking errors of the two axes, respectively. x_j and y_j are the actual trajectories of the two axes. ε is the contour error of the biaxial motion system.

The iterative learning law of the contour error is shown in Eq. (4). Combining individual axis ILC update laws (5) for the x-axis and y-axis with the CCILC update law (7), the combined ILC

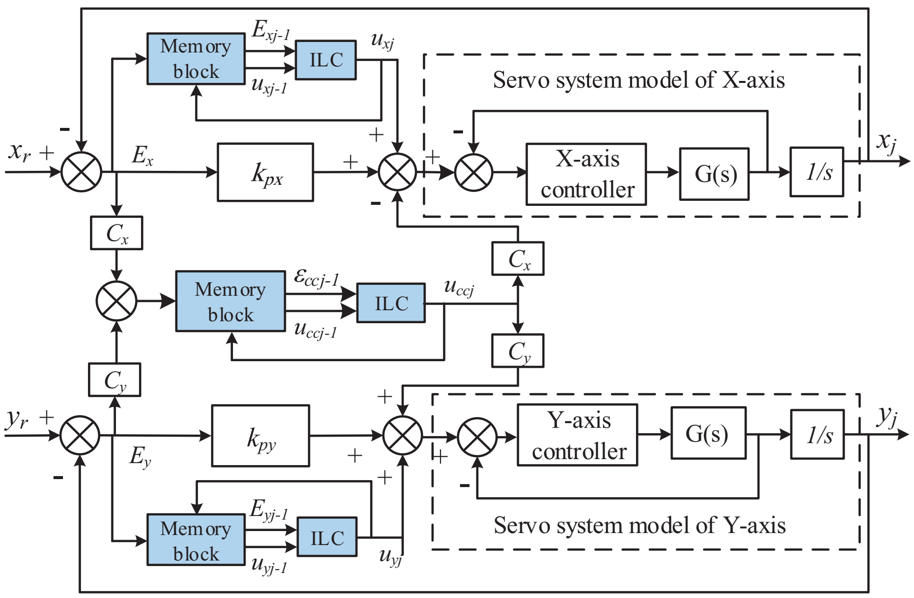


Fig. 5. Block diagram of the double Iterative learning and cross-coupling control

and CCILC update law can be written as:

$$u_{xj+1} = (u_x + L_x E_x - C_x L_\varepsilon \varepsilon)_j \,, \tag{5}$$

$$u_{yj+1} = \left(u_y + L_y E_y + C_y L_\varepsilon \varepsilon\right)_j \,, \tag{6}$$

where L_x and L_y are the learning function of the x-axis and y-axis, respectively. L_ε is defined as the learning function of the contour. The tracking errors of the two axes are

$$E_{xj}(t) = x_r(t) - x_j(t), \qquad E_{yj}(t) = y_r(t) - y_j(t).$$

Substituting Eq. (4) into Eq. (5) and Eq. (6), a matrix relating to the update control input with the previous input and periodic disturbances can be found.

$$\begin{bmatrix} u_x \\ u_y \end{bmatrix}_{j+1} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \cdot \begin{bmatrix} u_x \\ u_y \end{bmatrix}_j + \begin{bmatrix} d_{Lx} \\ d_{Ly} \end{bmatrix}, \tag{7}$$

where

$$\begin{aligned} M_{11} &= I - (L_x + C_x L_\varepsilon C_x) P_x \,, \\ M_{12} &= C_x L_\varepsilon C_y P_y \,, \\ M_{21} &= C_y L_\varepsilon C_x P_x \,, \\ M_{22} &= I - (L_y + C_y L_\varepsilon C_y) P_y \,. \end{aligned}$$

In order to guarantee the convergence of iterative learning control,

$$\lim_{j\to\infty} \left|u_\infty - u_j\right| = 0$$

must be met.

