Fixed-Time Sensor Fault Detection Observer With Actuator Fault Decoupling for Attack-Free Consensus Systems

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***Abstract*—This paper studies a fixed-time attack-free actuator fault decoupling observer (FTAF-AFDO) for sensor fault detection in multi-agent systems employing the attack-free consensus protocol, where only the local information of the monitored agent and the relative output information between agents measured by its internal sensors are available. The main difficulty is that the sensor faults studied here directly affect the control signal rather than the agent's local output, causing traditional observers based on control inputs and outputs to fail in detecting such sensor faults. In addition, sensor faults and actuator faults are coupled, as the relative output information measured by sensors is directly involved in the design of attack-free consensus protocol. To tackle these difficulties, we developed the FTAF-AFDO, inspired by unknown input observer and Luenberger observer. This observer generates a sensor fault indicator signal that fully decouples from estimation errors and actuator faults within a fixed time, without needing any prior knowledge of the actuator faults. Additionally, leveraging the proposed FTAF-AFDO, a distributed attack-free consensus protocol is developed, capable of completely isolating the impact of actuator faults. The effectiveness of the proposed method is validated through simulations of a formation-flying transport aircraft system.**

***Index Terms*—Sensor fault detection, actuator fault isolation, distributed fixed-time observer, attack-free, pure relative output information.**

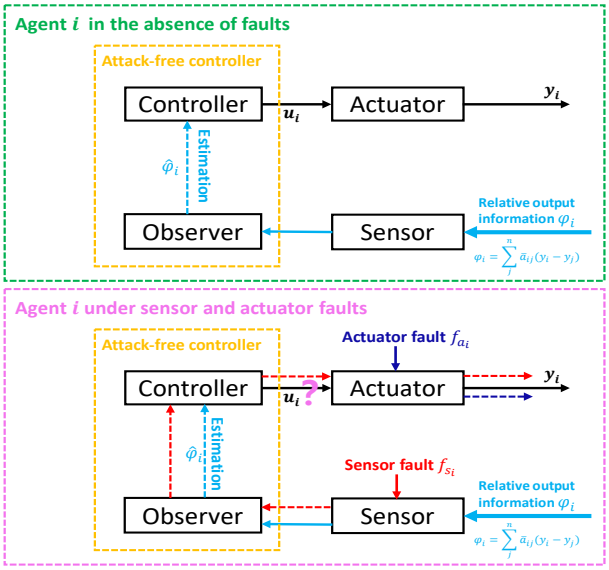


Fig. 1. Framework of the attack-free consensus protocol based on relative output information: the upper diagram illustrates the system without faults, while the lower diagram depicts the system under sensor and actuator faults.

I. Introduction

In recent years, consensus control in multi-agent systems has emerged as one of the critical research areas in the field of automatic control [1]–[3]. In practical applications, such as drone swarms [4], autonomous vehicle platoons [5], and distributed energy management systems [6], agents typically need to exchange information through network communication to achieve coordinated operation. However, when network communication becomes unreliable, for instance, due to cyber attacks [7] or signal interference [8], communication-based control strategies can fail to function effectively. To address this issue, over the past five years, direct consensus control protocols based on sensor measurements of relative output information have gained some attention [9]–[12].

Lv et al. [9], [12] proposed a fully distributed attack-free consensus protocol based on observers. This class of protocol is structured around sensors that measure the relative output information between agents and a pre-designed unknown input observer, as illustrated in the green dashed box in Fig. 1. The observer is designed based on the relative output information directly measured by the agents' internal sensors, eliminating the need for inter-agent communication. As a result, the consensus protocol based on the observer operates independently of the communication network, rendering it inherently attack-free. These protocols [9]–[12] do not rely on network communication but instead achieve consensus control through relative measurements between agents. These approaches have emerged as critical solutions to the consensus problem in multi-agent systems, particularly under conditions of unstable or entirely disrupted communication.

However, the reliability of such attack-free protocols [9]–[13] assumes that the sensors measuring relative output information within each agent are fault-free. When this assumption fails, as shown in the pink dashed box in Fig. 1, sensor faults directly affect the measured data. Since the observer is

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designed to estimate the relative output accurately and the consensus control protocol relies on this information, sensor faults compromise the observer's accuracy, ultimately affecting the agents' controllers. In other words, when sensors responsible for measuring relative output information experience faults, the reliability of these attack-free consensus protocols can no longer be assured. Hence, it is essential to develop a timely and accurate sensor fault detection method to ensure the robustness of such technologies [14].

A. Related Work

There has been extensive research on sensor fault detection methods based on observers, such as Kalman Filter [15], Luenburger observer [16], extended state observer [17], generalized proportional-integral observer (GPIO) [18], sliding mode observer [19], interval observer [20], [21] and unknown input observer (UIO) [22]. While these well-established observer-based fault detection methods have proven effective in addressing sensor or actuator faults in traditional systems, they may still be prone to failure when applied to the specific sensor fault detection problem investigated in this paper. This vulnerability arises primarily due to the following two factors:

1) The Absence of Additive Sensor Fault Information in the Local Output Signal: In many existing studies, sensor faults are commonly modeled as additive faults on the output signal [23]. And for systems subject to such sensor faults and actuator faults, the corresponding observer-based fault detection techniques have also become relatively mature [24], [25]. However, unlike traditional fault detection issues, the sensor faults studied here occur in sensors measuring relative output information between neighbors, not in sensors measuring the agents' own output signals. In other words, in the problem studied in this paper, the measurement of the agent's output signal no longer includes additive sensor fault information. Only the relative output information measured by the sensors contains fault information. Since this information is used in designing the consensus controller, the sensor faults studied in this paper are thus coupled into the control signal. Traditional observers [15]–[20], [22], [26] based on control and output signals generate residuals (for fault detection) that are decoupled from the control input. In addition, the local output signals used to generate the residuals lacks additive fault information, causing traditional fault detection observers [15]–[20], [22], [26] lose the ability to detect the sensor faults studied in this paper.

2) The Coupling of Sensor and Actuator Faults: As illustrated by the information flow in the pink dashed box of Fig. 1, the sensor faults directly affect the actuator via the controller signals. In other words, the sensor faults and actuator faults investigated in this paper are nearly completely coupled, both influencing the channel from the actuator to the output signal. Therefore, compared to traditional sensor/actuator fault detection problems [27], the sensor faults addressed in this paper within multi-agent systems utilizing attack-free consensus protocols present a greater challenge. Since attack-free consensus control technology has only recently emerged, there is a lack of research on sensor fault detection in systems employing these protocols. Moreover, achieving complete decoupling of sensor fault indication signals from actuator faults in sensor fault detection–without requiring any prior knowledge of actuator faults–remains highly challenging.

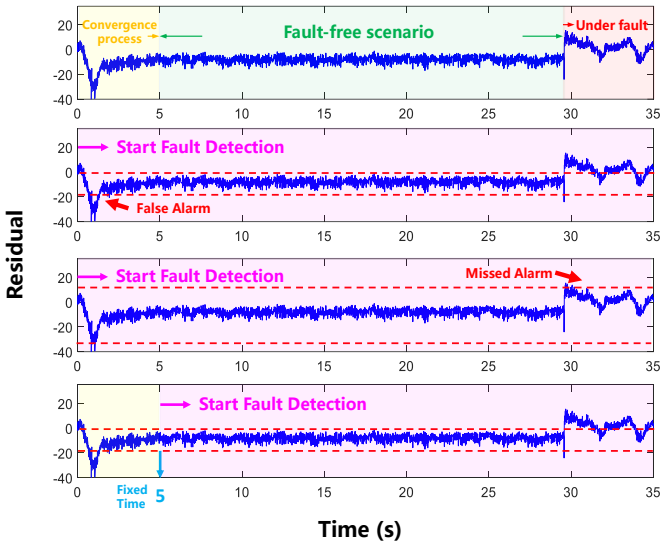


Fig. 2. Enhancing fault detection with fixed-time observers: Reducing false alarms and missed detections after fixed-time convergence.

