RING COUPLING-BASED COLLABORATIVE FAULT-TOLERANT CONTROL FOR MULTI-ROBOT ACTUATOR FAULT

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Abstract

In this paper, a ring coupling-based fault-tolerant control scheme is proposed to synchronize multi-robot systems with actuator faults. The control scheme includes a sliding-mode control law and a sliding-mode observer. The sliding-mode control law is given *via* the ring coupling strategy for a multi-robot system. To observe the status of unmeasurable variables and unknown fault control information, a sliding mode observer is designed such that the unknown fault information is accurately reconstructed by using the equivalent principle of sliding-mode variable structure. Based on the observed status value and fault reconstructed value, the sliding-mode control law can be adjusted online and thus the collaborative fault-tolerant control is realized online. Finally, simulations and experiments are given to demonstrate the effectiveness of the proposed method.

Key Words

Multi-robot system, actuator fault, ring coupling strategy, fault reconstruction, fault-tolerant control

1. Introduction

In recent years, multi-robot systems have been widely used in modern industrial systems, in which high requirements have also been proposed for their synchronization performance. Thus, many scholars have conducted extensive research and have made great progress on studying the problem of synchronous control of multiple controlled object systems [1]–[8]. Khalili *et al.* proposed a distributed adaptive fault-tolerant leader-following consensus control scheme [9]. Ai *et al.* developed a master–slave control algorithm and applied it on minimally invasive surgical robots to solve the workspace mismatch problem between

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the master hand and slave arm. However, this work did not consider the effects of unknown input disturbances [10]. In addition, Chen *et al.* indicated that the anti-jamming capacity of master–slave control strategy is not ideal [11]. Andert *et al.* applied the virtual shaft synchronous control strategy to the control of vehicle power system, which reduces the speed deviation and improves the synchronization accuracy; however, the influences of faults were not considered [12]. Liu *et al.* used the hybrid control scheme to achieve the consensus and multi-tracking for dynamical networks [13]–[15]. For the control problems of micro-nanotechnology-related equipment, Ulu *et al.* proposed a modular control method for cross-coupled control with combining the iterative learning control to improve system tracking accuracy [16]. But, the complexity of the cross-coupled control algorithm has considerably increased with the increase in number of controlled objects [17]. Shi *et al.* applied the relative coupling control strategy to multi-motor and multi-channel synchronous control, which shows a good synchronization performance [18]–[20]. However, as the number of controlled object increases, the complexity of the system control structure also increases [2]. Moreover, the fault information was not investigated in [16] and [18]–[20]. Compared with the four synchronous control strategies, namely, master–slave control, virtual shaft synchronous control, cross-coupled control, and relative coupling control, the ring coupling control strategy has greater robustness and is thus suitable for systems with multi-controlled objects [21]. Moreover, a control method based on ring coupling control and adaptive sliding-mode control was proposed by Li *et al.* for multi-motor speed synchronous tracking control, which ensures the convergence of the velocity tracking error and synchronization error to zero. However, the influence of fault was also not considered [22].

In this paper, by the spirit of the work by Li *et al.* [22], a collaborative fault-tolerant control method is proposed for multi-robot systems with actuator faults. First, the fault-tolerant control law based on ring coupling control strategy is proposed. An observer is designed to observe the status of unmeasurable variables and unknown fault information. Then, the fault reconstruction method is used to reconstruct the faults precisely. Finally, the observed

status value and fault reconstructed value are applied to the online adjustment of the control law.

The remainder of this paper is organized as follows. Section 2 introduces the faulty multi-robot system model. Section 3 presents the design of system fault-tolerant control rate. Section 4 describes the design of the sliding-mode observer. Section 5 presents the reconstruction of the actuator fault. Section 6 presents the online adjustment of fault-tolerant control rate. Section 7 gives the simulations with explanations. Finally, conclusion is presented in Section 8.

2. System Description

Assuming that the multi-robot system has n robots, the mathematical model of the actuator fault in the ith ($i = 1, \ldots, n$) robot is as follows:

$$M(q_i)\ddot{q}_i + B(q_i, \dot{q}_i)\dot{q}_i + G(q_i) = \tau_i + d_i + f_{ai} \qquad (1)$$

where q_i is the joint angular displacement; $M(q_i)$ is the robotic inertial matrix; $B(q_i, \dot{q}_i)$ denotes the centrifugal force and Coriolis force; $G(q_i)$ is the gravity term; τ_i is the control torque; d_i is the unknown bounded function, which represents the unknown input disturbance or system uncertainty; and f_{ai} denotes the actuator fault, which is an unknown bounded function.

There are three main types of actuator failures, namely, stuck, constant gain variation, and constant deviation failure. The fault models can be described as, respectively, $f_{ai}(t) = u_{si}$ (u_{si} as constant), $f_{ai}(t) = \rho_i(t)v_i(t)$ ($v_i(t)$ is controller output, $\rho_i(t)$ is the coefficient of constant gain variation), $f_{ai}(t) = v_i(t) + \Delta_i$ (Δ_i is a constant), and $i = 1, \ldots, n$. The three kinds of actuator failure models can be described as follows:

$$f_{ai}(t) = k_{1i}u_{si} + k_{2i}\rho_i(t)v_i(t) + k_{3i}\Delta_i, i = 1, \cdots, n \quad (2)$$

where k_{1i}, k_{2i}, $k_{3i} = 0$ or 1.

