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Robust Formation Control Based on Leader-Following Consensus in Multi-Agent Systems With Faults in the Information Exchange: Application in a Fleet of Unmanned Aerial Vehicles

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ABSTRACT In this paper, a robust leader-following consensus protocol for multi-agent systems (MASs) subject to faults in the information exchange and disturbance is presented. The problem under consideration is to guarantee the convergence of the agent trajectories to a leader agent when all the agent followers are under faults in the information exchange as smooth time-varying delays and disturbances. The main contribution in this paper is the design of a robust leader-following control through the Lyapunov approach and an optimal $\mathscr{H}_\infty$ criterion such that all agents follow a virtual leader agent despite faults in the information exchange and disturbances. Linear matrix inequalities (LMIs)-based conditions are obtained whose solution allows computing the robust controller gain. In order to show the effectiveness of the proposed approach, numerical examples are carried out comparing a state-of-the-art approach and the proposed strategy in a fleet of unmanned aerial vehicles (UAVs) subject to wind turbulence which are shown to achieve the formation control.

INDEX TERMS Consensus, communication faults, leader-following consensus, multi-agent systems.

I. INTRODUCTION

Nowadays, there are a wide range of applications found in the literature for unmanned aerial vehicles (UAVs) such as surveying and mapping [1], search and rescue [2], reconnaissance [3], cargo transport [4], or light shows [5], among others [6]. The use of multiple UAVs has become in a topic of interest in the last decades due to the advantage accomplishing missions that a single UAV cannot perform [6]. Coordination of multiple UAVs is a particular case of multiple robot coordination. The focus of coordination of multiple robots is to work together to accomplish a given mission by moving around in the environment [7]. In the same way, the focus of multiple UAVs is to coordinate the fleet in the environment to complete some missions. Multi-agent systems (MASs) theory has been used to solve the coordination control problems in multiple UAVs such as formation control [8], reinforcement learning [9], swarms in the agriculture [10], formation tracking [11], and among others cooperative missions [12]. The objective of synchronization in cooperative MASs is often to reach a common value in relation to the agents' states (UAVs' states). Consensus and leader-following consensus algorithms are used to synchronize the MASs [13], [14]. Consensus algorithms are used to reach an agreement in relation

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to the states of the other agents [15]–[17]. On the other hand, leader-following consensus algorithms are considered when all the agents must follow a physical or virtual leader agent [18].

Formation control in MASs consists to reach desired shapes [19]. This approach has been inspired by the behavior of some animals which consists of moving from one place to another using a defined formation [20]. Formation control can be used in a fleet of UAVs in order to achieve goals as cargo transport [4] or light shows [5]. According to [19]–[22], formation control can be achieved by using consensus algorithms. Consensus algorithms are extended to solve the formation control problem for mobile MASs by correctly satisfying some constraints. Energy-constraint formation is studied in [23] based on a formation function. A leader-following formation control is implemented in [11] for a group of quadrotors subject to switching topologies, and in [24], nonlinearities and disturbances are considered for multiple quadrotors. A time-varying formation control is designed for MASs subject to disturbances in [25]. However, the problem of faults in the exchange of information is not considered in [11], [24], and [25].

Recently, leader-following consensus for MASs have attracted interest due to its potential accomplishing missions. Several research works related to MASs have considered the focus on event-triggered approaches [26], additive, multiplicative noises, [27], time delays [28], switching topologies [29], among others. Nevertheless, it is well known that in real implementations there are several challenges to consider, such as faults in actuators, sensors, parameters or in communication; disturbances, parameter uncertainties, or measurement noise, which affect the consensus performance. A key point in leader-following consensus is the information exchange through digital networks [30]. However, delays, bandwidth limitations, or packet losses are challenges in real applications [31]. Delays is one of the most addressed problems for this type of systems considering additive, multiplicative, and measurement noises [27], [32], in multi-agent chaotic and Euler-Lagrange systems under switching topologies [33], [34], self-triggered and even-triggered mechanism [35]–[38], adaptive approaches in heterogeneous first-order MASs [39], or event-triggered mechanism with constant delays [40]. Time-varying delays affect the stability of the consensus [41]. The problem of faults in the information exchange has not been widely studied when a degradation in the communication is considered. The information exchange is crucial in order to achieve the desired final formation using consensus algorithms. In [42], communication faults are modeled as a modification in the weights of the adjacency matrix as a result of a malfunction in the information exchange.

Rejection of disturbances is one of the most important challenges in controller design [43]. Disturbances affect the performance of the controller [44] and the estimation [45]. MASs are subject to these type of undesired inputs which disturb the performance of the consensus [46]. To achieve a consensus in the context of MASs means that the agents are synchronized with respect to their states. If the performance of the consensus is affected by disturbances or uncertainties the mission of synchronization are not well executed. In order to reject external disturbances in multi-agent systems, $\mathscr{H}_\infty$ optimization problem has been classically studied from the robust control theory in different MASs works [47]. $\mathscr{H}_\infty$ optimization problem has been studied for high-order multi-agent systems with Lipschitz nonlinearities and switching topologies [48], Lipschitz nonlinear multi-agent systems with uncertain dynamics [49], event-based strategy in second-order multi-agent systems [50], discrete-time nonlinear multi-agent systems with missing measurements [51], delays and parameter uncertainties [52]. Nevertheless, the aforementioned works have not considered degradation in the information exchange dependent on the distances between agents.

