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CAN-based Synchronized Motion Control for Induction Motors

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Abstract: A control area network (CAN) based multi-motor synchronized motion control system with an advanced synchronized control strategy is proposed. The strategy is to incorporate the adjacent cross-coupling control strategy into the sliding mode control architecture. As illustrated by the four-induction-motor-based experimental results, the multi-motor synchronized motion control system, via the CAN bus, has been successfully implemented. With the employment of the advanced synchronized motion control strategy, the synchronization performance can be significantly improved.

Keywords: Multi-motor motion control system, speed synchronization, adjacent cross-coupling control, sliding mode control, CAN bus.

1 Introduction

Because of the quick evolution of manufacturing processes, the demand for flexible automation systems is on the rise. To meet these requirements, distributed motion control architecture based on intelligent drives and field-bus communication tends more and more to replace the traditional solutions. Many types of manufacturing equipment, such as printing machines, computer numerical control (CNC) machine tools, robots, and assembly lines, require operations of high speed and high precision as well as accurately coordinated motions among multiple motors. Therefore, many researches concerning synchronized motion control have been proposed in recent years. Lorenz and Schmidt[1] presented three approaches for process automation, namely, synchronization master-slave approach, master-slave approach, and relative dynamic stiffness approach. Cross coupling technique was initially proposed by Koren[2] for manufacturing systems and extended by Tomizuka et al.[3] Yeh and Hsu[4] proposed a new integrated control structure for multi-axis motion systems. Sun et al.[5, 6] combined adjacent cross-coupling control with adaptive control, and applied the control scheme to robot synchronization. Other approaches, such as relative coupling control[7], predictive control[8], optimal synchronization control[9] and sliding-mode[10], were also applied to the synchronized motion system.

However, the above mentioned synchronization control methods exhibit many problems[11,12], such as large numbers of wiring, complexity of electric circuits, noise and maintenance, which reduce reliability while increasing cost. Especially, many references mentioned above did not provide a possible way to extend their arrangements to more than two systems. Because of the rapid development of networked techniques[13,14] in practical applications, the integration of the control network and the multi-motor motion system becomes a promising prospect in modern industry[15−17]. In the networked control system, the wiring can be organized systematically by using a shared data network instead of hardwired connections, which can provide the control system with much more modularity, remote-control capability, and ease in diagnosis.

In this paper, total sliding mode control is adopted in adjacent cross-coupling control structure to implement speed synchronization of multi induction motors. The speed synchronization strategy is to stabilize synchronization errors between each motor and its two adjacent motors to zero. A distributed control area network (CAN) bus synchronized motion control system is designfed to simplify the control structure of the system. Finally, simulation results of a four-induction-motor experimental system demonstrate that the motion accuracy has been significantly improved and that flexibility and maintainability has become accessible to distribute the control structure.

2 Sliding-mode adjacent cross-coupling control strategy of multi-motor synchronization

Networked control system, in general, possesses advantages of flexibility and expandability, but its control performance is necessarily degraded relatively to a direct or centralized control architecture. Thus, to improve motion accuracy, applying the advanced motion control strategy to the distributed CAN bus synchronized motion control system becomes crucial. In order to realize this goal, an advanced motion control strategy, so-called sliding-mode adjacent cross-coupling control strategy, is developed to control the motor′s speed.

2.1 Adjacent cross-coupling control strategy

Consider a synchronized motion control system with n induction motors. The mechanical speed equation of the i-th motor is described by Marino[18]

$$\dot{\omega}_i + a_i\omega_i + f_i = b_i i_{qs(i)}(t) \tag{1}$$

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where $a_i = D_i/J_i$, $b_i = 3n_{p(i)}M_i\psi^*_{dr(i)}/(4J_iL_{r(i)})$, $f_i = T_{L(i)}/J_i$, $\psi^*_{dr(i)}$ is the desired flux of the i-th motor, D_i is the friction coefficient of the i-th motor, J_i is the motor-load moment of inertia of the i-th motor, $n_{p(i)}$ is the number of the pole pairs of the i-th motor, $L_{r(i)}$ is the rotor self-inductances of the i-th motor, M_i is the stator-rotor mutual inductance of the i-th motor, and $T_{L(i)}$ is the load torque of the i-th motor.

