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Fault tolerant multivehicle formation control framework with applications in multiquadrotor systems

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Compared with the traditional monolithic systems, a group of vehicles operating cooperatively in a formation can achieve greater efficiency and capability [1, 2]. However, faults may occur more frequently in multivehicle formations because a large number of controllers, sensors, and communication equipment exist [3]. Occasionally, a fault occurring in one vehicle of the formation may deteriorate the system performance or even cause catastrophic accidents. Thus, fault-tolerant formation control schemes are indispensable to achieve a reliable and safe operation.

Despite the critical requirement, only a few studies [4–6] have been performed. These studies on fault-tolerant formation control are extremely inadequate. First, external disturbance and measurement noise have not been considered. Next, the channel noise between adjacent vehicles are often ignored, which is, however, inevitable. Finally, the full-state feedback between neighbors may further increase the communication burden [7]. Motivated by the observations above, we herein investigated the fault-tolerant formation problem of stochastic multivehicle systems with actuator faults. Distributed observers and adaptive fault estimators have been constructed for estimating the immeasurable states and faults, and a novel fault-tolerant scheme has been proposed to drive vehicles to the desired formation configuration.

Problem formulation. Consider a formation of N vehicles; the dynamics of the i-th ($i = 1, 2, \ldots, N$) vehicle is

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bu_i(t) + Ff_i(t) + Ew_i(t), \\ y_i(t) = Cx_i(t) + v_i(t), \end{cases} \tag{1}$$

where $x_i(t)$, $u_i(t)$, $y_i(t)$, and $f_i(t)$ are the state, control input, the measurement, and fault, respectively. $w_i(t)$ and $v_i(t)$ are the disturbance and measurement noise, respectively.

For guaranteeing the scheduled formation configuration, the desired formation dynamic of the i-th vehicle can be described as

$$\dot{x}_i^r(t) = Ax_i^r(t). \tag{2}$$

According to [4] and the references therein, a requirement for the matrix A is that the pair (A, I) is observable, in which I is an identity matrix with the proper dimensions. The objective is to design a fault-tolerant formation protocol, such that

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all vehicles track the desired formation trajectories in mean square, and the desirable disturbance rejection performance can be maintained simultaneously.

Primary results. For designing the formation control law, stating $x_i(t)$ is necessary, which is estimated by the following observer:

$$\begin{cases} \dot{\hat{x}}_i(t) = A\hat{x}_i(t) + Bu_i(t) + F\hat{f}_i(t) \\ \qquad + \bar{L}[y_i(t) - \hat{y}_i(t)], \\ \hat{y}_i(t) = C\hat{x}_i(t). \end{cases} \tag{3}$$

Using the observer above, an adaptive fault estimator is designed as

$$\dot{\hat{f}}_i(t) = \Gamma R^{\mathrm{T}} e_{y,i}(t) - \sigma\Gamma\hat{f}_i(t), \tag{4}$$

where $e_{y,i}(t) \triangleq y_i(t) - \hat{y}_i(t)$ is the output estimation error, and $e_{f,i}(t) \triangleq f_i(t) - \hat{f}_i(t)$ is the fault estimation error. The parameters $\Gamma = \Gamma^{\mathrm{T}} > 0$, R, and $\sigma > 0$ are to be designed.

For the vehicle formation (1), the fault tolerant formation is guaranteed if the performance variable $\bar{e}_i(t) \triangleq [e_i^{\mathrm{T}}(t), e_{x,i}^{\mathrm{T}}(t), e_{f,i}^{\mathrm{T}}(t)]^{\mathrm{T}}$ satisfies $J = \int_0^\infty \mathbb{E}\|\bar{e}(t)\|^2 - \gamma^2\beta^2 \mathrm{d}t \leqslant 0$, in which $e_i(t) \triangleq x_i(t) - x_i^r(t)$, $e_{x,i}(t) \triangleq x_i(t) - \hat{x}_i(t)$, the parameter $\beta > 0$ depends on β_w, β_f, $\beta_{\dot{f}}$ (the upper bounds of $w(t)$, $f(t)$, and $\dot{f}(t)$, respectively). γ is a positive constant. In the following, we define $e_x(t) \triangleq [e_{x,1}^{\mathrm{T}}(t), e_{x,2}^{\mathrm{T}}(t), \ldots, e_{x,N}^{\mathrm{T}}(t)]^{\mathrm{T}}$, $e_f(t) \triangleq [e_{f,1}^{\mathrm{T}}(t), e_{f,2}^{\mathrm{T}}(t), \ldots, e_{f,N}^{\mathrm{T}}(t)]^{\mathrm{T}}$, $\bar{e}(t) \triangleq [\bar{e}_1^{\mathrm{T}}(t), \bar{e}_2^{\mathrm{T}}(t), \ldots, \bar{e}_N^{\mathrm{T}}(t)]^{\mathrm{T}}$. To guarantee the primary result of this study, Assumptions 1 and 2 are required.