The sufficient and necessary conditions for the convergence of iterative learning control can be written as:

$$\left|\lambda_i \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\right| < 1, \tag{8}$$

where: $i \in [1, n]$, λ is the spectral radius and $\max|\lambda_i| < 1$. A sufficient condition for monotonic convergence of the combined system is given by

$$\left\| \begin{matrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{matrix} \right\|_i < 1, \tag{9}$$

where $\|\cdot\|_2$ represents the 2-norm of the matrix. In Eq. (9), $\sigma(M) < 1$ is the necessary and sufficient conditions for monotonicity and stability of the control system. From Eq. (9), the double Iterative learning and cross-coupling controller can be decomposed into two matrix forms of ILC and CCILC, Eq. (11) and Eq. (12). The convergence and stability conditions of the integrated motion controller can be expressed as Eq. (10). Devising the controllers individually and then merging them into a single control input permits tuning the ILC or CCILC parameters respectively to improve a certain performance.

$$\left\|[\text{ILC}_{x,y}] + [\text{CCILC}]\right\|_2 < 1, \tag{10}$$

$$[\text{ILC}_{x,y}] = \begin{bmatrix} (I - L_x P_x) & 0 \\ 0 & I - L_y P_y \end{bmatrix}, \tag{11}$$

$$[\text{CCILC}] = \begin{bmatrix} (I - C_x L_\varepsilon C_x P_x) & C_x L_\varepsilon C_y P_y \\ C_y L_\varepsilon C_x P_x & (I - C_y L_\varepsilon C_y P_y) \end{bmatrix}. \tag{12}$$

The necessary condition for monotonicity (12) is easily verified on a generic desktop computer for small matrices. Moreover, this can be shown to provide more flexibility in designing a controller for the combined system.

3. Experimental verification

In order to test the performance of the double-iterative learning and cross-coupling control method, two sets of experiments with linear contour trajectories and non-linear contour trajectories were carried out. Each experiment was conducted by a CCILC experiment, a cross-coupled control of biaxial contour error and a single-axis ILC and CCC experiment, and an ILC and CCILC experiment. The single axis tracking error and contour error of the three control methods were compared by the experimental results of the three groups.

In this paper, the double-iterative learning and cross-coupling control algorithm is mainly verified by the actual control experiment. The experimental equipment is mainly composed of three parts: the host computer, motion controller and control target. The experimental system is shown in Fig. 6.