In contrast with [11], [23], [24], [30], and [25], this paper considers the $\mathscr{H}_\infty$ optimization problem in MAS subject to faults in the exchange of information as smooth-varying delays. This paper extends the approach presented in [30] to a robust control gain that guarantees stability in spite of faults in the information exchange and disturbances. Unlike [30], the main contribution in this paper is the design of a robust leader-following control for MASs subject to disturbance and faults in the information exchange. Linear matrix inequalities (LMIs)-based conditions are obtained through the Lyapunov approach and an optimal $\mathscr{H}_\infty$ criterion whose solution allow the compute of a robust control gain. The effectiveness of this proposed strategy is illustrated through numerical examples comprising a fleet of UAVs achieving a desired formation.

The paper is organized as follows. The problem statement is described in Section 2. The leader-following consensus analysis and the robust controller design are presented in Section 3. A numerical example considering the formation control problem is used to illustrate the effectiveness of the proposed strategy in Section 4. Finally, conclusions are presented in Section 5.

II. PROBLEM STATEMENT

Consider the following MAS:

$$\begin{aligned} \dot{p}_i(t) &= v_i(t), \\ \dot{v}_i(t) &= u_i(t) + \mathbf{w}_i(t), \end{aligned} \tag{1}$$

where $p_i(t)$, $v_i(t)$, $u_i(t) \in \mathbb{R}^{n_d}$ are respectively the position, velocity, and acceleration input in a n_d dimensional Euclidean space. $\mathbf{w}_i(t)$ is related with the wind turbulence. Let us define h_i, $h_j \in \mathbb{R}^{n_d}$ as the rigid desired formation, and the virtual agent dynamics as follows:

$$\dot{p}_r(t) = v_r(t), \tag{2}$$

where $p_r(t)$ and $v_r(t) \in \mathbb{R}^{n_d}$ are respectively the position and velocity of the virtual leader. The virtual leader is manipulated through its velocity. Then, the error between the agent i and the virtual leader agent is defined as $\tilde{p}_i(t) = p_i(t) - p_r(t)$,

$\tilde{v}_i(t) = v_i(t) - v_r(t)$, and $\delta_i(t) = \left[\tilde{p}_i(t)^T - h_i^T, \tilde{v}_i(t)^T\right]^T$, thus the error dynamic (1) and (2) can be presented as follows:

$$\dot{\delta}_i(t) = A\delta_i(t) + Bu_i(t) + D_u\zeta_i(t),$$
$$A = \begin{bmatrix} 0_{n_d\times n_d} & I_{n_d} \\ 0_{n_d\times n_d} & 0_{n_d\times n_d} \end{bmatrix}, \quad B = \begin{bmatrix} 0_{n_d\times n_d} \\ I_{n_d} \end{bmatrix}, \; D_u = B. \quad (3)$$

where $\zeta_i(t) = [0, \mathbf{w}_i(t)]^T$. The classical leader-following formation control reported in [53], and [21] subject to faults in the information exchange is defined as follows:

$$u_i(t) = \sum_{j\in\mathcal{N}_i} a_{ij}\left[p_j(t-\tau_{ij}(t)) - p_i(t-\tau_{ij}(t)) - (h_j - h_i)\right] + \sum_{j\in\mathcal{N}_i} a_{ij}\left[v_j(t-\tau_{ij}(t)) - v_i(t-\tau_{ij}(t))\right] - (p_i(t) - p_r(t) - h_i) - (v_i(t) - v_r(t)) \quad (4)$$

where $\tau_{ij}(t)$ is the fault in the information exchange between agent i and its neighbors j which is considered as smooth delay [27]. The derivative of the fault information exchange is bounded less than one as presented the following assumption.

Assumption 1: $\dot{\tau}_{ij}(t) \leq d_\tau < 1, \forall i \neq j, j \in \mathcal{N}_i$.

$$\tau_{ij}(t) = \left(\beta_1 - \beta_1\mathbf{e}^{-\beta_2\|p_i(t)-p_j(t)\|}\right) \times \left(0.5 + 0.5tanh\left(\beta_3(t-t_f)\right)\right) \quad (5)$$

Faults in the information exchange are considered dependent on the agent positions as reported in [30] which are described in (5), where $\beta_1 > 0$, $\beta_2 > 0$, and $\beta_3 > 0$; t_f is the fault occurrence time. The proposed function $\tau_{ij}(t)$ has been constructed such that the maximum value approximately is $\tau_{ij}(t) = \gamma$ because as the agents move away from each other, the function $\mathbf{e}^{-\beta_1\|p_i(t)-p_j(t)\|}$ decreases to zero. So that the faults are not abrupt, the term $\left(0.5 + 0.5tanh\left(\beta_2(t-t_f)\right)\right)$ is added. The domain of this term is between zero and one which depends on the time of fault occurrence. Communication faults can be associated to a degradation of the communication between agents in link with their distance. Similarly, such assumption has been considered in stochastic approach [54]. The control (4) is modified as follows:

$$u_i(t) = K_c\left[\sum_{j\in\mathcal{N}_i} a_{ij}\left(\delta_i(t-\tau_{ij}(t)) - \delta_j(t-\tau_{ij}(t))\right) + \alpha\delta_i(t)\right], \quad (6)$$

where $K_c \in \mathbb{R}^{n\times 2n}$ is the control gain to be designed and $\alpha > 0$ must be a positive constant.