$F_{ai} = d_i + f_{ai}$ is defined as the equivalent actuator fault. Thus, (1) can be rewritten as

$$M(q_i)\ddot{q}_i + B(q_i, \dot{q}_i)\dot{q}_i + G(q_i) = \tau_i + F_{ai} \qquad (3)$$

For a one-DOF (degree of freedom) manipulator, $M(q_i)$ and $B(q_i, \dot{q}_i)$ are both constants. Moreover, $G(q_i) = mgl\cos q_i$. Thus, (3) can be rewritten as

$$M_i\ddot{q}_i + B_i\dot{q}_i + mgl\cos q_i = \tau_i + F_{ai} \qquad (4)$$

3. Design of Collaborative Fault-tolerant Control Rate Based on Ring Coupling

The position-tracking error e_i of the ith robot is defined as

$$e_i = q_d - q_i \qquad (5)$$

where q_d is the given input position signal.

The position synchronization error ε_i of the ith robot and the $(i + 1)$th robot is

$$\varepsilon_i = q_i - q_{i+1} \qquad (6)$$

where $i = n$, $q_{i+1} = q_1$.

The tracking error E_i in the ith robot control system by using the ring coupling compensation is

$$E_i = e_i - k_i\varepsilon_i \qquad (7)$$

where k_i is a positive constant that needs to be designed.

A nominal system has no equivalent actuator fault, that is $F_{ai}(t) = 0$. An appropriate nominal control law τ_{i0} is used for a progressive and stabilization of the system. When the equivalent actuator fault occurs, that is $F_{ai}(t) \neq 0$, an additional control law τ_{if} may be designed to realize fault-tolerant adjustment. Thus, for the faulty system (4), the fault-tolerant control law τ_i consists of the nominal control law τ_{i0} and the additional control law τ_{if}, which is shown as follows:

$$\tau_i = \tau_{i0} + \tau_{if} \qquad (8)$$

Sliding-mode surface s is selected as

$$s_i = \dot{E}_i + c_i E_i \qquad (9)$$

where c_i is a positive constant. Therefore,

$$\begin{aligned} \dot{s}_i &= \ddot{E}_i + c_i\dot{E}_i \\ &= c_i\dot{E}_i + \ddot{q}_d - M_i^{-1}(\tau_i - B_i\dot{q}_i - mgl\cos q_i + F_{ai}) \\ &\quad -k_i\ddot{\varepsilon}_i \end{aligned} \qquad (10)$$

In the sliding-mode surface which is $s_i = 0$ near the origin, the following condition should be satisfied to ensure the existence of the sliding-mode area of the system:

$$s_i\dot{s}_i \leq 0$$

Thus,

$$\begin{aligned} s_i\dot{s}_i &= s_i[c_i\dot{E}_i + \ddot{q}_d - M^{-1}(\tau_i - B\dot{q}_i - mgl\cos q_i + F_{ai}) \\ &\quad -k_i\ddot{\varepsilon}_i] \leq 0 \end{aligned} \qquad (11)$$

The control law τ_i based on reaching law is set as

$$\begin{aligned} \tau_i &= M[c_i\dot{E}_i + \ddot{q}_d - k_i\ddot{\varepsilon}_i + as + b\,\text{sgn}(s_i)] \\ &\quad + B\dot{q}_i + mgl\cos q_i - F_{ai} \end{aligned} \qquad (12)$$

where a and b are constants to be determined later. When the fault does not occur (i.e., $F_{ai} = 0$), the control law τ_{i0} of the nominal system is

$$\begin{aligned} \tau_{i0} &= M[c_i\dot{E}_i + \ddot{q}_d - k_i\ddot{\varepsilon}_i + as + b\,\text{sgn}(s)] \\ &\quad + B\dot{q}_i + mgl\cos q_i \end{aligned} \qquad (13)$$

Otherwise, $F_{ai} \neq 0$, the additional control law τ_{if} is

$$\tau_{if} = -F_{ai} \qquad (14)$$

Theorem 1. *For the robot system described by Equation (4), the designed tolerant control law is shown in (12). When $a > 0$ and $b > 0$, the system satisfies the stability condition of the sliding mode.*

Proof: Let Lyapunov function be

$$V_i = \frac{1}{2} s_i^2 \tag{15}$$

The derivative of (15) yields

$$\dot{V}_i = s_i \dot{s}_i = s[c_i \dot{E}_i + \ddot{q}_d - M^{-1}(\tau_i - B\dot{q}_i - mgl \cos q_i + F_{ai}) - k_i \ddot{\varepsilon}_i] \tag{16}$$

Substituting (12) into (16) yields

$$\dot{V}_i = s_i \dot{s}_i = -as_i^2 - b|s_i| \tag{17}$$

When $a > 0$ and $b > 0$, the following can be obtained as

$$s_i \dot{s}_i \leq 0$$

Thus, the system satisfies the existence and reach ability conditions of a sliding mode, that is, the system will reach the sliding-mode surface $s_i = 0$ in a finite time from any initial state. Thus, the proof is complete.

By using Theorem 1 and (9), error E_i asymptotically converges to zero.