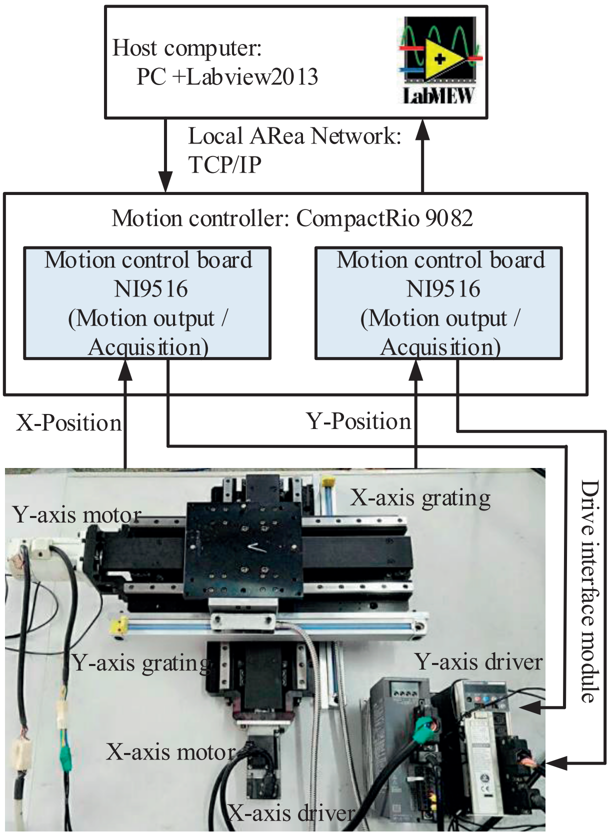


Fig. 6. Experimental system

As can be seen from Fig. 6, the host computer is HP z238 (OS Windows7, Inter(R), Xeon(R), CPU E3-1230 v5 of 3.40 GHz, memory 8 GB), running LabVIEW. The host computer is mainly used for programming and monitoring the data during the experiment. The motion controller is composed of NI CRIO-9082 and motion control board NI9516. The control target is an X-Y working platform consisting of a servo motor and a screw guide and the lead of the screw is 5 mm. In this paper, in order to make the dynamic characteristics inconsistent between the two axes, two different parameters of the permanent magnet synchronous motor are used in the x-axis and y-axis. One is using a MR-JE-10A series drive and HF-KN13J-S100 servo motor of Mitsubishi, the other is using a MSDA023A1A series drive and MSMA022A1C servo motor of Panasonic. The position information is collected by a line displacement series of closed grating with a resolution of 5 um.

3.1. Experiment of linear contour trajectory

When performing a linear contour trajectory experiment, the reference contour runs for 34 s and the sampling step is 0.005 s. The position controller parameter is $k_{px} = 80$ and the speed controller parameter is $k_{vp} = 200$, $k_{vi} = 50$ for the x-axis. The position controller parameter is $k_{py} = 100$ and the speed controller parameter is $k_{vp} = 120$, $k_{vi} = 20$ for the y-axis. The PD-type iterative learning rate parameters of the ILC and CCILC are shown in Table 1.

Table 1. PD-type iterative learning controller parameters for linear contour trajectories

Controller	k_p	k_d
***x*-axis**	18	0.01
Contour	8	0.005
***y*-axis**	20	0.02

In the experiment of the proposed control method, the stability of the control system is related to the parameters, and the tuning of the controller parameters is a very complicated process. Therefore, some guidelines for the choice of these parameters are given below:

1) Tuning PID gain for single-axis closed-loop controller through the simulation, this can minimize the tracking errors and maintain system stability.

2) The simulation of ILC is carried out based on step 1. Tuning parameters of iterative learning controller and fine-tuning PID gain on step 1 to ensure that the tracking error can converge to the minimum quickly.

3) Tuning PID gain for single-axis closed-loop controller through the simulation, this can minimize the tracking errors and maintain system stability.

4) The simulation of ILC is carried out based on step 1. Tuning parameters of iterative learning controller and fine-tuning PID gain on step 1 to ensure that the tracking error can converge to the minimum quickly.

5) The simulation of CCC is carried out based on step 1. Tuning coupling error PID gain of cross-coupling controller and fine-tuning PID gain on step 1 to ensure that the contour error can converge to the minimum quickly.

6) The simulation of CCILC is carried out based on step 3. Fine-tuning the parameters on step 2 and step 4 to ensure that the tracking error and the contour error can converge ensures that the tracking error can converge to the minimum quickly.

7) The simulation of ILC and CCILC is carried out based on step 2 and step 4. Fine-tuning the parameters determined by step 2 and step 4 to ensure that the tracking error and the contour error can converge to the minimum quickly.

8) Repeat step 1 to step 5 on NI Compact RIO. Fine-tuning the parameters determined by the above simulations.

The linear contours are shown in Fig. 7. The desired contour is compared with the CCILC experiment, ILC and CCC experiment, and ILC and CCILC experiment of three convergent contours. In Fig. 8, (a) and (b) are partial magnifications of two parts in Fig. 7, respectively.

As shows in Fig. 8, (a) and (b), compared with CCILC and ILC and CCC, the ILC and CCILC is closer to the desired contour and is more stable at the corner of the track when the trajectories are convergent.