Define the speed tracking error of the i-th motor as

$$e_i(t) = \omega_i(t) - \omega^*(t) \tag{2}$$

where $\omega_i(t)$ denotes the rotor speed of the i-th motor and $\omega^*(t)$ denotes the desired speed of the i-th motor. In the synchronized motion control system, besides $e_i(t) \to 0$, it is also required to regulate motion relationships amongst multiple motors during the speed tracking so that

$$e_1(t) = e_2(t) = \cdots = e_n(t). \tag{3}$$

Define synchronization errors of a subset of i-th motor from the total of n motors in the following way:

$$\begin{aligned}\varepsilon_{i1}(t) &= \omega_i(t) - \omega_{i-1}(t) = e_i(t) - e_{i-1}(t)\\ \varepsilon_{i2}(t) &= \omega_i(t) - \omega_{i+1}(t) = e_i(t) - e_{i+1}(t)\end{aligned} \tag{4}$$

where $\varepsilon_{i1}(t)$ is the synchronization error between the i-th and the $(i-1)$-th motor and $\varepsilon_{i2}(t)$ is the synchronization error between the i-th and the $(i+1)$-th motor. Obviously, if $\varepsilon_{i1}(t) \to 0$ and $\varepsilon_{i2}(t) \to 0$ for all $i \in 2, 3, \cdots, n-1$, then the goal of multi-motor synchronization of (3) is achieved.

As illustrated in Fig. 1, each controller of the multi-motor motion control system is designed to stabilize its speed tracking, while synchronizing the speed between this controller and other two controllers with adjacent sequence number. Especially, the controller of i-th motor is to control $e_i(t) \to 0$ and at the same time to synchronize motions of the $(i-1)$-th motor, the i-th motor and the $(i+1)$-th motor so that synchronization errors $\varepsilon_{i1}(t)$ and $\varepsilon_{i2}(t)$ converge to zero. By employing the above strategy, the synchronized motions of all motors can be achieved. Under the above strategy, the rotor speed of all motors is synchronized. The controller of each motor considers the motion responses of the other two controllers with adjacent sequence number.

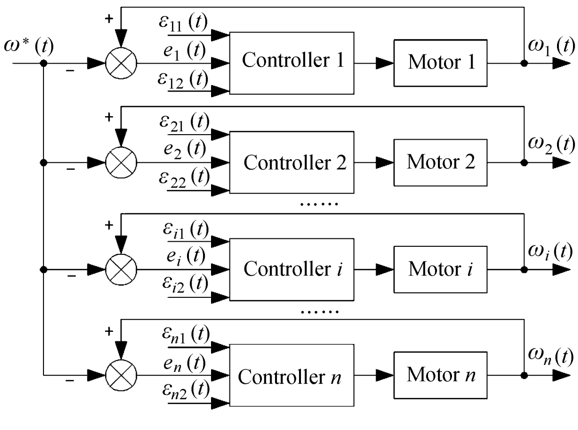

Fig. 1 Block diagram of adjacent cross-coupling control

2.2 Sliding-mode adjacent cross-coupling controller

Under the above proposed synchronization strategy, the i-th motor synchronization speed controller includes two parts: one tracking error controller and two synchronization error controllers. The tracking error controller is used to track the desired speed accurately, and the two synchronization error controllers are used to eliminate the synchronization errors between the controlled motor and its adjacent motors. The synchronous speed controller of the i-th motor is shown in Fig. 2, where C_2 is the tracking error controller, C_1 and C_3 are the synchronization error controllers. The output current of the tracking error controller is denoted as $i^*_{qs(i0)}(t)$, the output currents of the synchronization error controllers are denoted as $i^*_{qs(i1)}(t)$ and $i^*_{qs(i2)}(t)$, respectively. The output of the speed controller is the sum of the above currents.

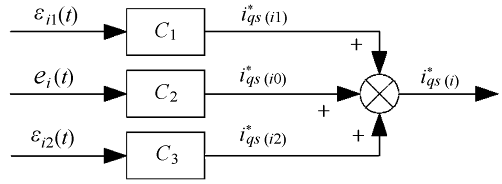

Fig. 2 Block diagram of i-th motor speed controller

Considering the variation of parameters and the uncertain factors, the mechanical speed equations of the $(i-1)$-th, i-th, $(i+1)$-th motors are described by