In addition, to the best of our knowledge, there is little research focused on designing fixed-time observers for sensor fault detection in multi-agent systems employing attack-free consensus protocols, particularly in systems where both sensor and actuator faults are present. Research on fixed-time observers for fault detection offers two key advantages: (1) Fixed-time observers ensure convergence of the estimation error within a specified period, enabling fault detection beyond this window to effectively reduce false alarms from dynamic responses to sudden scheduling events or external disturbances (see Fig. 2(b)). (2) Setting fault detection thresholds based on the residual signal amplitude after fixed-time convergence reduces missed detections caused by overly conservative thresholds designed to account for dynamic convergence processes (see Fig. 2(c)). Traditional observers start fault detection from 0 s, as shown in Fig. 2 (b)-(c), while the fixed-time fault detection observer performs fault detection after the fixed time, as shown in Fig. 2 (d). A comparison of subfigures (b), (c), and (d) in Fig. 2 clearly demonstrates that using a fixed-time observer for fault detection after the fixed time (5 s) effectively reduces both false alarm and missed detection rates. Therefore, this also serves as one of the key motivations for the research presented in this paper.

B. Contribution

Since traditional observers [9]–[13] can effectively detect actuator faults in the studied systems, this paper focuses on developing a fixed-time attack-free sensor fault detection observer to achieve complete decoupling of the fault indicator signal from actuator faults within a fixed time. The main contributions of this paper can be summarized as follows.

1) A distributed sensor fault detection observer, named FTAF-AFDO, is proposed. It relies only on local information from the monitored agent, including sensor-measured relative output data, making it immune to attacks.
2) The proposed FTAF-AFDO can generate a sensor fault indicator signal that is fully decoupled from both actuator faults and estimation errors after a fixed-time τ, without requiring any prior knowledge of actuator faults. This allows operators to determine sensor faults by checking if the fault indicator signal's amplitude is zero after time τ, simplifying the detection process and indicating certain application potential.
3) Even in the presence of actuator faults, the proposed FTAF-AFDO can accurately estimate the consensus error after the fixed-time τ. Furthermore, based on the generated consensus error estimation signal, an attack-free consensus protocol is given, enabling the isolation of actuator faults.

The rest of this article is organized as follows. Section II introduces the modeling of the research problem and its associated difficulties. Section III presents the modeling of the proposed FTAF-AFDO, along with its fixed-time convergence analysis and the design methodology for actuator fault decoupling. Additionally, a consistency protocol capable of achieving actuator fault decoupling based on FTAF-AFDO is proposed. In Section IV, a case study of a formation-flying transport aircraft is presented to further validate the effectiveness of the proposed methods. The corresponding conclusions are summarized in Section V.

II. Preliminaries and Problem Formulation

A. Notations and Graph Theory

Notation: For a matrix C, C^+ represents the left inverse of matrix C. I denotes the identity matrix of appropriate dimensions. $\lambda_{\mathrm{Re}}(C)$ represents the real part of the eigenvalues of matrix C. $\mathbb{R}$ represents the set of real numbers. $\mathbb{C}_+$ and $\mathbb{R}_+$ represent the set of complex numbers with positive real parts and the set of positive real numbers, respectively.

Graph Theory: Let an undirected graph $\mathbb{G} = (\mathbb{V}, \mathbb{E})$ depictes the communication topology among N agents, where $\mathbb{V} = \{1, ..., N\}$ and $\mathbb{E} \subseteq \mathbb{V} \times \mathbb{V}$ represent the sets of nodes and edges, respectively. The adjacency matrix $\bar{A} = [\bar{a}_{ij}] \in \mathbb{R}^{N\times N}$ of the graph $\mathbb{G}$ is defined as: $\bar{a}_{ii} = 0$; $\bar{a}_{ij} > 0$, when $(j, i) \in \mathbb{E}$; otherwise, $\bar{a}_{ij} = 0$.

As the proposed FTAF-AFDO is a distributed observer, it is equally applicable to a directed graph $\mathbb{G}$. For simplicity in analysis, we assume $\mathbb{G}$ to be undirected.

B. System Description

1) System and Actuator Fault f_{a_i}: Consider a homogeneous multi-agent system [28], where each individual agent can be modeled as the following linear time-invariant (LTI) system:

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bu_i(t) + B_a f_{a_i}(t) \\ y_i(t) = Cx_i(t), \quad i = 1, \ldots, N \end{cases} \tag{1}$$

where $x_i \in \mathbb{R}^{m_x}$ and $y_i \in \mathbb{R}^{m_y}$ represent the state and output of agent i. $f_{a_i} \in \mathbb{R}^{m_{a_i}}$ denotes actuator faults in agent i.

Assumption 1: A, B and C are known system matrices.

2) Attack-free Consensus Protocol $u_i \in \mathbb{R}^{m_u}$: This paper aims to provide a reliable fault detection scheme for the advanced attack-free consensus protocols proposed in recent years [9]–[12]. These attack-free protocols are designed solely based on pure relative output information between agents and can be modeled as

$$u_i(t) = g_i\left(\varphi_i(t)\right), \varphi_i(t) = \sum_{j=1}^{N} \bar{a}_{ij}\left(y_i(t) - y_j(t)\right) \tag{2}$$

where φ_i is the pure relative output information between agent i and its neighbours. $g(\cdot)$ is a pre-designed nonlinear function of φ_i [9]–[12].

Remark 1: φ_i is directly measured by the sensors inside agent i. The reliable operation of these attack-free consensus protocols is predicated on the assumption that the sensors measuring φ_i remain fault-free. In other words, if these sensors experience the malfunction, these protocols [9]–[12], which rely on relative output information, are likely to suffer from degraded control accuracy or, in the worst case, risk complete failure. Consequently, the development of an effective sensor fault detection scheme is crucial for ensuring the reliability of systems that utilize attack-free protocols.

3) Sensor Fault f_{s_i}: This study focuses on determining whether the sensor measuring φ_i has encountered a fault. In the event of a malfunction in the sensors within agent i, the relative output information between agent i and its neighbours can be re-modeled as follows:

$$\bar{\varphi}_i(t) = \varphi_i(t) + f_{s_i}(t) = \sum_{j=1}^{N} \bar{a}_{ij}\left(y_i(t) - y_j(t)\right) + f_{s_i}(t). \tag{3}$$

Meanwhile, the attack-free protocol u_i can be reformulated as

$$u_i(t) = g_i\left(\bar{\varphi}_i(t)\right) = g_i\left(\varphi_i(t) + f_{s_i}(t)\right). \tag{4}$$

Assumption 2: f_{s_i} and its derivative $\dot{f}_{s_i}$ are bounded.

Remark 2: Excessive sensor faults can compromise the functionality of the attack-free consensus controller, leading to a breakdown of consistency among agents. Therefore, when Assumption 2 is violated, it is inconsequential to investigate potential sensor faults in measuring the relative output information φ_i.

Remark 3: From the above analysis (1), (3), and (4), three key conclusions can be drawn: 1) The sensor fault f_{s_i} studied in this paper directly impacts the control signal u_i, meaning that, from an information-theoretic perspective, f_{s_i} essentially behaves as a controller fault. 2) Since f_{s_i} affects u_i, traditional fault detection observers designed based on u_i produce residual signals that are decoupled from u_i. This indicates that conventional fault detection observers [18], [26], [29]–[31] are ineffective for detecting the sensor faults addressed in this paper. 3) Controller and actuator faults both impact the actuator-to-output signal path, resulting in their coupling. Thus, the presence of actuator faults makes detecting the sensor faults studied here particularly challenging.