Remark 1: According to [19]–[22], and [53], the reachable formation have to satisfy the constraints $Ah_i = 0, \forall i = 1, 2\ldots, N$. By correctly satisfying the above constraints, the controller and observer gains can be calculated with Theorem 1 to solve the leader-following formation control problem using the control law in (6).

The following assumptions hold for the reaming of this paper.

Assumption 2: The graph $\mathcal{G}$ is strongly connected.

Assumption 3: All the agents have information of the virtual leader states.

Based on (6), (3) becomes:

$$\dot{\delta}_i(t) = A\delta_i(t) + BK_c\sum_{j\in\mathcal{N}_i} a_{ij}\left(\delta_i(t-\tau_{ij}(t)) - \delta_j(t-\tau_{ij}(t))\right) + \alpha BK_c\delta_i(t) + D_u\zeta_i(t). \quad (7)$$

Let us define $\delta(t) = \left[\delta_1(t)^T, \delta_2(t)^T, \ldots, \delta_N(t)^T\right]^T$, $\delta(t-\tau(t)) = \left[\delta_1(t-\tau_{1j}(t))^T, \delta_2(t-\tau_{2j}(t))^T, \ldots, \delta_N(t-\tau_{Nj}(t))^T\right]^T$, and $\zeta(t) = \left[\zeta_1(t)^T, \zeta_2(t)^T, \ldots, \zeta_N(t)^T\right]^T$, then, the synchronization error dynamic (7) is rewritten using the Kronecker product as follows:

$$\dot{\delta}(t) = (I_N \otimes (A + \alpha BK_c))\,\delta(t) + (\mathcal{L}\otimes BK_c)\,\delta(t-\tau(t)) + (I_N\otimes D_u)\,\zeta(t). \quad (8)$$

Lemma 1 [55]: The Laplacian matrix $\mathcal{L}$ associated with an undirected graph $\mathcal{G}$ has at least one zero eigenvalue and all of the nonzero eigenvalues are real positive.

The problem under consideration in this paper is to design a robust leader-following controller for the MASs subject to faults in the information exchange and disturbances such that all agents follow the virtual leader with $\mathcal{H}_\infty$ performance.

III. CONSENSUS ANALYSIS AND SYNTHESIS OF THE CONTROLLER

The following theorem provides LMI-based conditions to guarantee a robust leader-following consensus for the MAS (1) subject to communication faults and disturbances.

Theorem 1: Given the non-zero eigenvalues $\lambda_i(\mathcal{L})$, $i = 2, 3, \ldots, N$, scalars $\alpha > 0$, $\mu_1 > 0$, $\mu_2 > 0$, and $\dot{\tau}_{ij} \leq d_\tau < 1$; the leader-following consensus is stable with an $\mathcal{H}_\infty$ performance if there exist matrices $P_1 = P_1^T > 0$, $P_2 = P_2^T > 0$, and K_c such that the following inequalities (9), as shown at the bottom of the page, hold.

$$\begin{bmatrix} \text{He}\{P_1 A\} + 2I - \frac{2P_1}{\mu_1} + P_2 & 0 & P_1 D_u & -\lambda_j P_1 B & \frac{P_1}{\mu_1} + \mu_1\alpha BK_c \\ * & -(1-d_\tau)P_2 + I & 0 & -\mu_2 K_c^T & 0 \\ * & * & -\gamma^2 I & 0 & 0 \\ * & * & * & -2\mu_2 I & 0 \\ * & * & * & * & -I \end{bmatrix} < 0 \quad (9)$$

Proof: Let us define the following Lyapunov functional:

$$V_\tau = \delta(t)^T (I_N \otimes P_1)\delta(t) + \int_{t-\tau}^{t} \delta(s)^T (I_N \otimes P_2)\delta(s)ds. \tag{10}$$

The derivative of V_τ is given by:

$$\begin{aligned}\dot{V}_\tau &= 2\delta(t)^T (I_N \otimes P_1)\dot{\delta}(t) + \delta(t)^T (I_N \otimes P_2)\delta(t)\\ &\quad -(1-\dot{\tau}(t))\delta(t-\tau(t))^T (I_N \otimes P_2)\delta(t-\tau(t)).\end{aligned} \tag{11}$$

According to [56], (11) is negative-definite when

$$\begin{aligned}\dot{V}_d &= 2\delta(t)^T (I_N \otimes P_1)\dot{\delta}(t) + \delta(t)^T (I_N \otimes P_2)\delta(t)\\ &\quad -(1-d_\tau)\delta(t-\tau(t))^T (I_N \otimes P_2)\delta(t-\tau(t)) < 0.\end{aligned} \tag{12}$$

where $\dot{\tau}(t) \leq d_\tau < 1$ according to Assumption 1. Thus,

$$\begin{aligned}\dot{V}_d &= 2\delta(t)^T (I_N \otimes (P_1A + \alpha P_1BK_c))\delta(t)\\ &\quad +2\delta(t)^T (\mathcal{L} \otimes P_1BK_c)\delta(t-\tau(t))\\ &\quad +2\delta(t)^T (I_N \otimes P_1D_u)\zeta(t) + \delta(t)^T (I_N \otimes P_2)\delta(t)\\ &\quad -(1-d_\tau)\delta(t-\tau(t))^T (I_N \otimes P_2)\delta(t-\tau(t)).\end{aligned} \tag{13}$$