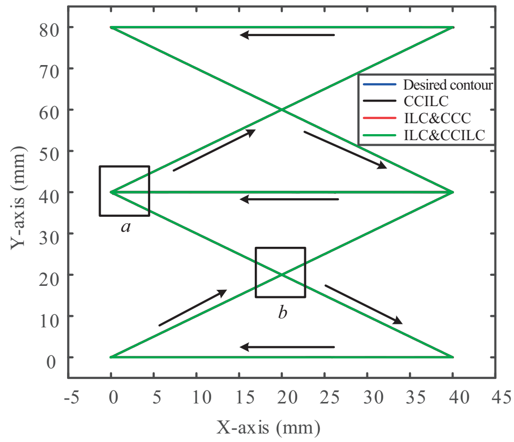
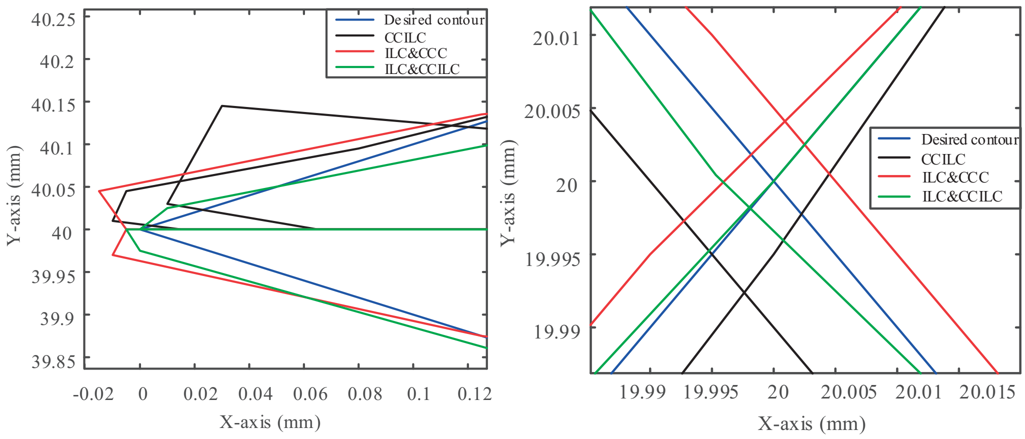


Fig. 7. Linear contour trajectories



(a) Contour trajectories (b) Contour trajectories

Fig. 8. Partial magnifications of two parts in Fig. 8

The contour errors of the three control methods are shown in Fig. 9, Fig. 10 and Fig. 11. The three figures show the contour error of the ILC and CCILC is smaller than that of the CCILC and ILC and CCC, and can significantly reduce the system's contour error. It can be seen from Fig. 12 that the ILC and CCILC has good stability and convergence for the linear contour trajectory, and the contour error in Fig. 12 is represented by the mean.