C. Problem Formulation

In conclusion, this paper mainly aims to address the following challenging issue: *For multi-agent systems employing attack-free protocols, how can we design a distributed fixed-time sensor fault detection observer that achieves complete decoupling of the fault indication signal from actuator faults?*

Remark 4: The sensor faults examined in this paper are concealed within the control signal, making the design of a fixed-time sensor fault detection observer based solely on local agent information a significant challenge. Additionally, the coupling of actuator and sensor faults complicates the development of the observer that can generate residual signals entirely decoupled from actuator faults. Given that established observers, such as proportional and unknown input observers, can effectively detect actuator faults in the studied system, this paper focuses specifically on the detection of sensor faults.

Additionally, this paper extends the work based on the proposed observer. Referring to the classical consensus protocol [9], [11], [12], we propose an attack-free consensus control protocol that can achieve isolation of actuator faults.

III. Main Results

A. Proposed FTAF-AFDO

To address the above issues, a fixed-time attack-free actuator fault decoupling observer (FTAF-AFDO) is proposed, which can be modeled as follow

$$\begin{cases} \dot{\hat{x}}_i(t) = A\hat{x}_i(t) + Bu_i(t) + L_1(y_i(t) - C\hat{x}_i(t)) \\ \dot{\bar{o}}_i(t) = \bar{A}_c\bar{o}_i(t) + \bar{B}_c\sum_{j=1}^{N}\bar{a}_{ij}\left(y_i(t) - y_j(t)\right) \\ \qquad\quad + \bar{L}_c(y_i(t) - C\hat{x}_i(t)) \\ \bar{\eta}_i(t) = \bar{D}_c\left[\bar{o}_i(t) - \exp\left(\bar{A}_c\tau\right)\bar{o}_i(t-\tau)\right] \\ \hat{\xi}_i(t) = \bar{\eta}_i(t) - H_3\sum_{j=1}^{N}\bar{a}_{ij}\left(y_i(t) - y_j(t)\right) \\ \qquad\quad + L_3(y_i(t) - C\hat{x}_i(t)) \\ \Delta\hat{\xi}_i(t) = \hat{\xi}_i(t) - C^{+}\sum_{j=1}^{N}\bar{a}_{ij}\left(y_i(t) - y_j(t)\right), \end{cases} \tag{5}$$

where $\bar{o}_i(t) = \left[\ \bar{o}_{1i}(t),\ \bar{o}_{2i}(t)\ \right]^T$ and

$$\bar{A}_c = \begin{bmatrix} H_1A - H_{21}C & 0 \\ 0 & H_1A - H_{22}C \end{bmatrix}, \bar{L}_c = \begin{bmatrix} L_{21} \\ L_{22} \end{bmatrix}$$
$$\bar{B}_c = \begin{bmatrix} H_{21}(I_{m_y} + CH_3) - H_1AH_3 \\ H_{22}(I_{m_y} + CH_3) - H_1AH_3 \end{bmatrix}, \bar{C} = \begin{bmatrix} I_{m_x} \\ I_{m_x} \end{bmatrix}$$
$$\bar{D}_c = \begin{bmatrix} I_{m_x} & 0 \end{bmatrix}\begin{bmatrix} \bar{C} & \exp\left(\bar{A}_c\tau\right)\bar{C} \end{bmatrix}^{-1}.$$

For the proposed FTAF-AFDO (5), $H_1 = I_{m_x} + H_3C$ and $H_3 = -B\left[(CB)^TCB\right]^{-1}(CB)^T$. The parameters L_1, $\bar{L}_c$, H_{21} and H_{22} require further design, with H_{21} and H_{22} being distinct. The initial value of $\bar{o}_i$ in time interval $[\tau, 0]$ can be set as zero. The fault indication signal $\Delta\hat{\xi}_i$ generated by FTAF-AFDO is used for sensor fault detection.

Define $\xi_i(t) = \sum_{j=1}^{N}\bar{a}_{ij}\left(x_i(t) - x_j(t)\right)$ as the consensus error between agent i and its neighbors j.

Remark 5: In the absence of sensor faults f_{s_i}, the proposed FTAF-AFDO's output signal $\hat{\xi}_i$ can accurately estimate the consensus error ξ_i within a fixed time τ. When both sensor and actuator faults occur, the fault indication signal $\Delta\hat{\xi}_i$ can achieve complete decoupling from the actuator fault f_{a_i} without any prior knowledge of f_{a_i}, retaining only sensor fault information after time τ. The above conclusions have be demonstrated in the subsequent subsections.

Remark 6: The proposed FTAF-AFDO operates solely on local information from agent i, eliminating the need for communication with its neighbors via networks. As a result, the FTAF-AFDO is a fully distributed observer and inherently resistant to cyber attacks.

B. Fixed-Time Convergence

First, we analyze the convergence of the proposed FTAF-AFDO, as detailed in the following theorem.

Theorem 1: For the agent i (1), when no faults occur and the following conditions are satisfied:

C_1: $L_{2i}C = (H_1A - H_{2i}C)L_3C - L_3C(A - L_1C), i = 1, 2$;

C_2: $A - L_1C$ and $H_1A - H_{2i}C, i = 1, 2$ are stable;

then, for the i-th FTAF-AFDO (5), there are:

$\bar{\mathrm{C}}_1$: The output signal $\hat{\xi}_i$ can estimate the exact consensus error ξ_i in fixed-time τ, i.e., $\hat{\xi}_i(t) = \xi_i(t), \forall t \geq \tau$.

$\bar{\mathrm{C}}_2$: The fault detection signal $\Delta\hat{\xi}_i$ can converge to zero in fixed-time τ, i.e., $\Delta\hat{\xi}_i(t) = 0, \forall t \geq \tau$.

Proof: Further analysis of (5) yields

$$\dot{\bar{o}}_i(t) = \bar{A}_c\bar{o}_i(t) + \bar{B}_cC\xi_i(t) + \bar{L}_c(y_i(t) - C\hat{x}_i(t)). \tag{6}$$

Define an intermediate variable $\tilde{o}_i(t)$ as:

$$\tilde{o}_i(t) = \bar{o}_i(t) - \bar{C}H_1\xi_i(t) + \bar{L}_3(y_i(t) - C\hat{x}_i(t)), \tag{7}$$

where $\bar{L}_3 = \left[L_3,\ L_3\right]^T$. Then, the dynamics of $\tilde{o}_i$ can be modeled as:

$$\begin{aligned} \dot{\tilde{o}}_i(t) &= \dot{\bar{o}}_i(t) - \bar{C}H_1\dot{\xi}_i(t) + \bar{L}_3(\dot{y}_i(t) - C\dot{\hat{x}}_i(t)) \\ &= \bar{A}_c\bar{o}_i(t) + \bar{B}_cC\xi_i(t) + [\bar{L}_cC + \bar{L}_3C(A - L_1C)]e_{xi}(t) \\ &\quad - \bar{C}H_1[A\xi_i(t) + B\sum_{j=1}^{N}\bar{a}_{ij}\left(u_i(t) - u_j(t)\right)] \end{aligned} \tag{8}$$

where $e_{xi}(t) = x_i(t) - \hat{x}_i(t)$.