$$\begin{aligned}&\dot{\omega}_{i-1} + (a_{i-1} + \Delta a_{i-1})\omega_{i-1} + (f_{i-1} + \Delta f_{i-1}) =\\ &\quad (b_{i-1} + \Delta b_{i-1})i_{qs(i-1)}(t)\end{aligned} \tag{5}$$

$$\dot{\omega}_i + (a_i + \Delta a_i)\omega_i + (f_i + \Delta f_i) = (b_i + \Delta b_i)i_{qs(i)}(t) \tag{6}$$

$$\begin{aligned}&\dot{\omega}_{i+1} + (a_{i+1} + \Delta a_{i+1})\omega_{i+1} + (f_{i+1} + \Delta f_{i+1}) =\\ &\quad (b_{i+1} + \Delta b_{i+1})i_{qs(i+1)}(t).\end{aligned} \tag{7}$$

2.2.1 Tracking error controller

Differentiating $e_i(t)$ with respect to time yields

$$\dot{e}_i(t) = \dot{\omega}_i(t) - \dot{\omega}^*(t) = -a_ie_i(t) + u_i(t) + d_i(t) \tag{8}$$

where

$$u_i(t) = b_ii_{qs(i)}(t) - a_i\omega^*(t) - f_i - \dot{\omega}^*(t) \tag{9}$$

and the uncertain term

$$d_i(t) = -\Delta a_i\omega_i(t) - \Delta f_i - \Delta b_ii_{qs(i)}(t). \tag{10}$$

According to the sliding-mode control method[19], if $e_i(t)$ converges to zero asymptotically, the following condition should be satisfied:

$$\dot{e}_i(t) = (k_i - a_i)e_i(t) \tag{11}$$

where k_i is the convergence rate of the tracking error controller, and $(k_i - a_i) < 0$.

The sliding-mode surface of $e_i(t)$ is designed in the following form according to (11):

$$S_{i0} = e_i(t) - \int_0^t (k_i - a_i)e_i(\tau)\mathrm{d}\tau. \tag{12}$$

$u_i(t)$ is designed as

$$u_{i0}(t) = k_i e_i(t) - \eta_i \text{sgn}(S_{i0}) \qquad (13)$$

where sgn(·) is the signal function, and η_i is the switch gain with $\eta_i > |d_i(t)|$.

Substituting (13) into (9), we obtain the tracking error controller of the i-th motor as

$$i^*_{qs(i0)}(t) = b_i i_{qs(i)} = [k_i e_i(t) - \eta_i \text{sgn}(S_{i0}) + a_i\omega^*(t) + \dot{\omega}^*(t) + f_i]. \qquad (14)$$

2.2.2 Synchronization error controller

Consider synchronization error controller C_1 first. From (5), (6) and the synchronization error $\varepsilon_{i1}(t)$ of the i-th motor, we obtain

$$\dot{\varepsilon}_{i1}(t) = \dot{\omega}_i(t) - \dot{\omega}_{i-1}(t) = -a_i\varepsilon_{i1}(t) + u_{i1}(t) + d_{i1}(t) \qquad (15)$$

where

$$u_{i1}(t) = b_i i_{qs(i)}(t) - f_i - b_{i-1} i_{qs(i-1)}(t) + a_{i-1}\omega_{i-1}(t) + f_{i-1} - a_i\omega_{i-1}(t) \qquad (16)$$

and the uncertain term

$$d_{i1}(t) = \Delta b_i i_{qs(i)}(t) - \Delta a_i\omega_i(t) - \Delta f_i - \Delta b_{i-1} i_{qs(i-1)}(t) + \Delta a_{i-1}\omega_{i-1}(t) + \Delta f_{i-1}. \qquad (17)$$

If $\varepsilon_{i1}(t)$ converges to zero asymptotically, the following condition should be satisfied

$$\dot{\varepsilon}_{i1}(t) = (c_{i1} - a_i)\varepsilon_{i1}(t) \qquad (18)$$

where C_{i1} is the convergence rate of the synchronization error controller C_1 and $(c_{i1} - a_i) < 0$.

The sliding-mode surface of $\varepsilon_{i1}(t)$ is designed in the following term by (18):

$$S_{i1} = \varepsilon_{i1}(t) - \int_0^t (c_{i1} - a_i)\varepsilon_{i1}(\tau)\text{d}\tau. \qquad (19)$$

We design $u_{i1}(t)$ as

$$u_{i1}(t) = c_{i1}\varepsilon_{i1}(t) - \eta_{i1}\text{sgn}(S_{i1}) \qquad (20)$$

where η_{i1} is the switch gain with $\eta_{i1} > |d_{i1}(t)|$.