Let us perform a spectral decomposition such that $\mathcal{L} = TJT^{-1}$ with an invertible matrix $T \in \mathbb{R}^{N\times N}$ and a diagonal matrix $J = diag(\lambda_1 = 0, \lambda_2, \lambda_3, \ldots, \lambda_N) \in \mathbb{R}^{N\times N}$. Let us define the following change of coordinates:

$$\begin{aligned}\varphi(t) &= \left(T^{-1} \otimes I_N\right)\delta(t),\\ \varphi(t-\tau(t)) &= \left(T^{-1} \otimes I_N\right)\delta(t-\tau(t)),\\ \omega(t) &= \left(T^{-1} \otimes I_N\right)\zeta(t).\end{aligned} \tag{14}$$

Replacing (14) in (13) leads to:

$$\begin{aligned}\dot{V}_d &= 2\varphi(t)^T (I_N \otimes (P_1A + \alpha P_1BK_c))\varphi(t)\\ &\quad +2\varphi(t)^T (J \otimes P_1BK_c)\varphi(t-\tau(t))\\ &\quad +2\varphi(t)^T (I_N \otimes P_1D_u)\omega(t) + \varphi(t)^T (I_N \otimes P_2)\varphi(t)\\ &\quad -(1-d_\tau)\varphi(t-\tau(t))^T (I_N \otimes P_2)\varphi(t-\tau(t)).\end{aligned} \tag{15}$$

By Lemma 1, (15) can be rewritten as follows:

$$\begin{aligned}\dot{V}_d = \sum_{j=2}^{N} \Big[&\varphi_j(t)^T \mathrm{He}\{P_1A + \alpha P_1BK_c\}\varphi_j(t)\\ &+2\varphi_j(t)^T \left(\lambda_j P_1BK_c\right)\varphi_j(t-\tau(t))\\ &+2\varphi_j(t)^T (P_1D_u)\omega_j(t) + \varphi_j(t)^T (P_2)\varphi_j(t)\\ &-(1-d_\tau)\varphi_j(t-\tau(t))^T (P_2)\varphi_j(t-\tau(t))\Big].\end{aligned} \tag{16}$$

According to the classical robust control theory [57], the following condition must be satisfied:

$$\|\psi(t)\| \leq \gamma \|\omega(t)\|, \tag{17}$$

where $\psi(t) = [\varphi(t)^T, \varphi(t-\tau)^T]^T$, $\omega(t) \in [0, \infty)$ in order to consider the $\mathscr{H}_\infty$ optimization problem. Then, based on the above condition, the following performance index is obtained:

$$\begin{aligned}J_d &= \int_0^\infty \sum_{j=2}^{N} \Big(\varphi_j(t)^T\varphi_j(t) + \varphi_j(t-\tau(t))^T\varphi_j(t-\tau(t))\\ &\qquad -\gamma^2\omega_j(t)^T\omega_j(t)\Big)dt,\\ J_d &\leq \int_0^\infty \sum_{j=2}^{N} \Big(\varphi_j(t)^T\varphi_j(t) + \varphi_j(t-\tau(t))^T\varphi_j(t-\tau(t))\\ &\qquad -\gamma^2\omega_j(t)^T\omega_j(t) + \dot{V}_d\Big)dt.\end{aligned} \tag{18}$$

Substituting (16) into (18) and let $\eta_j = [\varphi_j(t)^T, \varphi_j(t-\tau(t))^T, \omega_j(t)^T]^T$, then

$$J_d \leq \sum_{i=2}^{N} \eta_j^T \Theta_j \eta_j, \tag{19}$$

where Θ_j is defined in (20). When $\Theta_j < 0$ in (19) $\forall j = 2, 3, \ldots, N$, the leader-following problem is stable for the MAS (1) under communication faults in a consensus quadratically with an $\mathscr{H}_\infty$ norm bound γ by (6). Due to the product of decision variables, Θ_i presents a bilinear matrix inequality and the controller cannot be calculated using conventional tools. With the goal of obtaining simpler-to-handle LMIs, let use the Schur complement in (9) obtaining:

$$\Theta_j = \begin{bmatrix} \mathrm{He}\{P_1A + \alpha P_1BK_c\} + P_2 + I & \lambda_j P_1BK_c & P_1D_u\\ * & -(1-d_\tau)P_2 + I & 0\\ * & * & -\gamma^2 I \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} Q_1 & 0 & P_1D_u & -\lambda_j P_1B\\ * & -(1-d_\tau)P_2 & 0 & -\mu_2 K_c^T\\ * & * & -\gamma^2 I & 0\\ * & * & * & -2\mu_2 I \end{bmatrix} < 0. \tag{21}$$

where $Q_1 = \mathrm{He}\{P_1A\} + I - \frac{2P_1}{\mu_1} + \frac{P_1}{\mu_1} + P_2 + (\mu_1\alpha BK_c)^T(\mu_1\alpha BK_c)$. Multiplying (21) the left and the right sides by

$$\begin{bmatrix} I & 0 & 0 & 0\\ 0 & I & 0 & -K_c^T\\ 0 & 0 & I & 0 \end{bmatrix}$$

and its transpose, it is obtained:

$$\begin{bmatrix} Q_1 & \lambda_j P_1BK_c & P_1D_u\\ * & -(1-d_\tau)P_2 & 0\\ * & * & -\gamma^2 I \end{bmatrix} < 0. \tag{22}$$