Since $H_1B = (I_{m_x} + H_3C)B = 0$ and

$$\begin{aligned} \bar{B}_cC - \bar{C}H_1A &= \begin{bmatrix} H_{21}C + H_{21}CH_3C - H_1AH_3C - H_1A \\ H_{22}C + H_{22}CH_3C - H_1AH_3C - H_1A \end{bmatrix} \\ &= \begin{bmatrix} (H_{21}C - H_1A)\,H_1 \\ (H_{22}C - H_1A)\,H_1 \end{bmatrix} = -\bar{A}_c\bar{C}H_1, \end{aligned}$$

then, (8) can be further modeled as

$$\begin{aligned} \dot{\tilde{o}}_i(t) &= \bar{A}_c\bar{o}_i(t) - \bar{A}_c\bar{C}H_1\xi_i(t) + \bar{A}_c\bar{L}_c(y_i(t) - C\hat{x}_i(t)) \\ &\quad + [\bar{L}_cC + \bar{L}_3C(A - L_1C) - \bar{A}_c\bar{L}_cC]e_{xi}(t) \\ &= \bar{A}_c\tilde{o}_i(t) + \bar{L}e_{xi}(t) \end{aligned}$$

where $\bar{L} = \bar{L}_cC + \bar{L}_3C(A - L_1C) - \bar{A}_c\bar{L}_cC$.

Since

$$\bar{L} = \begin{bmatrix} L_{21}C + L_3C(A - L_1C) - (H_1A - H_{21}C)\,L_3C \\ L_{22}C + L_3C(A - L_1C) - (H_1A - H_{22}C)\,L_3C \end{bmatrix}$$

and the condition C_1 is satisfied, then there is $\bar{L}=0$ and

$$\dot{\tilde{o}}_i(t)=\bar{A}_c\tilde{o}_i(t). \tag{9}$$

Also, when the condition C_2 is satisfied, there is

$$\tilde{o}_i(t)=\exp(\bar{A}_c\tau)\tilde{o}_i(t-\tau),\ \forall t\geq\tau. \tag{10}$$

Combine (7) and (10), we can get

$$\begin{aligned}\bar{o}_i(t)&-\exp(\bar{A}_c\tau)\bar{o}_i(t-\tau)\\&=\bar{C}H_1\xi_i(t)+\exp\left(\bar{A}_c\tau\right)\bar{C}H_1\xi_i(t-\tau)\\&\quad-\bar{L}_3Ce_{xi}(t)+\exp\left(\bar{A}_c\tau\right)\bar{L}_3Ce_{xi}(t-\tau),\ \forall t\geq\tau.\end{aligned}$$

Then, we can further obtain that for $\forall t\geq\tau$

$$\begin{aligned}\bar{\eta}_i(t)=&\bar{D}_c\left[\bar{C}H_1\xi_i(t)+\exp\left(\bar{A}_c\tau\right)\bar{C}H_1\xi_i(t-\tau)\right]\\&-\bar{D}_c\left[\bar{L}_3Ce_{xi}(t)-\exp\left(\bar{A}_c\tau\right)\bar{L}_3Ce_{xi}(t-\tau)\right].\end{aligned}$$

Since $\bar{D}_c\bar{C}=I_{m_x}$, $\bar{L}_3=\bar{C}L_3$, and $\bar{D}_c\exp(\bar{A}_c\tau)\bar{C}=0$, $\bar{\eta}_i(t)$ can be reformulated as

$$\bar{\eta}_i(t)=H_1\xi_i(t)-L_3Ce_{xi}(t),\ \forall t\geq\tau. \tag{11}$$

Furthermore, we can obtain

$$\begin{aligned}\hat{\xi}_i(t)=&\bar{\eta}_i(t)-H_3C\xi_i(t)+L_3(y_i(t)-C\hat{x}_i(t))\\&=\xi_i(t),\ \forall t\geq\tau\end{aligned} \tag{12}$$

and

$$\begin{aligned}\Delta\hat{\xi}_i(t)&=\hat{\xi}_i(t)-C^+\sum_{j=1}^{N}\bar{a}_{ij}\left(y_i(t)-y_j(t)\right)\\&=\xi_i(t)-C^+C\xi_i(t)=0,\ \forall t\geq\tau.\end{aligned} \tag{13}$$

The proof is completed. ■

Remark 7: Theorem 1 reveals two important insights under fault-free conditions: 1) The fault indicator signal $\Delta\hat{\xi}_i$ generated by the FTAF-AFDO converges to zero within a fixed time τ, meaning that when $t>\tau$, $\Delta\hat{\xi}_i$ no longer contains estimation error information. This is critical for enhancing the precision of sensor fault detection. 2) The output signal $\hat{\xi}_i$ can accurately estimate the synchronization error ξ_i within the fixed time τ, suggesting that $\hat{\xi}_i$ can be leveraged in the design of fixed-time consensus protocols for multi-agent systems [12].

Remark 8: The proposed FTAF-AFDO is essentially composed of three asymptotical observers, and by introducing time delays, it achieves fixed-time estimation. From (7) and (9), it follows that when condition C_2 in Theorem 1 is satisfied, both asymptotical observers $\bar{o}_{1i}$ and $\bar{o}_{2i}$ are capable of estimating $\bar{C}H_1\xi_i$. The other observer $\hat{x}_i$ can asymptotically estimate the system state x_i. Additionally, the matrix H_1 is designed as $H_1B=(I_{m_x}+H_3C)B=0$ to remove the dependency of the FTAF-AFDO on control input information from neighboring nodes, thereby enabling fully decentralized operation.

Then, we analyze the existence conditions of the proposed FTAF-AFDO.

Theorem 2: For the agent i (1), if the following conditions are satisfied:

C_1: $\operatorname{rank}\begin{bmatrix}C\\CA\\\vdots\\CA^{m_x}\end{bmatrix}=m_x$;

C_2: $\operatorname{rank}\begin{bmatrix}sI-A&B\\C&0\end{bmatrix}=m_x+m_u,\forall s\in\mathbb{C}_+$;

C_3: $\operatorname{rank}(CB)=\operatorname{rank}(B)=m_u$;

there exists a fixed-time attack-free actuator fault decoupling observer (5).

Proof: From (5), one can get that the existence of the proposed FTAF-AFDO depends on the following three conditions:

1) The observability of (A,C) and (H_1A,C): It is obvious that the condition C_1 ensures the observability of (A,C). The observability of (H_1A,C) requires that $\operatorname{rank}\begin{bmatrix}sI-H_1A\\C\end{bmatrix}=m_x$.

Since $\operatorname{rank}\begin{bmatrix}H_1\\(B^TB)^{-1}B^T\end{bmatrix}=m_x$, there exists a column full-rank matrix $\bar{W}_0$:

$$\bar{W}_0=\begin{bmatrix}H_1&0\\(B^TB)^{-1}B^T&0\\0&I\end{bmatrix}$$

Then, there is

$$\begin{aligned}&\operatorname{rank}\begin{bmatrix}sI_{m_x}-A&B\\C&0\end{bmatrix}\\&=\operatorname{rank}\left(\bar{W}_0\begin{bmatrix}I&0&-sH_3\\0&I&0\\0&0&I\end{bmatrix}\begin{bmatrix}sI-A&B\\C&0\end{bmatrix}\begin{bmatrix}I&0\\W_1&I\end{bmatrix}\right)\\&=\operatorname{rank}\begin{bmatrix}sI-H_1A&0\\0&B^TB\\C&0\end{bmatrix}\\&=\operatorname{rank}\begin{bmatrix}sI-H_1A\\C\end{bmatrix}+m_u,\end{aligned}$$

where $W_1=-(B^TB)^{-1}B^T(sI-A)$. Thus, when condition C_2 is satisfied, there is $\operatorname{rank}\begin{bmatrix}sI-H_1A\\C\end{bmatrix}=m_x$, i.e., (H_1A,C) is observable.