Using (5) and (6) yields

$$\begin{aligned} E_i &= e_i - k_i \varepsilon_i \\ &= (1 + k_i) e_i - k_i e_{i+1} \end{aligned} \tag{18}$$

Equation (18) can be written as follows:

$$\begin{bmatrix} 1+k_1 & -k_1 & \cdots & & \cdots & 0 \\ \vdots & \ddots & & & & \vdots \\ 0 & \cdots & 1+k_i & -k_i & \cdots & 0 \\ \vdots & & & \ddots & & \vdots \\ -k_n & \cdots & & \cdots & 0 & 1+k_n \end{bmatrix} \begin{bmatrix} e_1 \\ \vdots \\ e_i \\ \vdots \\ e_n \end{bmatrix} = \begin{bmatrix} E_1 \\ \vdots \\ E_i \\ \vdots \\ E_n \end{bmatrix} \tag{19}$$

Matrix A is set as

$$A = \begin{bmatrix} 1+k_1 & -k_1 & \cdots & & \cdots & 0 \\ \vdots & \ddots & & & & \vdots \\ 0 & \cdots & 1+k_i & -k_i & \cdots & 0 \\ \vdots & & & \ddots & & \vdots \\ -k_n & \cdots & & \cdots & 0 & 1+k_n \end{bmatrix} \tag{20}$$

If $1 + k_i \neq 0$ and $1 + k_n - \frac{k_n!}{(1+k_{n-1})!} \neq 0$, that is, $k_i \neq -1$, then k_i is a positive constant that needs to be designed.

Thus, matrix A is a non-singular matrix. If $E_i = (1+k_i)e_i - k_i e_{i+1} = 0$, then $[e_1, \ldots, e_n]^T$ has only one zero solution; thus, $\varepsilon_1 = \cdots = \varepsilon_n = 0$. At this point, the tracking and synchronization errors can be eliminated.

In (12), the designed control law τ_i includes system status variable $\dot{q}_i$ and equivalent actuator fault F_{ai}, which is usually unknown. Their exact value should be obtained through a certain method. In the next section, a sliding-mode observer based on the equivalent actuator fault reconstructed accurately to observe system status; thus, the corresponding observed status value and the reconstructed value of equivalent actuator fault can be acquired and then substituted into the control law i for the online fault-tolerant control.

4. State of the Sliding-Mode Observer and Fault Reconstruction

System is selected according to (4).

$$x_1 = q_i, \quad x_2 = \dot{q}_i$$

The dynamic equation of (4) becomes:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = M^{-1}[\tau_i + F_{ai} - Bx_2 - mgl \cos x_1] \end{cases} \tag{21}$$

The sliding-mode observer is designed as follows:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + v_1 \\ v_1 = L_1 \operatorname{sgn}(x_1 - \hat{x}_1) \end{cases} \tag{22}$$

$$\begin{cases} \dot{\hat{x}}_2 = M^{-1}(\tau_i - B\hat{x}_2 - mgl \cos x_1) + v_2 \\ v_2 = L_2 \operatorname{sgn}(x_2 - \hat{x}_2) \end{cases} \tag{23}$$

where $\hat{x}_1$ and $\hat{x}_2$ are the observed value of x_1 and x_2, respectively; v_1 and v_2 are the control terms of the sliding mode; and L_1 and L_2 are the positive constants to be designed.

Errors $\hat{e}_1$ and $\hat{e}_2$ of the observer are defined as

$$\begin{cases} \hat{e}_1 = x_1 - \hat{x}_1 \\ \hat{e}_2 = x_2 - \hat{x}_2 \end{cases} \tag{24}$$

According to (21)–(24), the error equations are

$$\dot{\hat{e}}_1 = \hat{e}_2 - v_1 \tag{25}$$

$$\dot{\hat{e}}_2 = -M^{-1}B(x_2 - \hat{x}_2) + M^{-1}F_{ai} - v_2 \tag{26}$$

Considering the error dynamic in (25) and (26), sliding-mode surfaces $\hat{s}_1$ and $\hat{s}_2$ are selected as follows:

$$\hat{s}_1 = \hat{e}_1, \quad \hat{s}_2 = \hat{e}_2 \tag{27}$$

Theorem 2. *If L_1 and L_2 are sufficiently large (i.e., satisfying inequalities $L_1 \geq |\hat{e}_2| + \eta_1$ and $L_2 \geq |M^{-1}f_{ai}| + \eta_2$, where η_1 and η_2 are both positive constants), then the value of the equivalent actuator fault is $F_{ai} = ML_2 \, \mathrm{sgn}[L_1 \, \mathrm{sgn}\, \hat{e}_1]$.*

Proof: The Lyapunov function is selected as follows:

$$\hat{V}_1 = \frac{1}{2}\hat{e}_1^2.$$

According to (25),

$$\dot{\hat{V}}_1 = \hat{e}_1 \dot{\hat{e}}_1 = \hat{e}_1 \hat{e}_2 - \hat{e}_1 v_1$$
$$= |\hat{e}_1|[|\hat{e}_2| - L_1] \tag{28}$$

When constant L_1 is sufficiently large, that is, $L_1 \geq |\hat{e}_2| + \eta_1$, then

$$\dot{\hat{V}}_1 \leq -\eta_1|\hat{e}_1| \tag{29}$$

As shown in the above demonstration, the system satisfies the existence and reach ability conditions of the sliding mode; that is, within a finite time, the system departing from any initial conditions will reach sliding-mode surface $\hat{s}_1 = 0$. According to the sliding mode equivalent principle [23], when the sliding-mode surface $\hat{s}_1$ is reached, $\hat{s}_1 = \dot{\hat{s}}_1 = 0$.