Assumption 1. Disturbance and measurement noise are independent white Gaussian noises with bounded amplitudes.

Assumption 2. The actuator fault and its derivative are bounded. The multivehicle system is strongly connected and balanced.

In some existing studies, such as [8], the strongly connected and balanced topology of multiagent systems has been used.

In the current work, the actuator fault is considered. Without the loss of generality, we assume that $F = [B_{q_1}, B_{q_2}, \ldots, B_{q_q}]$, where B_{q_j} $(j = 1, 2, \ldots, q)$ is the q_j-th column of matrix B. Therefore, a matrix $\bar{F}$ exists that satisfies $B\bar{F} = F$. In fact, $\bar{F} \triangleq [\bar{f}]_{i,j}$ is the matrix whose elements are zeros except for $\bar{f}_{q_i,q_i} = 1$ $(i = 1, 2, \ldots, q)$.

Based on the assumptions above, the state observers, and the fault estimators, the primary conclusion can be obtained as follows.

Theorem 1. The desired formation configuration can be attained for the multivehicle system using the following fault-tolerant control scheme:

$$u_i(t) = cK\sum_{j\in N_i} a_{ij}\big(1 + \sigma_{ij}\xi_{ij}(t)\big)\big(\hat{x}_j(t) - \hat{x}_i(t) - \Delta_{ij}(t)\big) + cg_iK\big(x_i^r(t) - \hat{x}_i(t)\big) - \bar{F}\hat{f}_i(t), \tag{5}$$

where the gain matrices K, $\bar{L}$, R, Γ and parameters c and σ satisfy the conditions:

$$K = B^{\mathrm{T}}P^{-1}, \quad R^{\mathrm{T}}C = F^{\mathrm{T}}P^{-1}, \tag{6}$$

$$c \leqslant \frac{\lambda_{\min}(\tilde{H})\lambda_{\min}(P)}{4\sigma^2\lambda_{\max}(B^{\mathrm{T}}B)\lambda_{\max}(\tilde{L})}, \tag{7}$$

$$AP + PA^{\mathrm{T}} + 2P^2 + \frac{1}{\gamma_1^2}EE^{\mathrm{T}} + \frac{1}{\gamma_2^2}FF^{\mathrm{T}} - \frac{1}{2}\lambda_{\min}(\tilde{H})(I \otimes BB^{\mathrm{T}}) < 0, \tag{8}$$

$$(A - \bar{L}C)P + P(A - \bar{L}C)^{\mathrm{T}} + 2P^2 + \frac{1}{\gamma_3^2}EE^{\mathrm{T}} + c\lambda_{\max}(\tilde{H})BB^{\mathrm{T}} < 0, \tag{9}$$

$$\frac{1}{\gamma_4^2}\Gamma^{-1}\Gamma^{\mathrm{T}} + \frac{1}{\gamma_5^2}\sigma^2 I - 2\sigma I + (\gamma_2^2 + 1)I < 0, \tag{10}$$

where P is a symmetric positive definite matrix; γ_1, γ_2, γ_3, γ_4, and γ_5 are positive constants. I is the identity matrices with proper dimensions. $\bar{L}$, R, Γ are the intermediate variables (matrices).

$\Delta_{ij}(t) \triangleq x_j^r(t) - x_i^r(t)$, $\sigma_{ij}\xi_{ij}(t) \in \mathbb{R}$, and $\sigma_{ij} \geqslant 0$ are the noise intensities. $\xi_{ij}(t)$ is a random variable to show the stochastic behavior of the channel noises. $\tilde{H} = \frac{1}{2}(H + H^{\mathrm{T}})$, in which $H = \mathcal{L} + \mathcal{G}$, $\mathcal{L}$ is the Laplacian matrix of the multivehicle system, $\mathcal{G} = \mathrm{diag}\{g_1, g_2, \ldots, g_N\}$.