2) The existence of H_3: Since $\operatorname{rank}(CB)\leq\operatorname{rank}(B)\leq m_u$, then existence of $H_3=-B\left[(CB)^TCB\right]^{-1}(CB)^T$ requires that the matrix (CB) is a column full-rank matrix, i.e., $\operatorname{rank}(CB)=\operatorname{rank}(B)=m_u$. Therefore, when condition C_3 is satisfied, there exists a matrix H_3.

3) The invertibility of $\begin{bmatrix}\bar{C}&\exp\left(\bar{A}_c\tau\right)\bar{C}\end{bmatrix}$: Since

$$\begin{aligned}\det\begin{bmatrix}\bar{C}&\exp\left(\bar{A}_c\tau\right)\bar{C}\end{bmatrix}&=\det\begin{bmatrix}I&\exp\left(\bar{A}_{c1}\tau\right)\\I&\exp\left(\bar{A}_{c2}\tau\right)\end{bmatrix}\\&=\det\begin{bmatrix}I&\exp\left(\bar{A}_{c1}\tau\right)\\0&\exp\left(\bar{A}_{c2}\tau\right)-\exp\left(\bar{A}_{c1}\tau\right)\end{bmatrix}\\&=\det\left(\exp\left(\bar{A}_{c2}\tau\right)\right)\det\left(I-\exp\left(-\bar{A}_{c2}\tau\right)\exp\left(\bar{A}_{c1}\tau\right)\right)\end{aligned}$$

where $\bar{A}_{c1}=H_1A-H_{21}C$ and $\bar{A}_{c2}=H_1A-H_{22}C$. It's obvious that for $\forall\tau\in\mathbb{R}_+$, there is $\det\left(\exp\left(\bar{A}_{c2}\tau\right)\right)\neq0$. When condition C_2 is satisfied, we can design the matrices H_{21} and H_{22} such that $\lambda_{\mathrm{Re}}(\bar{A}_{c1})<\mu<\lambda_{\mathrm{Re}}(\bar{A}_{c2})$. Then, $\det\left(I-\exp\left(-\bar{A}_{c2}\tau\right)\exp\left(\bar{A}_{c1}\tau\right)\right)$ is an analytic function of τ, which means that this term has only isolated zeros. In other words, when condition C_2 is satisfied, there exists H_{21} and H_{22} such that $\begin{bmatrix}\bar{C}&\exp\left(\bar{A}_c\tau\right)\bar{C}\end{bmatrix}$ is invertible for almost all $\tau\in\mathbb{R}_+$. The proof is completed. ■

The conditions in Theorem 2 impose requirements on the system matrices A, B, and C. When Assumption 1 holds, these conditions can be easily verified.

C. Fixed-Time Actuator Fault Decoupling

This section presents the design methodology for decoupling actuator faults in the FTAF-AFDO, as detailed in Theorem 3.

Theorem 3: For the agent i (1) subject to sensor fault f_{s_i} and actuator fault f_{a_i}, when the following conditions are satisfied:

C_1: $L_{2i}C = (H_1A - H_{2i}C)L_3C - L_3C(A - L_1C), i = 1, 2$;

C_2: $A - L_1C$ and $H_1A - H_{2i}C, i = 1, 2$ are stable;

C_3: $\bar{C}L_3C = \sum_{j=1}^{N} \bar{a}_{ij}\bar{C}H_1$

then, for the i-th FTAF-AFDO (5), there are:

$\bar{\mathrm{C}}_1$: The fault indicator signal $\Delta\hat{\xi}_i$ can be fully decoupled from actuator faults f_{a_i} in fixed-time τ without requiring prior knowledge of B_a.

$\bar{\mathrm{C}}_2$: $\Delta\hat{\xi}_i(t) = \bar{D}_c \int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1 - C^+ f_{s_i}(t)$, $\forall t \geq \tau$.

Proof: Define an intermediate variable $\tilde{o}_i(t)$ as (7). Then, when sensor and actuator faults occur in system (1), the dynamics of $\tilde{o}_i$ can be reformulated as:

$$\begin{aligned}\dot{\tilde{o}}_i(t) &= \dot{\bar{o}}_i(t) - \bar{C}H_1\dot{\hat{\xi}}_i(t) + \bar{L}_3(\dot{y}_i(t) - C\dot{\hat{x}}_i(t)) \\ &= \bar{A}_c\bar{o}_i(t) + \bar{B}_cC\xi_i(t) + [\bar{L}_cC + \bar{L}_3C(A - L_1C)]e_{xi}(t) \\ &\quad - \bar{C}H_1[A\xi_i(t) + B\sum_{j=1}^{N}\bar{a}_{ij}\left(u_i(t) - u_j(t)\right)] \\ &\quad + \bar{B}_c f_{s_i}(t) + (\bar{L}_3CB_a - \bar{C}H_1B_a\sum_{j=1}^{N}\bar{a}_{ij})f_{a_i}(t)\end{aligned}$$

where $e_{xi}(t) = x_i(t) - \hat{x}_i(t)$.

Since $H_1B = (I_{m_x} + H_3C)B = 0$, $\bar{L}_3 = \bar{C}L_3$ and $\bar{B}_cC - \bar{C}H_1A = -\bar{A}_c\bar{C}H_1$, $\dot{\tilde{o}}_i(t)$ can be further modeled as

$$\begin{aligned}\dot{\tilde{o}}_i(t) &= \bar{A}_c\bar{o}_i(t) - \bar{A}_c\bar{C}H_1\xi_i(t) + \bar{A}_c\bar{L}_c(y_i(t) - C\hat{x}_i(t)) \\ &\quad + [\bar{L}_cC + \bar{L}_3C(A - L_1C) - \bar{A}_c\bar{L}_cC]e_{xi}(t) \\ &\quad + \bar{B}_c f_{s_i}(t) + (\bar{L}_3CB_a - \bar{C}H_1B_a\sum_{j=1}^{N}\bar{a}_{ij})f_{a_i}(t) \\ &= \bar{A}_c\tilde{o}_i(t) + \bar{L}e_{xi}(t) + \bar{B}_c f_{s_i}(t) \\ &\quad + (\bar{C}L_3C - \bar{C}H_1\sum_{j=1}^{N}\bar{a}_{ij})B_a f_{a_i}(t) \qquad (14)\end{aligned}$$

where $\bar{L} = \bar{L}_cC + \bar{L}_3C(A - L_1C) - \bar{A}_c\bar{L}_cC$.

When conditions C_1-C_3 are satisfied, there is

$$\dot{\tilde{o}}_i(t) = \bar{A}_c\tilde{o}_i(t) + \bar{B}_c f_{s_i}(t). \qquad (15)$$

Then, we have

$$\tilde{o}_i(t) = \exp(\bar{A}_c\tau)\tilde{o}_i(t-\tau) + \int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1,\ \forall t \geq \tau.$$

Since $\tilde{o}_i(t) = \bar{o}_i(t) - \bar{C}H_1\xi_i(t) + \bar{L}_3Ce_{xi}(t)$, there is

$$\begin{aligned}&\bar{o}_i(t) - \exp(\bar{A}_c\tau)\bar{o}_i(t-\tau) \\ &\quad = \bar{C}H_1\xi_i(t) + \exp\left(\bar{A}_c\tau\right)\bar{C}H_1\xi_i(t-\tau) \\ &\quad\quad - \bar{L}_3Ce_{xi}(t) + \exp\left(\bar{A}_c\tau\right)\bar{L}_3Ce_{xi}(t-\tau) \\ &\quad\quad + \int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1,\ \forall t \geq \tau.\end{aligned}$$