According to (25),

$$\hat{e}_2 = v_1 = L_1 \, \mathrm{sgn}\, \hat{e}_1 \tag{30}$$

The selected Lyapunov function is

$$\hat{V}_2 = \frac{1}{2}(\hat{e}_1^2 + \hat{e}_2^2) \tag{31}$$

Thus,

$$\dot{\hat{V}}_2 = \hat{e}_1 \dot{\hat{e}}_1 + \hat{e}_2 \dot{\hat{e}}_2$$
$$= \dot{V}_1 + \hat{e}_2 \dot{\hat{e}}_2 .$$

According to (26),

$$\hat{e}_2 \dot{\hat{e}}_2 = \hat{e}_2[-M^{-1}B(x_2 - \hat{x}_2) + M^{-1}F_{ai} - v_2]$$
$$\leq -M^{-1}B\hat{e}_2^2 + |\hat{e}_2|\left[|M^{-1}F_{ai}| - L_2\right] \tag{32}$$

When constant $L_2 \geq |M^{-1}f_{ai}| + \eta_2$, then

$$\hat{e}_2 \dot{\hat{e}}_2 \leq -M^{-1}B\hat{e}_2^2 - \eta_2|\hat{e}_2|$$
$$\leq -\eta_2|\hat{e}_2| \tag{33}$$

Together (29) with (33), we obtain

$$\dot{\hat{V}}_2 \leq -\eta_1|\hat{e}_1| - \eta_2|\hat{e}_2| \tag{34}$$

Therefore, the system satisfies the existence and reach ability conditions of sliding mode; that is, within a finite time, the system departing from any initial conditions will reach sliding-mode surface $\hat{s}_2$. Similarly, when the sliding-mode surface $\hat{s}_2$ is reached, $\hat{s}_2 = \dot{\hat{s}}_2 = 0$.

According to (26) and (30), the value of equivalent actuator fault is

$$F_{ai} = Mv_2$$
$$= ML_2 \, \mathrm{sgn}[L_1 \, \mathrm{sgn}\, \hat{e}_1] \tag{35}$$

Thus, the proof is complete.

Using the sigmoid function in replacing $\mathrm{sgn}(s)$ to weaken the buffeting of the sliding mode, the reconstructed value of the equivalent actuator fault becomes

$$\hat{F}_{ai} = ML_2 \left(\frac{2}{1 + e^{-a_1 L_1 \, \mathrm{sgn}\, \hat{e}_1}} - 1 \right) \tag{36}$$

where $a_1 > 0$.

5. Online Adjustment of Fault-tolerant Control Rate

The online fault-tolerant control for system (4) can be described as follows. The observed value $\hat{x}$ of the system status (i.e., $\hat{q}$) and the reconstructed value $\hat{F}_{ai}$ of the equivalent actuator fault are substituted into the control law of (12). The adjusted online fault-tolerant control law τ_i is

$$\tau_i = M[c_i \dot{E}_i + \ddot{q}_d - k_i \ddot{\varepsilon}_i + as + b \, \mathrm{sgn}(s_i)]$$
$$+ B\dot{\hat{q}}_i + mgl \cos q_i - \hat{F}_{ai} \tag{37}$$

When the system does not have an equivalent actuator fault [i.e., $F_{ai}(t) = 0$], the control law τ_{i0} (13) of the nominal system is adjusted to

$$\tau_{i0} = M[c_i \dot{E}_i + \ddot{q}_d - k_i \ddot{\varepsilon}_i + as + b \, \mathrm{sgn}(s_i)]$$
$$+ B\dot{\hat{q}}_i + mgl \cos q_i \tag{38}$$

When the equivalent actuator fault occurs [i.e., $F_{ai}(t) \neq 0$], the designed additional control law τ_{if} (14) is adjusted to

$$\tau_{if} = -\hat{F}_{ai} \tag{39}$$

Theorem 3. *The online fault-tolerant control law designed for the robot system described by (4) is shown in (37). When $b \geq ||M^{-1}BL_1|| + L_2$, the system satisfies the stability condition of the sliding mode.*

Proof: By selecting the Lyapunov function,

$$V_i' = \frac{1}{2}s_i^2 \tag{40}$$

Considering the derivative of (40) and then substituting it into the adjusted control law (37),

$$\dot{V}_i' = s_i \dot{s}_i$$
$$\leq -as_i^2 - b|s_i| + |s_i|(||M^{-1}B\hat{e}_2|| + ||M^{-1}(F_{ai} - \hat{F}_{ai})||) \tag{41}$$

According to (27), (32), and (33)

$$\dot{V}_i' \leq -as_i^2 - b|s_i| + |s_i|(||M^{-1}BL_1|| + L_2) \tag{42}$$

When $b \geq ||M^{-1}BL_1|| + L_2$, thus

$$\dot{V}_i' \leq -as_i^2$$

The proof is thus complete.