From (16) and (20), we obtain the first synchronization error controller C_1 of the i-th motor as

$$i^*_{qs(i1)}(t) = b_i i_{qs(i)}(t) - b_{i-1} i_{qs(i-1)}(t) = c_{i1}\varepsilon_{i1}(t) - \eta_{i1}\text{sgn}(S_{i1}) + f_i - a_{i-1}\omega_{i-1}(t) - f_{i-1} + a_i\omega_{i-1}. \qquad (21)$$

Similarly, the second synchronization error controller C_3 of the i-th motor is defined as

$$i^*_{qs(i2)}(t) = b_i i_{qs(i)}(t) - b_{i+1} i_{qs(i+1)}(t) = c_{i2}\varepsilon_{i2}(t) - \eta_{i2}\text{sgn}(S_{i2}) + f_i - a_{i+1}\omega_{i+1}(t) - f_{i+1} + a_i\omega_{i+1} \qquad (22)$$

where c_{i2} is the convergence rate of the synchronization error controller C_3, and $(c_{i2} - a_i) < 0$.

From (14), (21), and (22), the synchronization speed controller of the i-th motor is

$$i^*_{qs(i)} = i^*_{qs(i0)}(t) + i^*_{qs(i1)}(t) + i^*_{qs(i2)}(t). \qquad (23)$$

Theorem 1. The proposed sliding-mode adjacent cross-coupling controller (23) guarantees asymptotic convergence to zero of both speed tracking errors and synchronization errors, i.e., $e_i(t) \to 0$, $\varepsilon_{i1}(t) \to 0$, and $\varepsilon_{i2}(t) \to 0$ as time $t \to \infty$.

Proof. See [6].

Theorem 1 indicates that the proposed control strategy (23) is globally stable. The block diagram of the proposed i-th motor control system is illustrated in Fig. 3. In the experimental simulations, $i^*_{qs(i)}$ is the discrete command, and it will hold on until the next control signal arrives.

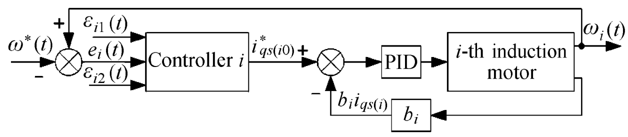

Fig. 3 Structural diagram of the i-th motor control system

3 Multi-motor synchronized motion control system based on CAN bus

3.1 Applications of CAN bus

The CAN bus is a serial communication protocol which supports distributed real-time control with high reliability and low cost[20,21]. Fig. 4 shows the structure of the multi-motor synchronized motion control system via the CAN bus. In each communication cycle, the central controller, namely industrial computer, receives speed measurement messages of each motion controller and sends synchronization messages to all motion controllers, both via the CAN network. When the central controller receives the measurement messages from each motor, the new speed command adopting the adjacent cross-coupling control strategy can be calculated. At the next speed command transmission period, the synchronization speed command $i^*_{qs(i)}$ $(i = 1, 2, \cdots, n)$ of each motor will be sent through a data packet which is composed of multiple data frames. As to the implementation, the DSP TMS320F2812 from Texas Instrument is selected to be the core of the motion controller. The motion controller has 32 mailboxes that can be configured to transmit or receive messages. Every mailbox has a unique identification (ID), and the motion controllers are able to receive speed commands simultaneously via the CAN broadcast messages. When the motion controller receives complete speed commands, the motion controller can select the useful command according to the ID number. The ID with the highest priority is assigned to the speed command transmission. Later, the lower priority messages such as the error feedback signals can still be sent back to the central controller under the non-destructive bus arbitration mechanism. In each motion controller, mailbox 6 is used to receive the synchronization speed command, and mailbox 4 is used to send the rotor speed signal in the present communication. The dotted lines shown in Fig. 5 refer to CAN message flow of the multi-motor synchronized motion control system.