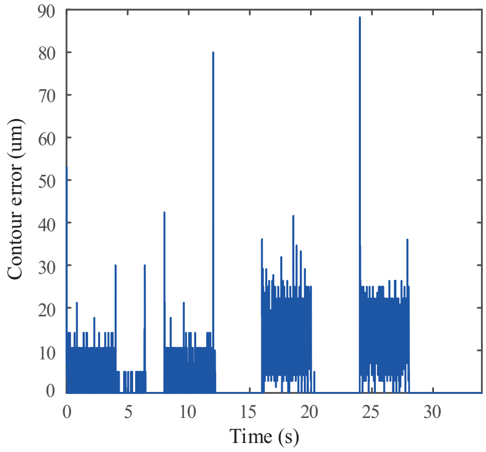


Fig. 9. Contour errors of CCILC

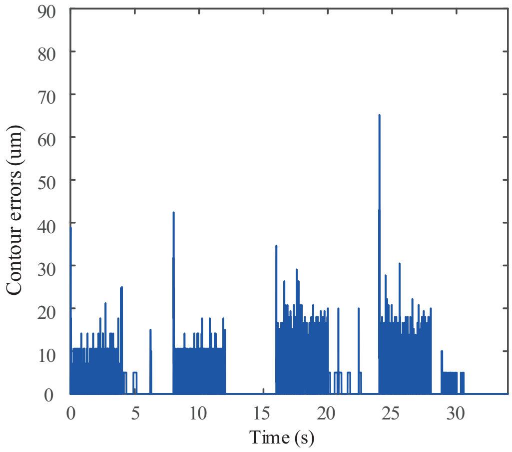


Fig. 10. Contour errors of ILC and CCC

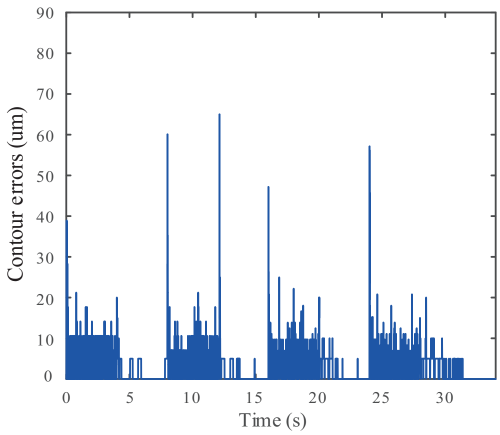


Fig. 11. Contour errors of ILC and CCILC

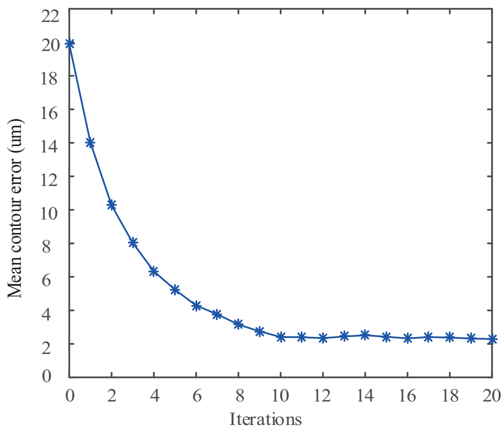


Fig. 12. Mean contour error values of ILC and CCILC

The errors of the three different control methods are shown in Table 2. When moving on the linear contour trajectory, the CCILC can improve the accuracy of contour control, but the single-axis tracking performance is not good, and the single axis tracking error of the ILC and CCILC and ILC and CCC is significantly less than that of the CCILC control method. Among them, the x-axis tracking error of ILC and CCILC is 72.65% of ILC and CCC, the y-axis tracking error of ILC and CCILC is 79.46% of ILC and CCC, and the contour error of ILC and CCILC is 87.71% of ILC and CCC. The contour error of ILC and CCILC is 65.15% of CCILC. The experimental results show the double-iterative learning and cross-coupling control (ILC and CCILC) has a significant improvement in both the single-axis tracking performance and the contour tracking performance on linear contour trajectories.

Table 2. RMS Errors of the three control methods on linear contour trajectory

Control method	**RMS value (um)**		
	RMS X	RMS⁻	RMS Y
CCILC	49.57	7.23	23.44
ILC and CCC	9.03	5.37	6.67
ILC and CCILC	6.56	4.71	5.30

3.2. Experiment of non-linear contour trajectory

When performing a non-linear contour trajectory experiment, the reference contour runs for 34 s and the sampling step is 0.005 s. The position controller parameter is $k_{px} = 60$ and the speed controller parameter is $k_{vp} = 150$, $k_{vi} = 30$ for the x-axis. The position controller parameter is $k_{py} = 80$ and the speed controller parameter is $k_{vp} = 120$, $k_{vi} = 12$ for the y-axis. The PD-type iterative learning rate parameters of the ILC and CCILC are shown in Table 3.