Then, we can further obtain that

$$\begin{aligned}\bar{\eta}_i(t) &= \bar{D}_c\left[\bar{C}H_1\xi_i(t) + \exp\left(\bar{A}_c\tau\right)\bar{C}H_1\xi_i(t-\tau)\right] \\ &\quad - \bar{D}_c\left[\bar{C}L_3Ce_{xi}(t) - \exp\left(\bar{A}_c\tau\right)\bar{L}_3Ce_{xi}(t-\tau)\right] \\ &\quad + \bar{D}_c\int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1,\ \forall t \geq \tau.\end{aligned}$$

Since $\bar{D}_c\bar{C} = I_{m_x}$ and $\bar{D}_c\exp(\bar{A}_c\tau)\bar{C} = 0$, $\bar{\eta}_i(t)$ can be reformulated as

$$\begin{aligned}\bar{\eta}_i(t) &= H_1\xi_i(t) - L_3Ce_{xi}(t) \\ &\quad + \bar{D}_c\int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1,\ \forall t \geq \tau.\end{aligned} \qquad (16)$$

Then, we can also obtain that

$$\begin{aligned}\hat{\xi}_i(t) &= \bar{\eta}_i(t) - H_3C\xi_i(t) + L_3Ce_{x_i}(t) \\ &= \xi_i(t) + \bar{D}_c\int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1,\ \forall t \geq \tau\end{aligned} \qquad (17)$$

and

$$\begin{aligned}\Delta\hat{\xi}_i(t) &= \hat{\xi}_i(t) - C^+\sum_{j=1}^{N}\bar{a}_{ij}\left(y_i(t) - y_j(t)\right) - C^+ f_{s_i}(t) \\ &= \bar{D}_c\int_{t-\tau}^{t} e^{\bar{A}_c(t-\tau_1)}\bar{B}_c f_{s_i}(\tau_1)d\tau_1 - C^+ f_{s_i}(t),\ \forall t \geq \tau.\end{aligned} \qquad (18)$$

From (18), it follows that the conclusions $\bar{\mathrm{C}}_1$ and $\bar{\mathrm{C}}_2$ of Theorem 3 hold true. The proof is completed. ■

Remark 9: As indicated by (18), after time τ, the fault indicator signal $\Delta\hat{\xi}_i$ becomes completely decoupled from both the actuator fault f_{a_i} and the estimation error $\hat{\xi}_i - \xi_i$. Furthermore, the analysis of (14) and (15) demonstrates that the proposed FTAF-AFDO is capable of fully decoupling the actuator fault f_{a_i} without the need for the prior knowledge of B_a. This capability is of substantial engineering significance.

Remark 10: After fixed-time τ, the fault indication signal $\Delta\hat{\xi}_i$ contains only information related to the sensor fault. Thus, by evaluating whether the amplitude of $\Delta\hat{\xi}_i$ is zero at after time τ, one can effectively ascertain the occurrence of a sensor fault f_{s_i} within the system i. The removal of the requirement for a fault detection threshold considerably simplifies the design complexity of the proposed fault detection method.

Remark 11: As indicated by (17), the estimated consensus error $\hat{\xi}_i$ generated by the proposed FTAF-AFDO is decoupled from the actuator fault f_{ai}. In other words, for systems with high sensor reliability ($f_{si} = 0$), an actuator fault-tolerant consensus controller u_i can be designed based on the $\hat{\xi}_i$ generated by the proposed FTAF-AFDO, which can fully decouple the impact of actuator faults on the control system (1). For example, an actuator fault-tolerant controller u_i can be designed as follows:

$$\begin{aligned}u_i(t) &= \left(\rho_i(t) + \varrho_i(t)\right)K\hat{\xi}_i(t) - \beta\tilde{h}_i(\hat{\xi}_i(t)) \qquad (19)\\ \varrho_i(t) &= \hat{\xi}_i^T(t)Q\hat{\xi}_i(t) \\ \dot{\rho}_i(t) &= \hat{\xi}_i^T(t)QBB^TQ\hat{\xi}_i(t) - \sigma_i\left(\rho_i(t) - 1\right) \\ \tilde{h}_i(\hat{\xi}_i(t)) &= \begin{cases} \frac{B^TQ\hat{\xi}_i(t)}{\left\|B^TQ\hat{\xi}_i(t)\right\|} & \text{if } \left\|B^TQ\hat{\xi}_i(t)\right\| > \kappa_i \\ \frac{B^TQ\hat{\xi}_i(t)}{\kappa_i} & \text{if } \left\|B^TQ\hat{\xi}_i(t)\right\| \leq \kappa_i \end{cases} \qquad (20)\end{aligned}$$

Algorithm 1 Detect Mechanism for Sensor Faults in Agent i

Input: $u_i(t)$; $y_i(t)$; τ; relative output information: $\bar{\varphi}_i(t)$;

Output: Sensor fault detection results;

1: Calculate L_1 based on the pole placement method that satisfies the condition C_2 in Theorem 1.
2: Calculate H_1, H_3 according to $H_1 = I_{m_x} + H_3 C$ and $H_3 = -B\left[(CB)^T CB\right]^{-1}(CB)^T$.
3: Calculate L_3 according to the condition C_3 in Theorem 3.
4: Optimize and solve the matrices H_{21} and H_{22} so that $\bar{A}_c$ is stable and $\left[\begin{array}{cc} \bar{C} & \exp\left(\bar{A}_c\tau\right)\bar{C} \end{array}\right]$ is invertible.
5: Calculate $\bar{L}_c$ according to the condition C_1 in Theorem 3.
6: Construct the FTAF-AFDO (5) and generate the fault indication signal $\Delta\hat{\xi}_i(t)$.
7: After time τ, if the amplitude of $\Delta\hat{\xi}_i(t)$ is non-zero, a sensor fault f_{s_3} has occurred in the system; otherwise, no sensor fault is present.

Note: Based on the $\hat{\xi}_i$ generated by the FTAF-AFDO, one can construct an actuator fault-tolerant controller (19).

where $\hat{\xi}_i(t)$ is designed based on (17) and the relevant stability proof can be found in Lemma 1.

Lemma 1: When $f_{a_i} \neq 0$ and $f_{s_i} = 0$, the consensus tracking problem of the multi-agent system (1) can be solved by the attack-free adaptive protocol (19).

Proof: The proof of Lemma 1 follows a similar approach to Theorem 5 in [12]. Since the proposed actuator fault-tolerant controller is an extension of the FTAF-AFDO and due to space limitations, the proof is omitted.

In summary, the sensor fault detection mechanism based on the proposed FTAF-AFDO is outlined in Algorithm 1.

IV. Simulation

This section will use a multi-agent system composed of six transport aircrafts [9] flying in formation as a test case to validate the effectiveness of the proposed FTAF-AFDO. The communication topology between aircrafts is shown in Fig. 3. The short-term dynamic model of i-th single transport aircraft is as follows:

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bu_i(t) + B_a f_{a_i}(t) \\ y_i(t) = Cx_i(t), \quad i = 1, \ldots, 6 \end{cases}$$

where $A = \left[\begin{array}{cc} -0.8060 & 1.0 \\ -9.1486 & -4.59 \end{array}\right], B = \left[\begin{array}{c} -0.04 \\ -4.59 \end{array}\right], B_a = \left[\begin{array}{c} 0.01 \\ 1 \end{array}\right], C = \left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array}\right]$. The attack-free consensus controller u_i is designed with reference to (19), where $\beta = 10, \sigma_i = 0.1, \kappa_i = 0.05$, and $\rho_i(0) = 1, i = 1, 2 \cdots, 6$ and $Q = \left[\begin{array}{cc} 0.1011 & 0.0456 \\ 0.0456 & 0.0372 \end{array}\right]$. The initial states of the six transport aircraft are set randomly.