Proof. Design the following Lyapunov function:

$$V(t) = e^{\mathrm{T}}(t)(I_N \otimes P^{-1})e(t) + e_x^{\mathrm{T}}(t)(I_N \otimes P^{-1})e_x(t) + e_f^{\mathrm{T}}(t)(I_N \otimes \Gamma^{-1})e_f(t). \tag{11}$$

Using the It$\hat{o}$ formula as

$$\mathrm{d}V(x,t) = \frac{\partial V}{\partial t}\mathrm{d}t + \frac{\partial V}{\partial x^{\mathrm{T}}}F\mathrm{d}t + \frac{1}{2}\mathrm{tr}\left(G^{\mathrm{T}}\frac{\partial^2 V}{\partial x\partial x^{\mathrm{T}}}G\right)\mathrm{d}t + \frac{\partial V}{\partial x^{\mathrm{T}}}G\mathrm{d}w(t). \tag{12}$$

Subsequently, using the time derivative of $V(t)$, we can obtain the conclusions in Theorem 1.

Experimental results of quadrotors. An experimental platform is used to demonstrate the fault-tolerant formation scheme obtained herein. As shown in Figure 1(a), it consists of a ground control station and three quadrotors embedded with a flight control system. The interaction topology and the desired formation configuration of the formation system are shown in Figure 1(a).

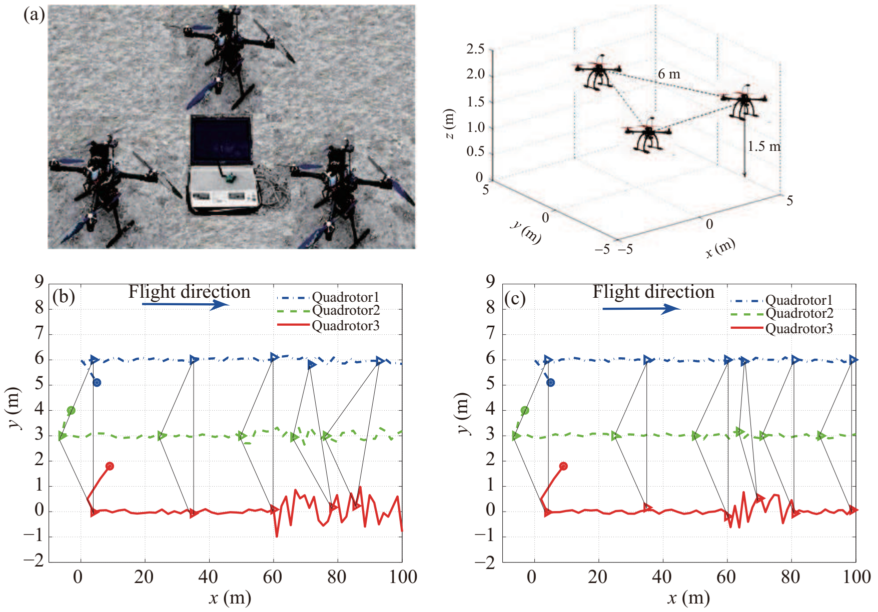

Figure 1 (Color online) Quadrotor formation experimental results. (a) Experimental platform and desired formation configuration; (b) formation trajectories without FTC; (c) formation trajectories with FTC.

For simplicity, all quadrotor flights are set in the x-y plane. The height and yaw angle of each vehicle are constants. The desired formation configuration is that the three quadrotors form an isosceles triangle (see Figure 1(a)) and fly in straight lines at 3 m intervals. At some instant, the fault occurs in quadrotor 3. The fault in quadrotor 3 means that the actuators exert additional but undesirable control signals on the quadrotor. The root cause of the actuator fault considered here may be the abnormality of the electrical and mechanical devices in the motors and steering engines of the vehicles. The formation experimental results without and with fault-tolerant control are shown in Figures 1(b) and (c), respectively, from which we observed that the desired formation configuration of the multivehicle system can be guaranteed by the proposed fault-tolerant control scheme.

Conclusion. We investigated the fault-tolerant formation control problem of multivehicle systems with actuator faults, disturbance, measurement, and channel noises. A novel distributed observer and an adaptive fault estimator were proposed to design the fault-tolerant control scheme for driving all the vehicles to the desired formation configuration with the prescribed attenuation level.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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