Table 3. PD-type iterative learning controller parameters for linear contour trajectories

Controller	k_p	k_d
***x*-axis**	14	0.01
Contour	2	0.05
***y*-axis**	18	0.02

The parameter tuning method of the non-linear contour trajectory can refer to the parameter tuning of the linear contour trajectory. The non-linear contours in the experiment are shown in Fig. 13. Taking the "8" trajectory as an example, the desired contour is compared with the CCILC

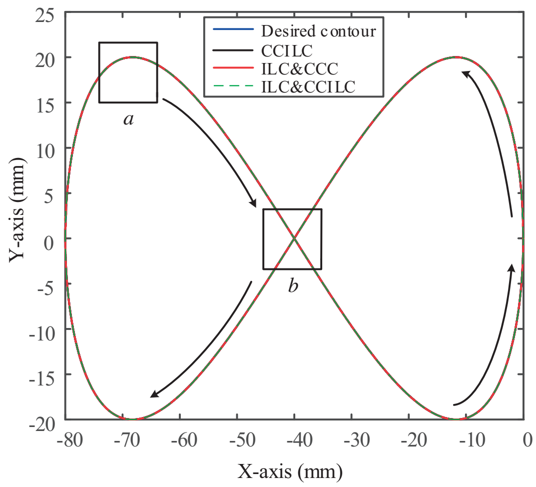
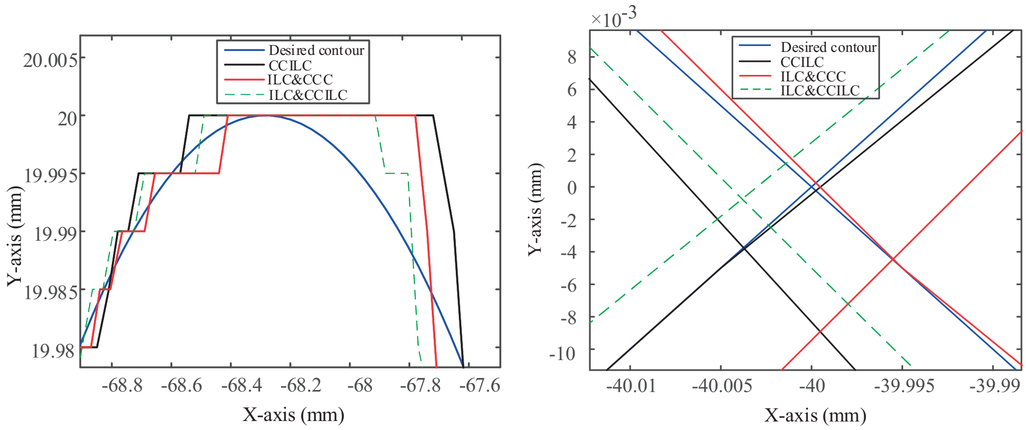


Fig. 13. Non-linear contour trajectories

experiment, ILC and CCC experiment and ILC and CCILC experiment of three convergent contours. Figs. 14 (a) and (b) are partial magnifications of two parts in Fig. 13, respectively. As shows in Figs. 14 (a) and (b), compared with the CCILC and ILC and CCC, the ILC and CCILC is closer to the desired contour and is more stable at the corner of the track when the trajectories are convergent.



(a) Contour trajectories (b) Contour trajectories

Fig. 14. Partial magnifications of two parts in Fig. 14

The contour trajectories of the "8" for the three control methods are shown in Fig. 15, Fig. 16 and Fig. 17. The three figures show the contour error of the ILC and CCILC is smaller than the CCILC and ILC and CCC, and can significantly reduce the system's contour error. It can be seen from Fig. 18 that the ILC and CCILC has good stability and convergence for the linear contour trajectory, and the contour error in Fig. 18 is represented by the mean.