Based on Algorithm 1, the parameter matrices for the proposed FTAF-AFDO are derived as follows:

$$\bar{A}_c = \left[\begin{array}{cccc} -1.2407 & 0.6536 & 0 & 0 \\ -0.0257 & -0.0118 & 0 & 0 \\ 0 & 0 & -1.3816 & 1.0637 \\ 0 & 0 & 0.2768 & -0.2573 \end{array}\right]$$

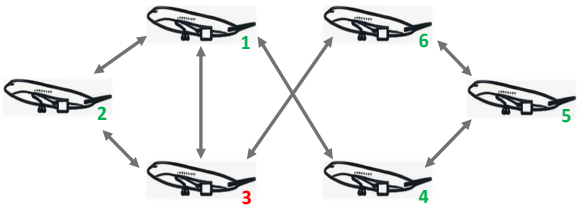


Fig. 3. The communication graph of the transport aircrafts.

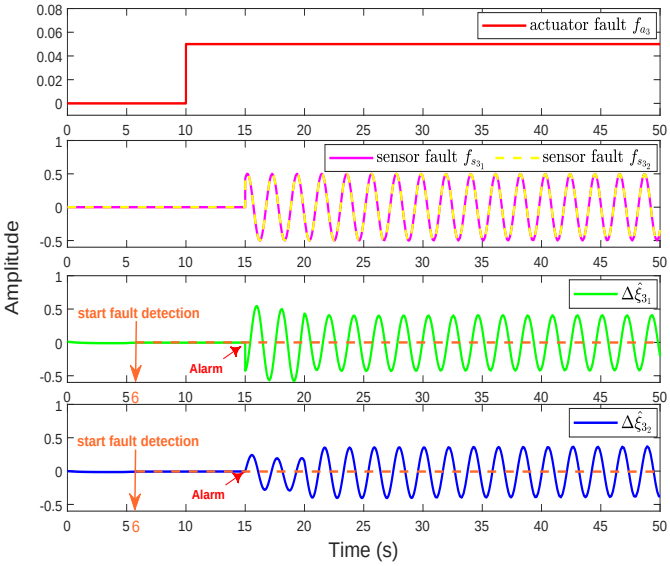


Fig. 4. Sensor fault indication signals $\Delta\hat{\xi}_{3_1}$, $\Delta\hat{\xi}_{3_2}$ generated by the FTAF-AFDO under sensor faults f_{s_3}, actuator faults f_{a_3}.

$$\bar{B}_c = \left[\begin{array}{cccc} 0.5201 & 0.0320 & 0.6645 & -0.2727 \\ 1.0291 & -0.0093 & 1.0278 & -0.0066 \end{array}\right]^T$$

$$\bar{L}_c = \left[\begin{array}{cccc} 3.5069 & -0.1036 & 3.2180 & 0.5058 \\ -0.0480 & 0.0011 & -0.0455 & -0.0043 \end{array}\right]^T$$

$$\bar{D}_c = \left[\begin{array}{cccc} 4,9202 & 4.1764 & -3.9202 & -4.1764 \\ 3.3880 & 7.1082 & -3.3880 & -6.1082 \end{array}\right],$$

and τ is set as $\tau = 6$.

In the simulation, we assume that only the third transport aircraft experiences an actuator fault f_{a3} at 10 seconds and a sensor fault f_{s3} at 15 seconds, where

$$f_{a_3}(t) = \begin{cases} 0, & t < 10 \\ 0.05, & t \geq 10 \end{cases} \tag{21}$$

$$f_{s_3}(t) = \begin{cases} \left[\begin{array}{c} 0 \\ 0 \end{array}\right], & t < 15 \\ \left[\begin{array}{c} 0.5\sin(0.4772t) \\ 0.5\sin(0.4772t) \end{array}\right], & t \geq 15. \end{cases} \tag{22}$$

The sensor faults f_{s_3}, actuator faults f_{a_3}, and the fault indication signals $\Delta\hat{\xi}_{3_1}$, $\Delta\hat{\xi}_{3_2}$ generated by the FTAF-AFDO constructed in the third transport aircraft are specifically shown in Fig. 4. The orange dashed lines in the third and fourth subplots represent the sensor fault detection threshold, which is set to 0.

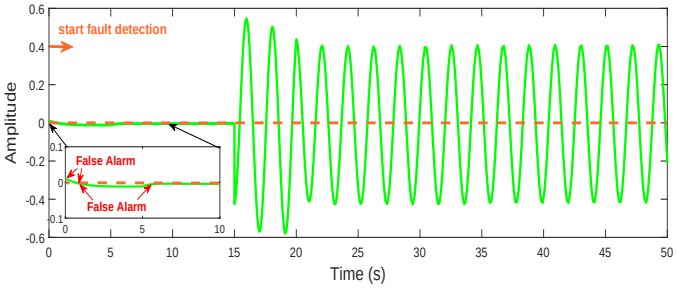


Fig. 5. Sensor fault indication signals $\Delta\hat{\xi}_{3_1}$ generated by the FTAF-AFDO under f_{s_3} and f_{a_3}: The convergence process of the observer error system (0-6s) is incorrectly detected as a sensor fault.

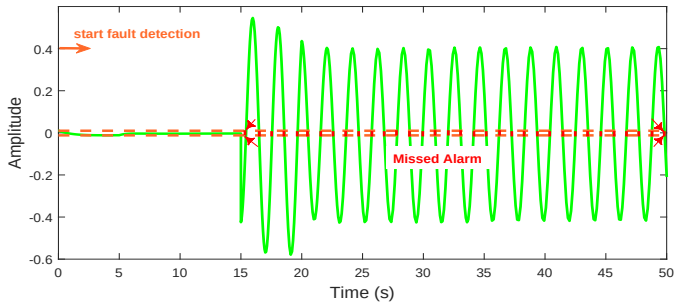


Fig. 6. Sensor fault indication signals $\Delta\hat{\xi}_{3_1}$ generated by the FTAF-AFDO under f_{s_3} and f_{a_3}: Threshold design considering convergence process leads to partial sensor fault misses.

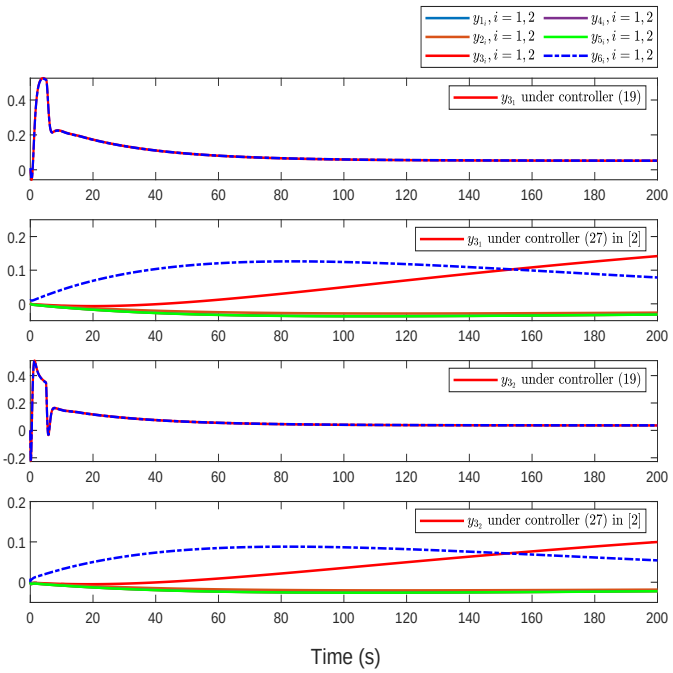


Fig. 7. Comparison of output signals $y_{i_1}, y_{i_2}, i = 1, 2, \cdots, 6$ of the six transport aircraft under the proposed actuator fault-tolerant controller (19) and the controller proposed in [12] when only f_{a_3} occurs.