The above analysis shows that the system satisfies the existence and reach ability conditions of the sliding mode; that is, the system departing from any initial state other than the sliding-mode surface $s = 0$ will reach the sliding-mode surface within a finite time.

6. Analysis on Simulation and Experiment Results

In dynamic (4) of one-DOF manipulator,

$$M_i = [M_1, M_2, M_3, M_4] = \left[\frac{3}{4}ml^2, \frac{4}{3}ml^2, ml^2, \frac{9}{8}ml^2\right],$$

$$B_i = 2.0, \quad (i = 1, 2, 3, 4)$$

Herein, $m = 1$, $l = 0.25$, and $g = 9.8$. A multi-robot system with four one-DOF manipulators is used. The initial position of the system is $q_{i0} = [-0.5 \quad -1.5 \quad 0.5 \quad 1]^T$, and the given input position signal is $q_d = 2\cos(\pi t)$.

The design parameters are as follows:

$$k_i = 1$$

$$c_1 = 6, \quad c_2 = 8, \quad c_3 = 12, \quad c_4 = 9$$

$$a = 3, \quad b = 30, \quad L_1 = 5, \quad L_2 = 15.$$

6.1 Simulation Results

The performance of the proposed fault-tolerant control scheme is evaluated with a detailed simulation model using the MATLAB/Simulink R2007b. When no equivalent actuator fault exists in the system (*i.e.*, $F_{ai} = 0$), it is a nominal system and the control law is τ_{i0}. In this case, Fig. 1 shows the errors e_1, e_2, e_3, and e_4 between the system states q_1, q_2, q_3, and q_4 of four robots and the given input position signals q_d. Figure 2 shows the synchronization errors e_{12}, e_{23}, e_{34}, e_{41} of the tracking status between adjacent robots. The simulation results are as follows.

The given input signals can be stably tracked by all four robots, as shown by the tracking error in Fig. 1. This result suggests good tracking effect. Figure 2 shows that the synchronization error of the tracking status between
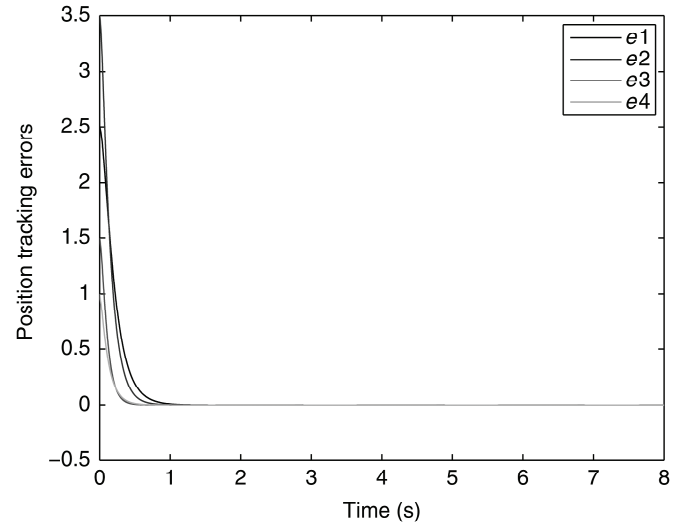

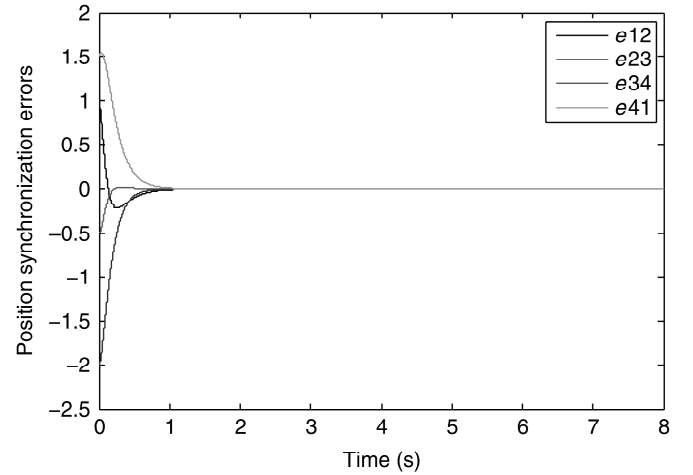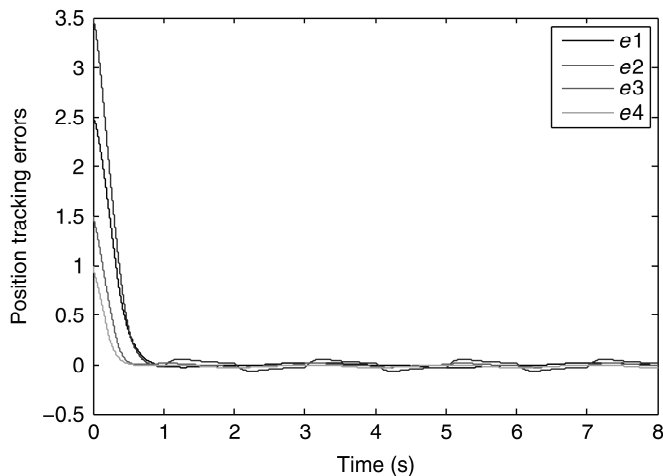Figure 1. Position-tracking error.