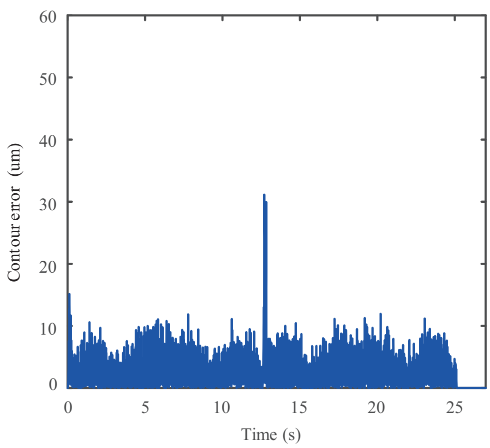


Fig. 15. Contour errors of CCILC

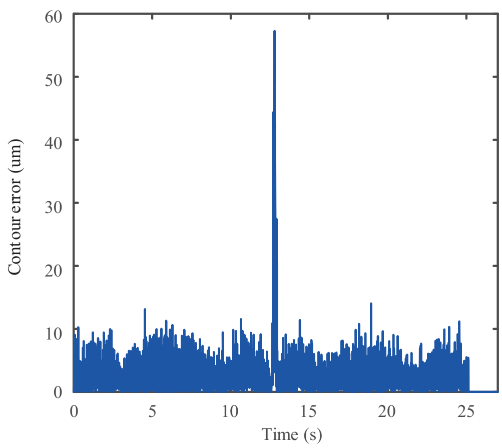


Fig. 16. Contour errors of ILC and CCC

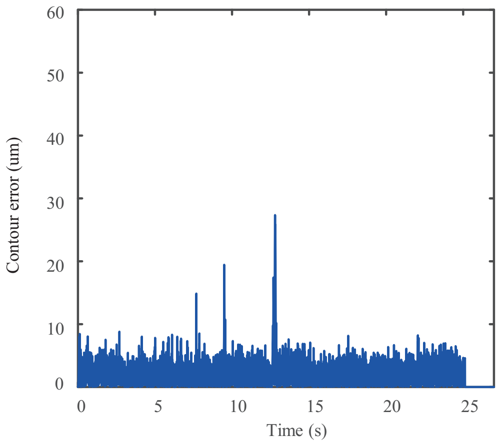


Fig. 17. Contour errors of ILC and CCILC

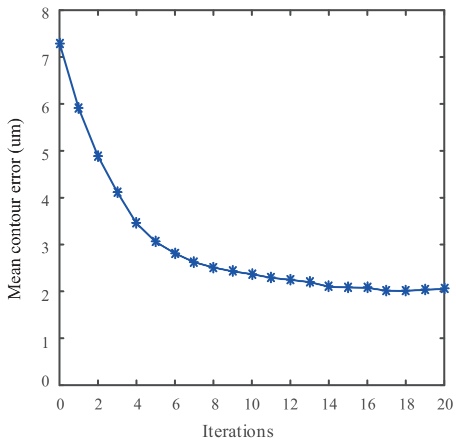


Fig. 18. Experimental mean contour error values of ILC and CCILC

The errors of the three different control methods are shown in Table 4. When moving on the non-linear contour trajectory, the CCILC can improve the accuracy of contour control, but the single-axis tracking performance is not good, and the single axis tracking error of the ILC and CCILC and ILC and CCC is significantly less than that of the CCILC control method. Among them, the x-axis tracking error of ILC and CCILC is 54.39% of ILC and CCC, the y-axis tracking error of ILC and CCILC is 62.5% of ILC and CCC, and the contour error of ILC and CCILC is 62.22% of ILC and CCC. The contour error of ILC and CCILC is 75.68% of CCILC. The experimental results show the ILC and CCILC has a significant improvement in both the single-axis tracking performance and the contour tracking performance on linear contour trajectories.

Table 4. RMS Errors of the three control methods on non-linear contour trajectory

Control method	**RMS value (um)**		
	RMS X	RMS	RMS Y
CCILC	49.68	3.66	45.22
ILC and CCC	5.71	4.55	4.03
ILC and CCILC	3.12	2.79	2.50

4. Conclusions

This paper has presented the double iterative learning and cross-coupling controllers (ILC and CCILC) for multi-axis systems. Compared to the result using CCILC and ILC and CCC, experiment data indicated that the proposed method of the ILC and CCILC can improve the single-axis tracking performance and reduce the multi-axis contour error significantly. The convergence and stability condition was developed to tuning the ILC or CCILC parameters. The paper provides the six step tuning guidelines for the choice of the controller coefficients for specific tracking improvements.

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