From the analysis of Fig. 4, we can draw three main conclusions:

1) By analyzing the amplitude of sensor fault indication signals $\Delta\hat{\xi}_{3_1}$ and $\Delta\hat{\xi}_{3_2}$ within 0-10 s, we can conclude that when no fault occurs in the system, the amplitudes of $\Delta\hat{\xi}_{3_1}$ and $\Delta\hat{\xi}_{3_2}$ converge to 0 within 5 s. This indicates that the proposed FTAF-AFDO can achieve fixed-time convergence of $\Delta\hat{\xi}_{3_i}, i = 1, 2$.

2) By analyzing the amplitude of sensor fault indication signals $\Delta\hat{\xi}_{3_1}$ and $\Delta\hat{\xi}_{3_2}$ within 10-15 s, we can conclude that when an actuator fault f_{a_3} occurs in the system, the amplitude of the sensor fault indication signals $\Delta\hat{\xi}_{3_i}, i = 1, 2$ generated by the proposed FTAF-AFDO remains at 0. This demonstrates that the fault indication signals $\Delta\hat{\xi}_{3_i}, i = 1, 2$ are completely decoupled from the actuator fault f_{a_3}.

3) By analyzing the amplitude of sensor fault indication signals $\Delta\hat{\xi}_{3_1}$ and $\Delta\hat{\xi}_{3_2}$ after 15 s, we can conclude that when the sensor measuring the relative output information between aircrafts in transport aircraft 3 experiences a fault, the fault indication signals $\Delta\hat{\xi}_{3_i}, i = 1, 2$ generated by the proposed FTAF-AFDO show non-zero amplitudes. This indicates that the sensor fault was accurately detected.

Fig. 5 shows the false alarms caused by performing fault detection from the initial moment, misinterpreting the convergence process of the observer's internal error system as a sensor fault. Designing the fault detection threshold by considering the amplitude characteristics of the convergence process effectively mitigates false alarms, as shown in Fig. 6. However, adjusting the detection threshold introduces the risk of missed alarms. This risk becomes more significant, particularly when the amplitude or rate of change of the sensor fault is small, as the detection threshold increases. A comparative analysis of the detection results in Fig. 4 to Fig. 6 underscores the necessity of studying a fixed-time fault detection observer.

Remark 12: The proposed FTAF-AFDO simplifies the difficulty for operators in detecting sensor faults and has potential for practical applications. 1) For disturbance-free scenarios, operators only need to observe whether the amplitude of the sensor fault indication signal generated by the FTAF-AFDO is zero after time τ in order to determine whether a sensor fault has occurred in the system. 2) When noise is present in the system, operators can also design a fault detection threshold based on characteristics such as the mean and variance of the fault indication signal's amplitude after time τ when no fault occurs. The fixed-time convergence ensures that after time τ, the fault indication signal no longer contains estimation errors, which simplifies the design of the fault detection threshold and facilitates improving fault detection accuracy.

Additionally, when only the sensor fault f_{a_3} occurs, the comparison of output signals y_{i_1} and $y_{i_2}, i = 1, 2$ of the different transport aircraft under the proposed actuator fault-tolerant consensus controller (19) and the consensus controller [12] is shown in Fig. 7. From the analysis of Fig. 7, it is evident that when an actuator fault occurs in transport aircraft 3, the proposed consensus controller (19) effectively decouples the impact of the actuator fault, allowing transport aircraft 3 to maintain consistent output signals with the other aircraft. However, the traditional consensus controller [12] does not have actuator fault tolerance. Consequently, when f_{a_3} occurs, the output signal of transport aircraft 3 diverges from that of

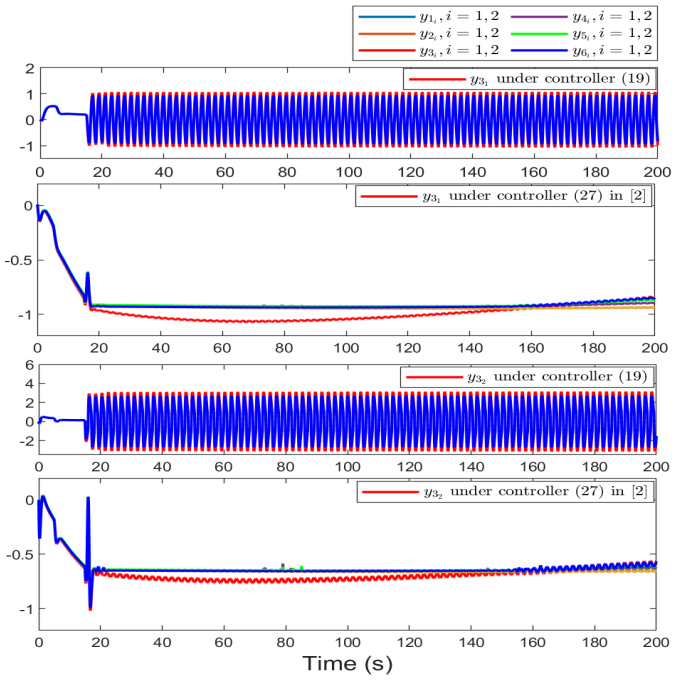


Fig. 8. Comparison of output signals $y_{i_1}, y_{i_2}, i = 1, 2, \cdots, 6$ of the six transport aircraft under the proposed actuator fault-tolerant controller (19) and the controller proposed in [12] when f_{a_3} and f_{s_3} occur.

the other aircraft.

Remark 13: While the proposed actuator fault-tolerant consensus controller and the traditional consensus controller are similar in form to (19), the key distinction lies in the estimation signal $\hat{\xi}_i$. Our proposed FTAF-AFDO generates $\hat{\xi}_i$, which not only accurately estimates the consensus error ξ_i within a fixed time but also completely decouples the actuator fault f_{a_3}, a capability the traditional observer [2] cannot achieve.

When both sensor fault f_{a_3} and sensor fault f_{s_3} occur, the comparison of output signals y_{i_1} and $y_{i_2}, i = 1, 2$ of the different transport aircraft under the proposed controller (19) and the traditional controller [12] is shown in Fig. 8. This result further demonstrates that the proposed controller possesses strong fault tolerance for actuator failures and emphasizes the importance of designing actuator fault-tolerant controllers. In the multi-agent systems studied, when the sensor of one agent fails, the other agents can still achieve new synchronization by treating it as a virtual "leader." However, if an actuator within an agent fails, that agent will be unable to maintain high-precision synchronization with the others.

V. Conclusion

This paper proposes a fixed-time attack-free observer designed for sensor fault detection. The proposed FTAF-AFDO achieves complete decoupling of the fault indication signal from actuator faults without requiring any prior knowledge of the actuator fault itself. Furthermore, after a fixed time τ, the generated fault indication signal is guaranteed to be fully decoupled from estimation errors, providing information solely related to the sensor fault. This approach enhances fault detection reliability while simplifying the detection process. Additionally, based on the proposed FTAF-AFDO, this paper also introduces an actuator fault-tolerant consensus controller. The controller not only fully decouples the impact of actuator faults on the control system, but, like the FTAF-AFDO, it does not require inter-agent information exchange, making both immune to attacks.

As a next step, we will focus on developing an attack-free consensus controller for sensor fault isolation based on the propopsed observer, further enhancing system robustness.

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