Note that,

$$\begin{aligned}&\mathrm{He}\{P_1A + \alpha P_1BK_c\} + P_2 \leq \mathrm{He}\{P_1A + \alpha P_1BK_c\} + P_2\\ &\quad +\alpha^2 (P_1BK_c)^T (P_1BK_c)\\ &= \mathrm{He}\{P_1A\} + P_2 - \frac{P_1^2}{\mu_1^2} + \left(\frac{P_1}{\mu_1} + \alpha BK_c\right)^T \left(\frac{P_1}{\mu_1} + \alpha BK_c\right),\end{aligned} \tag{23}$$

where $\mu_1 > 0$. The following inequality is introduced:

$$\left(I - \frac{P_1}{\mu_1}\right)\left(I - \frac{P_1}{\mu_1}\right) \geq 0,$$
$$I - \frac{2P_1}{\mu_1} \geq -\frac{P_1^2}{\mu_1^2}. \tag{24}$$

Based on (24) and (23), it is obtained:

$$\text{He}\{P_1A + \alpha P_1BK_c\} + P_2 \leq \text{He}\{P_1A\} + I + P_2 - \frac{2P_1}{\mu_1} + \left(\frac{P_1}{\mu_1} + \alpha BK_c\right)^T\left(\frac{P_1}{\mu_1} + \alpha BK_c\right). \tag{25}$$

It is recovered (20) replacing (22) in (25). Hence, Theorem 1 is proved. □

Remark 2: Theorem 1 allows to compute the control gain reducing the malfunction effects in the faulty agents and the disturbances. If there exist such matrices the synchronization error is guaranteed stable, and the agents can reach the desired formation in spite of communication faults. This strategy can be used for one or all agents with communication faults.

Fig. 1 shows the steps to follow in order to design the proposed control.

In the following Section, a numerical example is presented to illustrate the effectiveness of the proposed approach considering a group of UAVs subject to faults in the exchange of information and disturbances as wind turbulence.

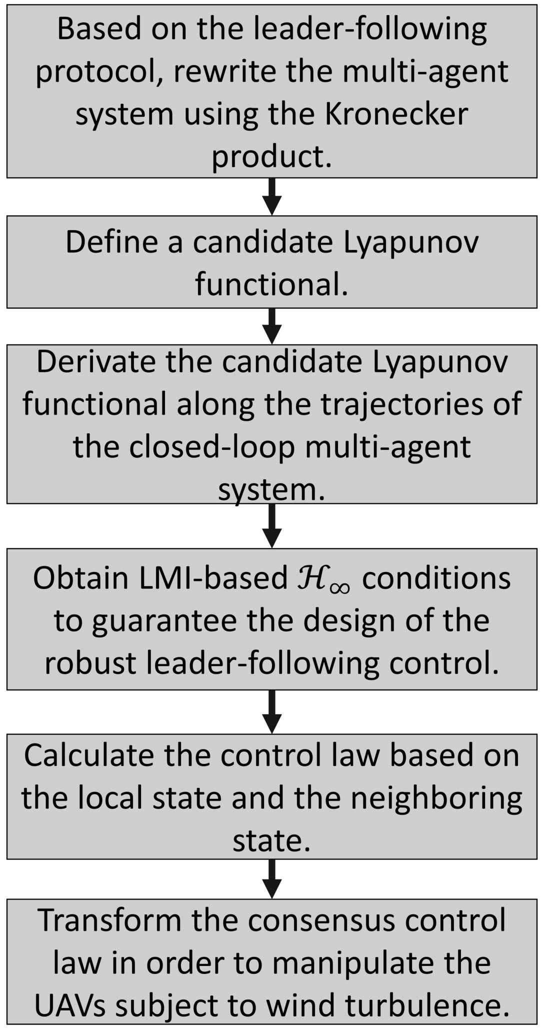


FIGURE 1. Steps for designing the robust control.

IV. NUMERICAL EXAMPLE: A FLEET OF UAVs WITH COMMUNICATION FAULTS

In order to show the effectiveness of the proposed control, the following numerical example presents a comparison between a classical leader-following formation control and our proposed control in a fleet of unmanned aerial vehicles (UAVs) subject to wind turbulence. Let us consider the basic motions of an UAV represented in Fig. 2. Four rotors with fixed angles represent four forces in each agent. The body fixed frame is assumed to be at the UAV gravity center. This body axis is related to the inertial frame by a position vector $(\mathbf{x}_i, \mathbf{y}_i, \mathbf{z}_i)$ and three Euler angles $(\phi_i, \theta_i, \psi_i)$. The dynamic model can be obtained via a Lagrange approach as it is reported in [59] and [60]. Using the force and moment balance, the motion equations can be written as follows:

$$\begin{aligned}
\ddot{\mathbf{x}}_i &= \frac{T_i(\cos\psi_i \sin\theta_i \cos\phi_i + \sin\psi_i \sin\phi_i)}{m_s} \\
\ddot{\mathbf{y}}_i &= \frac{T_i(\sin\psi_i \sin\theta_i \cos\phi_i - \cos\psi_i \sin\phi_i)}{m_s} \\
\ddot{\mathbf{z}}_i &= \frac{T_i(\cos\theta_i \cos\phi_i) - m_s g}{m_s} \\
\ddot{\phi}_i &= \frac{\dot{\theta}_i\dot{\psi}_i(J_y - J_z) + \tau_{\phi_i}}{J_x} \\
\ddot{\theta}_i &= \frac{\dot{\phi}_i\dot{\psi}_i(J_z - J_x) + \tau_{\theta_i}}{J_y} \\
\ddot{\psi}_i &= \frac{\dot{\phi}_i\dot{\theta}_i(J_x - J_y) + \tau_{\psi_i}}{J_z}
\end{aligned} \tag{26}$$