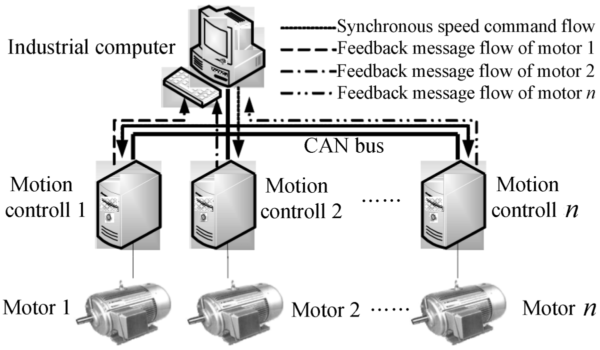

Fig. 4 Structure of the multi-motor synchronized motion control system via the CAN bus

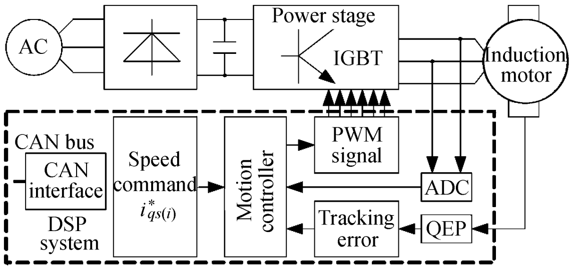

Fig. 5 Block diagram of the single motion control system

3.2 The single motion control system

In order to construct a precise distributed multi-motor motion control system, all single-motor control systems should be well designed first. The single-motor control system for an alternating current (AC) induction motor is shown in Fig. 5. It consists of a TI DSP TMS320F2812, the protection circuit, the insulated gate bipolar transistor (IGBT) power stage, the AC induction motor with optical encoder and hall sensors. The motion controller is typically for two tasks. The first task is to convert the instantaneous motor speed measurement to a packet, and then send it to the central controller. The second task is to send out pulse width modulator (PWM) signals to the power stage to drive the induction motor. The current feedback signal is measured through the DSP built-in analog to digital converter (ADC) interface. The induction motor speed is obtained by the quadrature encoding pulse (QEP) interface with a 1 ms sampling period.

3.3 The multi-motor synchronized motion control system

In Fig. 4, the multi-motor synchronized motion control system consists of the CAN bus network, the industrial computer, and some single motion control systems. The internal CAN bus interface in the single motion control system serves as the communication channel between the industrial computer and the motion controller. The industrial computer, with a plug-and-play CAN adapter, can receive all messages which are sent by the motion controllers, and the motion controllers can only receive the message from the industrial computer. The adjacent cross-coupling control scheme is thus implemented in this distributed multi-motor control system through the CAN bus so as to coordinate speed error and reduce synchronization speed error for all motors. With respect to the transmission, the motion command, the feedback, and the adjacent cross-coupling control are all effectively transmitted by the CAN bus. Thus, the reliable and real-time motion control can thus be realized.

4 Numerical simulation and experimental results

In this paper, the proposed control strategy is simulated on a synchronized motion control system consisting of four motors. The parameters of these motors are listed in Table 1. The simulation and experimentation are carried out using Matlab and Borland C software, respectively. To investigate the effectiveness of the control scheme, both the proposed synchronization control strategy and the independent control strategy without synchronization are simulated.

Table 1 The parameters of the four motors

Parameters	IM1	IM2	IM3	IM4
ψ_r^* (Wb)	0.86	0.86	0.9	0.9
T_L (N·m)	6.0	6.0	7.0	7.0
R_s (Ω)	6.7	6.7	5.46	5.46
R_r (Ω)	5.5	5.5	4.45	4.45
L_s (H)	0.475	0.475	0.492	0.492
L_r (H)	0.47	0.47	0.492	0.492
L_m (H)	0.45	0.45	0.475	0.475
J (kg·m^2)	0.015	0.015	0.008	0.008
B (N·m·s)	0.01	0.01	0.005	0.005
n_p	2	2	2	2

4.1 Numerical simulation

The numerical simulation test involves the following operating sequences: the unloaded motors are required to reach the speed 20 rad/s with the reference trajectory $\omega^* = 20(1 - \mathrm{e}^{-1.5t})$; at $t = 18$ s, the load torques, which are unknown to the controllers and whose parameters are listed in Table 2, are applied to the four motors. The specific control parameters of the proposed strategy are listed in Table 3.