Figure 2. Position-synchronization error.

robots basically converges to zero, which suggests a high synchronization accuracy of the system. When equivalent actuator fault does not occur in the system, the simulation results show that the nominal control law τ_{i0} can meet the control requirements.

In the presence of an equivalent actuator fault (*i.e.*, $F_{ai} \neq 0$) a sinusoidal signal $[F_{a1} = 1.2\sin(\pi t)]$, a square wave signal with a period of 2 s and an amplitude of 2, a cosine signal $[F_{a3} = 1.5\cos(3t)]$, an isosceles triangular wave signal with a period of 2 s and an amplitude of 1.8 are selected to simulate the actuator fault. Nevertheless, the fault-tolerant control is not performed. That is, the additional control law τ_{if} is not used, and the nominal control law τ_{i0} is still applied to the control. At this point, Fig. 3 shows the errors e_1, e_2, e_3, and e_4 between the system states q_1, q_2, q_3, and q_4 of four robots and the given input position signals q_d. Figure 4 shows the synchronization errors e_{12}, e_{23}, e_{34}, and e_{41} of the tracking status between adjacent robots. The simulation results are as follows.
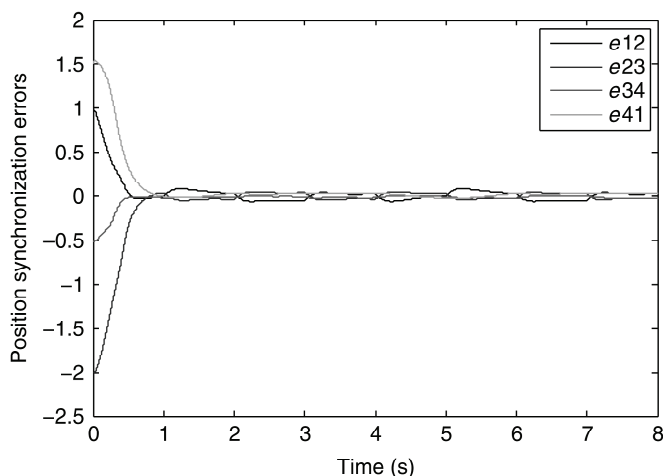
Figure 3. Position-tracking error.

Figure 4. Position-synchronization error.

Figure 5. Actual and reconstruction values of equivalent actuator fault F_{a1}.
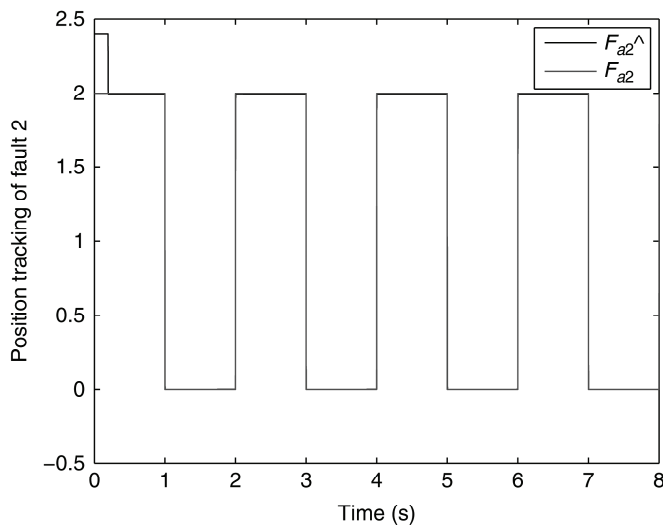
Figure 6. Actual and reconstruction values of equivalent actuator fault F_{a2}.

Figure 3 show unsatisfactory tracking of the given input position signal for the four robots due to certain tracking error. As shown in Fig. 4, the system synchronization accuracy is also unsatisfactory due to certain error. The simulation results show that the nominal control law τ_{i0} does not meet the control requirements in the presence of the equivalent actuator fault without fault-tolerant control.

Figures 5–8 present the actual values of the equivalent actuator fault for each individual robot, namely, F_{a1}, F_{a2}, F_{a3}, and F_{a4}, and the corresponding reconstruction value.

As shown in Figs. 5–8, the reconstructed value of the equivalent actuator fault is basically similar to the actual value. Thus, the reconstruction error is acceptable, and the equivalent actuator fault F_{ai} can be accurately reconstructed using the proposed algorithm.

In the case of fault-tolerant control, by adding the additional control law τ_{if}, the control law is τ_i. Figure 9 shows the errors e_1, e_2, e_3, and e_4 between the system states q_1, q_2, q_3, and q_4 of four robots and the given input position signals q_d. Figure 10 shows the synchronization errors e_{12}, e_{23}, e_{34}, and e_{41} of the tracking status between adjacent robots. The simulation results are as follows.