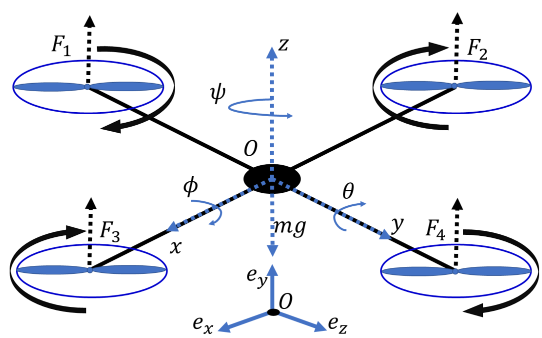


FIGURE 2. Quadrotor aircraft scheme [58].

where m_s is the UAV mass, g is the gravitational acceleration, T_i is the upward thrust force, J_x, J_y, J_z are the inertial of the UAV, Ω_r is the total sum of motor velocities, and J_r is the moment of rotational inertia around the axis of the propeller. In [58], Ω_r is considered as a disturbance because of the absence of sensors in the motors, thus, it is ignored for the design of controllers.

TABLE 1. **Desired final shape and the initial positions.**

Desired positions	Initial position	Initial velocity
$h_1 = [0, 0, 0]^T$	$p_1(0) = [-4, -1, 0]^T$	$v_1(0) = [0, 0, 0]^T$
$h_2 = [4, 0, 0,]^T$	$p_2(0) = [-1, 1, 0]^T$	$v_2(0) = [0, 0, 0]^T$
$h_3 = [6, 2\sqrt{3}, 0]^T$	$p_3(0) = [-2, -2, 0]^T$	$v_3(0) = [0, 0, 0]^T$
$h_4 = [4, 4\sqrt{3}, 0]^T$	$p_4(0) = [-2, 4, 0]^T$	$v_4(0) = [0, 0, 0]^T$
$h_5 = [0, 4\sqrt{3}, 0]^T$	$p_5(0) = [3, 2, 0]^T$	$v_5(0) = [0, 0, 0]^T$
$h_6 = [-2, 2\sqrt{3}, 0]^T$	$p_6(0) = [2, 3, 0]^T$	$v_6(0) = [0, 0, 0]^T$

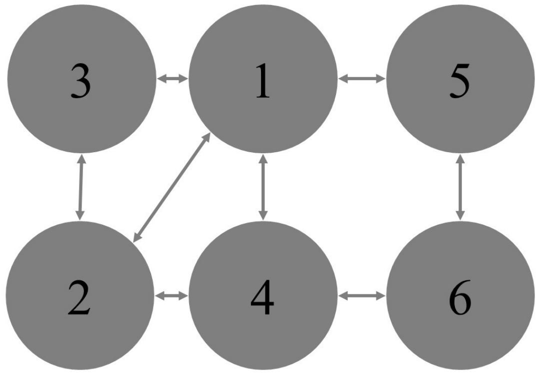


FIGURE 3. **Communication topology between agents.**

According to [61] and [62], a fleet of UVAs can be represented as a double integrator MAS manipulating the angles of the UAV with the following references:

$$\begin{aligned} \psi_{d_i} &= 0, \\ \theta_{d_i} &= \arctan\left(\frac{u_{x_i}}{u_{z_i}+g}\right), \\ \phi_{d_i} &= \arcsin\left(\frac{-u_{y_i}}{\sqrt{u_{x_i}^2+u_{y_i}^2+(u_{z_i}+g)^2}}\right), \\ T_i &= m_s\sqrt{u_{x_i}^2+u_{y_i}^2+\left(u_{z_i}+g\right)^2}. \end{aligned} \tag{27}$$

where $u_i(t) = \left[u_{x_i}(t), u_{y_i}(t), u_{z_i}(t)\right]^T$ is the leader-following consensus control. Thus, the fleet of UAVs can be manipulated as a second-order MAS:

$$\begin{aligned} \dot{p}_i(t) &= v_i(t), \\ \dot{v}_i(t) &= u_i(t). \end{aligned} \tag{28}$$

$$\mathbf{w}_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i)}(t) = \mathbf{w}_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),0} + \sum_{s=1}^{S} a_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),s} \times \sin\left(\Upsilon_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),s}t + \varrho_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),s}\right) \tag{29}$$

In this work, wind turbulence affecting the fleet of UVAs is considered as reported in [63] and [64]. Air mass motion is represented in (29) where $\Upsilon_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),s}$ and $\varrho_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),s}$ are randomly selected frequencies and phase shifts in each component of each UAV, S is the number of sinusoids, $\mathbf{w}_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),0}$ is the static wind vector, and the coefficients $a_{(\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i),s}$ defines the power spectral density selected as reported in [63]. Then, considering the wind in each axes $\mathbf{w}_i(t) = \left[\mathbf{w}_{\mathbf{x}_i}, \mathbf{w}_{\mathbf{y}_i}, \mathbf{w}_{\mathbf{z}_i}\right]^T$, the second-order MAS subject wind turbulence is modified as follows:

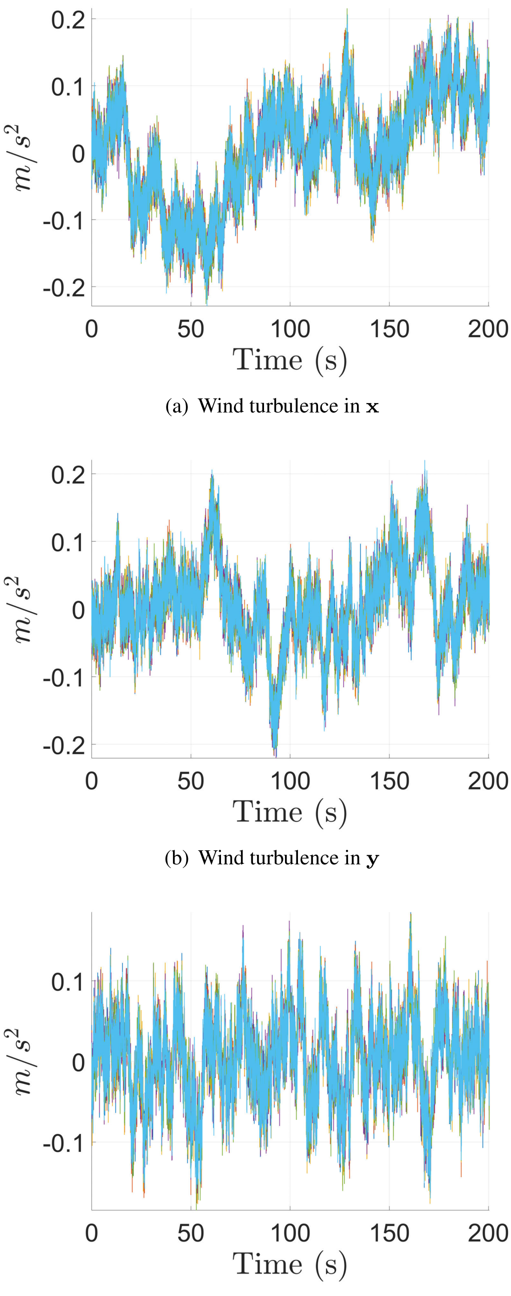
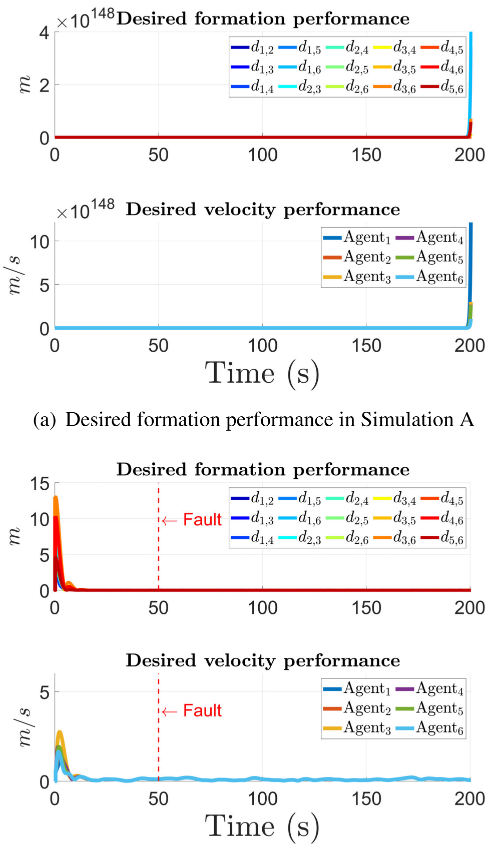


FIGURE 4. **Profile of the wind turbulence affecting the fleet of UAVs.**

$$\begin{aligned} \dot{p}_i(t) &= v_i(t), \\ \dot{v}_i(t) &= u_i(t) + \mathbf{w}_i(t). \end{aligned} \tag{30}$$

The UAVs' parameters used in this example are: $g = 9.81\, m/s^2$, $J_x = 21.6 \times 10^{-3} Kgm^2$, $J_y = 21.6 \times 10^{-3} Kgm^2$, $J_z = 43.2 \times 10^{-3} Kgm^2$, $m_s = 1.9 Kg$. LMIs in Theorem 1 is solved with the following parameters: $\mu_1 = 0.6$, $\mu_2 = 0.1$, $\gamma = 1$, $d_\tau = 0.4$, and $\alpha = 1$. The faults in the information