Table 2 The load torques of the four motors

IM1	IM2	IM3	IM4
5 N·m	6 N·m	5 N·m	6 N·m

Table 3 The control parameters of the four motors

Parameters	IM1	IM2	IM3	IM4
k_i	−5	−5	−5	−5
η_i	60	60	60	60
c_{i1}	−5	−5	−5	−5
η_{i1}	250	150	500	400
c_{i2}	−5	−5	−5	−5
η_{i2}	80	60	300	60

Speed tracking errors of the four induction motors, with the proposed control strategy and CAN bus, are shown in

Fig. 6, which illustrates that the proposed control strategy can track the reference value accurately within 4 s. High robustness is achieved when the load torque changes. Fig. 7 illustrates the synchronization error curves of using adjacent cross-coupling sliding-mode control via the CAN bus. We can see that the precision of using the proposed control approach is very good among four induction motors. When external disturbances are added at 18 s, high robustness of the proposed control method is held. The speed synchronizations are slightly affected by the disturbances because when the sliding surface is reached the system becomes insensitive to the boundary external disturbances. Figs. 8 and 9 illustrate the speed tracking error responses and the speed synchronization error responses with the independent control without synchronization, namely $i^*_{qs(i)} = i^*_{qs(i0)}(t)$ for the i-th motor, for comparison. The tracking errors are similar as those in Fig. 8, but the major difference between results of the two methods lies in the synchronization errors. It can be seen from the comparison of Figs. 7 and 9 that the proposed adjacent cross-coupling sliding-mode controller can effectively reduce transient speed synchronization errors while driving speed tracking errors to converge to zero. The adjacent cross-coupling sliding-mode control strategy plays the major role in the synchronization.

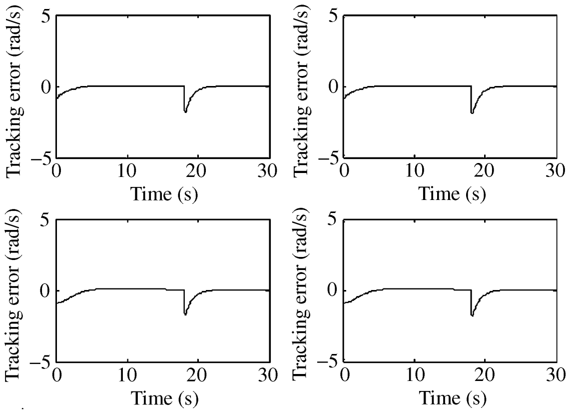

Fig. 6 Speed tracking errors of the four motors with adjacent cross-coupling synchronization control strategy

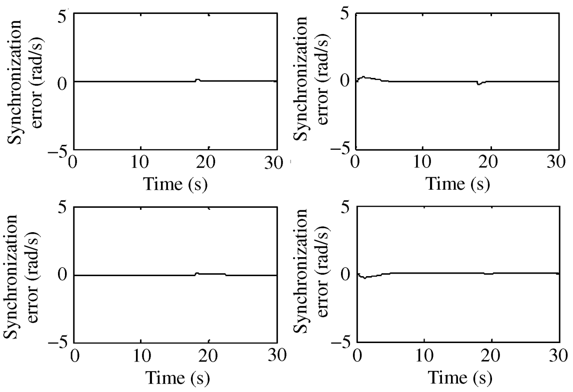

Fig. 7 Speed synchronization errors of the four motors with adjacent cross-coupling synchronization control strategy

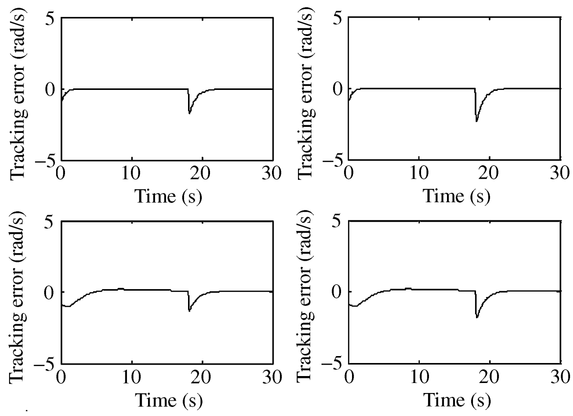

Fig. 8 Speed tracking errors of the four motors with independent control without synchronization