As shown in Figs. 9 and 10, after adding the additional control law τ_{if} for fault-tolerant control, the given input
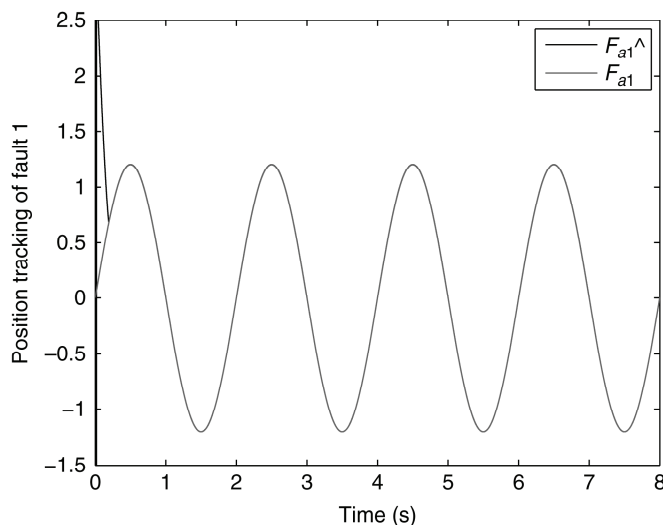
position signal can be accurately tracked with promising synchronization performance, showing insignificant tracking and synchronization errors. Therefore, the designed control law τ_i can meet the control requirements in the presence of equivalent actuator faults and with fault-tolerant control.

6.2 Semi-physical Experiment

A semi-physical experiment platform is established for the multi-robot system, to approximate the whole simulation process to the real engineering environment, better evaluate controller performance, and verify the accuracy and feasibility of the theoretical method proposed in this section.

The entire simulation platform consists of DSP controller, OP5600 simulator, related connected line, and multi-robot system model in the software part and PC monitor interface.
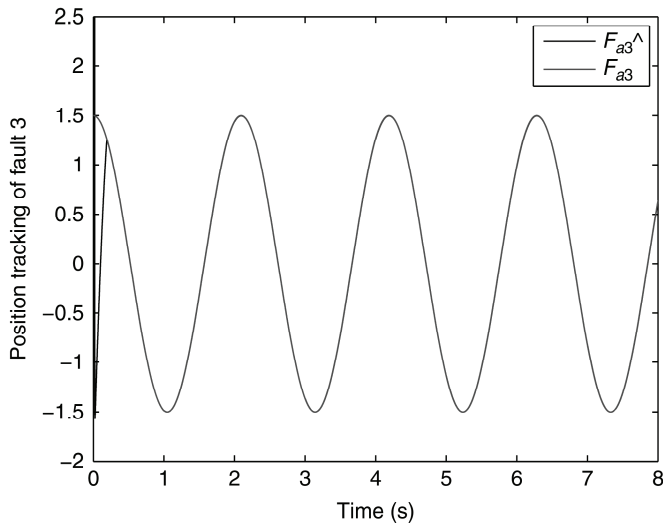
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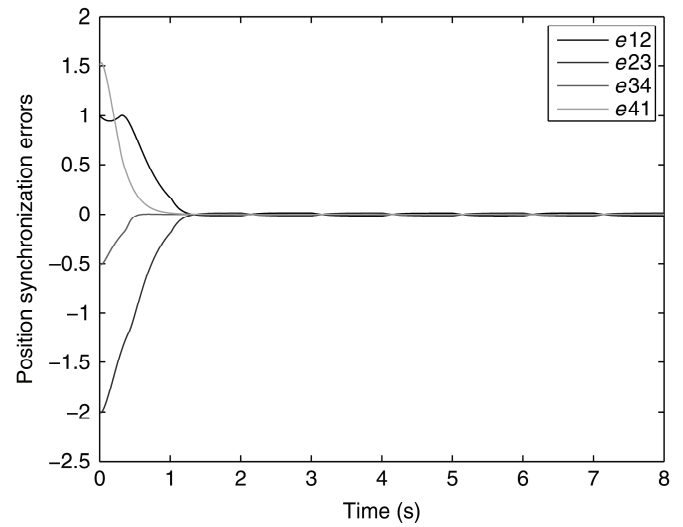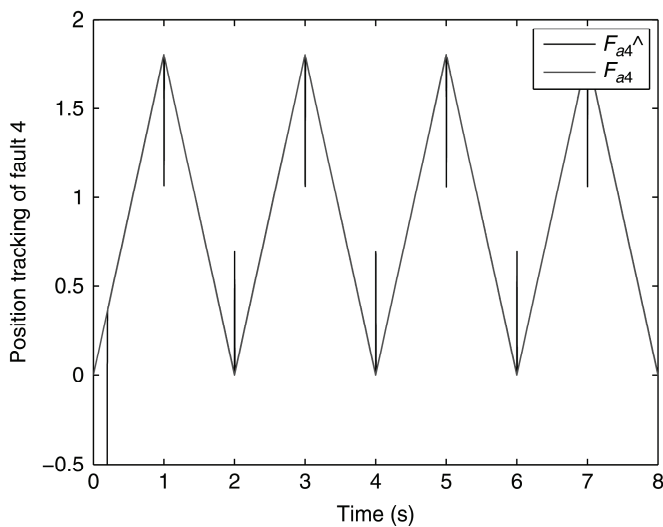Figure 7. Actual and reconstruction values of equivalent actuator fault F_{a3}.

Figure 8. Actual and reconstruction values of equivalent actuator fault F_{a4}.
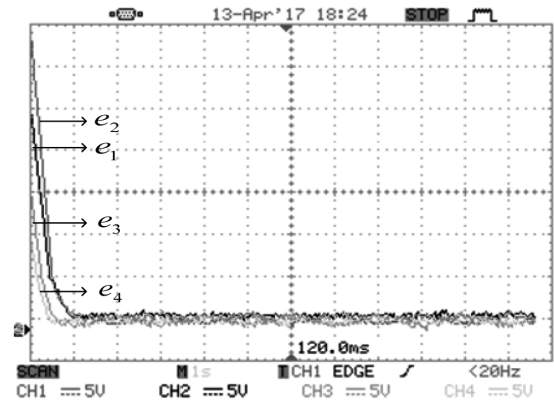

Figure 9. Position-tracking error.