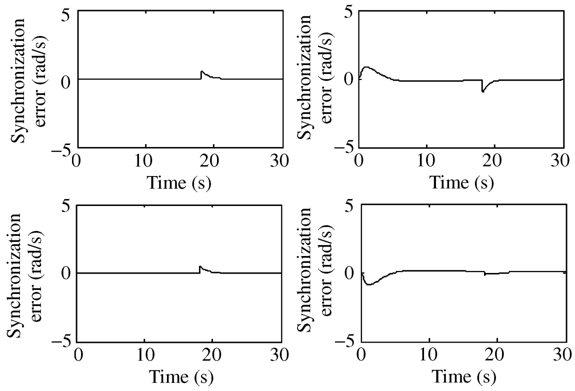

Fig. 9 Speed synchronization errors of the four motors with independent control without synchronization

4.2 Experimental results

Some experimental results are provided here to further verify the effectiveness of the proposed multi-motor control strategy. The experimental conditions are the same as the numerical simulation. Fig. 10 shows the actual multi-motor control system.

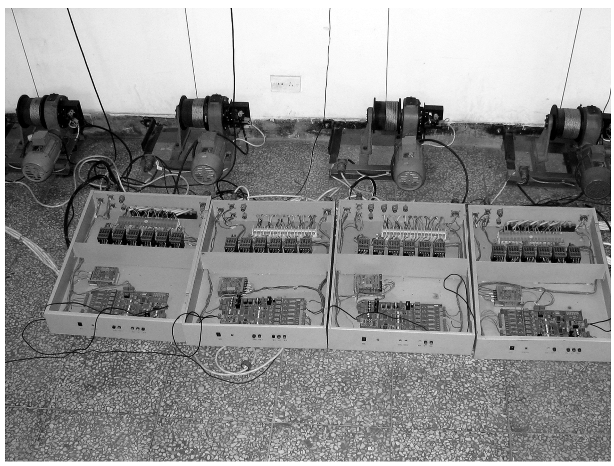

Fig. 10 Actual multi-motor synchronized motion control system via the CAN bus

In order to assess the performance of the synchronized motion control system, a performance index, namely, absolute integral error criteria (IAE), is defined as

$$\text{IAE} = \int_0^T |e| \mathrm{d}t \quad \text{or} \quad \text{IAE} = \sum_{k=k_0}^{k_t} |e_k| \cdot T.$$

As shown in Figs. 11 and 12, experimental results in speed tracking accuracy and speed synchronization accuracy for the four motors are summarized as follows:

1) The CAN bus has been successfully included in a multi-motor synchronized motion control system to transfer speed commands to each individual DSP-based control motor.

2) The speed tracking error cannot be reduced greatly, but the speed tracking error of each motor for the proposed synchronized motion control system is closer to the average value compared with that of the independent control system without synchronization.

3) By employing adjacent cross-coupling control strategy, the speed synchronization errors of each motor are substantially reduced.

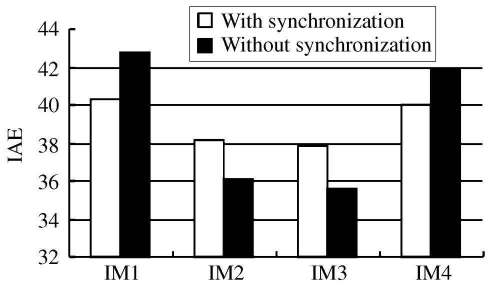

Fig. 11 IAE of speed tracking errors for the four motors

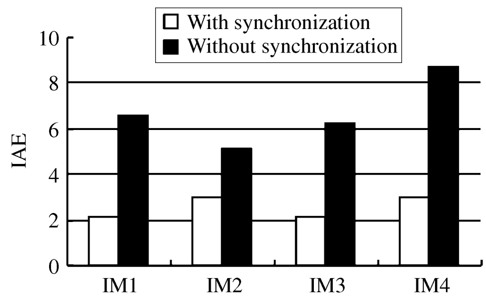

Fig. 12 IAE of speed synchronization errors for the four motors

5 Conclusions

In this paper, a synchronization control scheme for a four motors synchronized motion control system via CAN bus has successfully been implemented. A new sliding-mode adjacent cross-coupling control strategy has been proposed for speed synchronization of multiple motion motors. The experiment results show that the present distributed structure is more flexible and expandable than traditional centralized methodology. Moreover, they also show that control performance can be enhanced by applying advanced motion control strategy. In summary, a multi-motor motion system with an advanced control strategy is successfully realized via the CAN bus.

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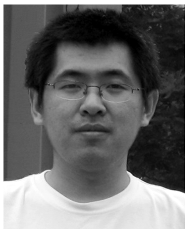

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