Figure 10. Position-synchronization error.
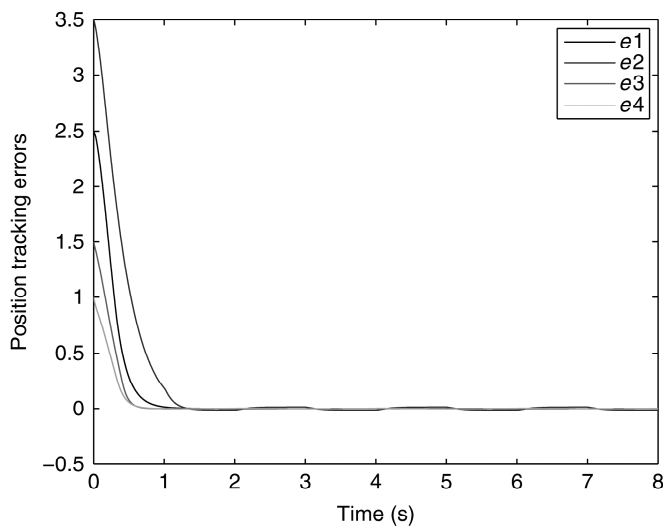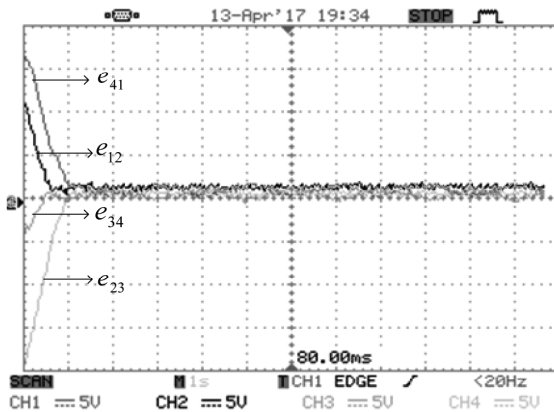

Figure 11. Position-tracking error (e_i: 1/unit).

Figure 12. Position-synchronization error (e_{i+1}: 1/unit).

In the presence of equivalent actuator faults and without fault-tolerant control, the corresponding tracking and synchronization errors are shown in Figs. 11 and 12.

As shown in Figs. 11 and 12, the tracking performance and synchronization accuracy of the multi-robot system do not meet the control requirements due to certain errors, which is consistent with the simulation results.
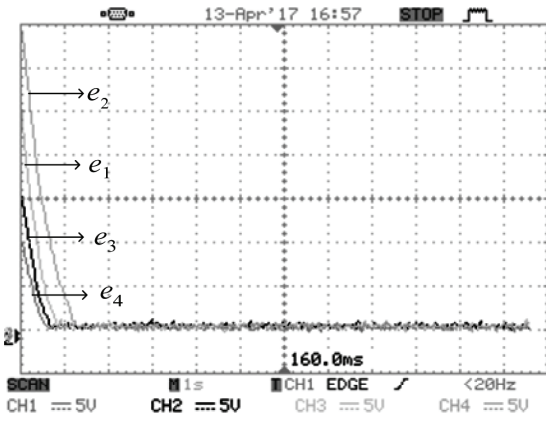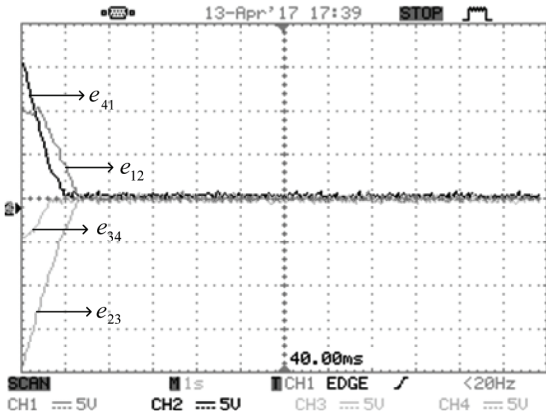
Figure 13. Position-tracking error (e_i: 1/unit).

Figure 14. Position-synchronization error(e_{ii+1}: 1/unit).

In the case of fault-tolerant control, the tracking and synchronization errors are shown in Figs. 13 and 14, respectively.

At this point, the tracking and synchronization errors of the multi-robot system are extremely insignificant; thus, the control requirements are satisfied, which is consistent with the simulation results.

7. Conclusion

For the problem of synchronous fault-tolerant control for a class of multi-robot systems with actuator faults, a cooperative fault-tolerant control method based on ring coupling has been proposed in this paper. The proposed method can obtain unknown system states, fault information, which can realize online fault-tolerant control and is not limited by the number of controlled objects. Consequently, the multi-robot system has strong robustness and high synchronization accuracy. The simulation and semi-physical experiment results verified the effectiveness of the proposed method. The object considered in this paper is a kind of single DF manipulator, which is not considered in the robot system with multiple DFs and can be further studied in the next step.

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