(a) Desired formation performance in Simulation A

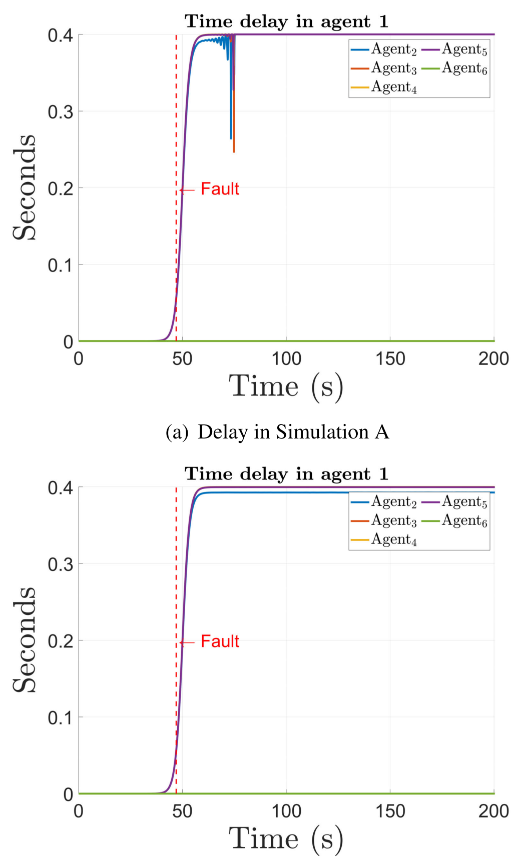
(b) Desired formation performance in Simulation B

FIGURE 5. Desired performance of the final positions and velocities under faults in the information exchange.

exchange use the following parameters: $\beta_1 = 0.4$, $\beta_2 = 1$, $\beta_3 = 0.3$, and $t_f = 50$. Six agents are considered shaping a hexagon with the parameters in Table 1. The target velocity is $v_r = [0, 0, 0.5]^T$. The communication topology is shown in Fig. 3. A comparison of two simulations is presented with agent 1 faulty. Simulation A uses the classical formation control gain ($K_c = -\left[I_{n_d}, I_{n_d}\right]$). Simulation B uses the formation control gain presented in this work. In Fig. 4, the profile of the wind turbulence which affects the fleet of the UAVs is shown.

Let us calculate the desired formation performance as $d_{ij} = \left\|\left(p_i - p_j\right) - \left(h_i - h_j\right)\right\|$ and $\|v_i - v_r\|$ is the velocity target performance. If $d_{ij} = 0$, $\forall i \neq j$, it means that the agents reach the desired formation. Fig. 5 shows the profile of the consensus performance of each agent. Simulation A presents an unstable consensus, and the agents cannot maintain the desired formation, this is due to the communication faults. The agents do not obtain the exact position and velocity of the neighboring agents in order to calculate the control law. So that, the control law value is inaccurate to tolerate such faults. In contrast with Simulation B, which reaches the desired formation and follow the target velocity since the design of the proposed control contemplates such faults and disturbances. The control performance ensures that agents converge to formation and the effects of communication faults and disturbances are tolerated.

Fig. 6 illustrates a comparison of the faults in the information exchange in the agent 1, i.e., the evaluation of (5) in the agent 1 is plotted. Both simulations use the same initial conditions and parameters. As described above, the magnitude of the fault is dependent on how far the agents are from each other. The maximum value is a fixed value, so the agents, no matter how far are the magnitude has the same value in this case 0.4s. In Simulation A, the oscillations in the fault are due to the unstable formation and because the agents are separating from each other's seconds after the fault occurred. Despite the fact that the agents have moved too far, they still have the same magnitude of the fault. In simulation B, the oscillations do not exist because the agents reach the desired formation when the fault occurs compared to Simulation A.

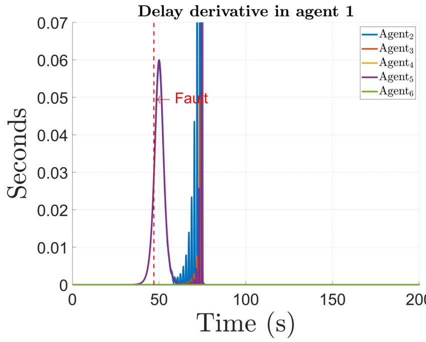


(a) Delay in Simulation A

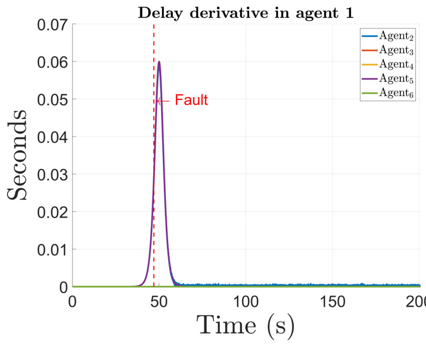
(b) Delay in Simulation B

FIGURE 6. Comparison of the faults in the information exchange in the agent 1.

Fig. 7 presents a comparison of derivative of the communication fault in order to show that the derivative of the delay is less than one. In Simulation A, because the agents start to oscillate and the delay are dependent of the position of each agent, the delay derivative oscillates and it is stable while the delay is constant. It is important to check the value of the



(a) Derivative of the delay in Simulation A



(b) Derivative of the delay in Simulation B

FIGURE 7. Comparison of derivative of the faults in the information exchange in the agent 1.

derivative because it is a constraint for the proposed control to work properly as it is done in Simulation B.

V. CONCLUSION

This paper has proposed a robust leader-following control design for MASs subject to faults in the information exchange and disturbances. LMIs-based conditions have been obtained through the Lyapunov approach and an optimal $\mathscr{H}_\infty$ criterion that guarantee the design of a robust controller such that all the agents converge to the leader agent's trajectories in the presence of faults in the information exchange and disturbances. The proposed strategy has been extended to solve the formation control problem in a fleet of UAVs subject to wind turbulence and faults in the information exchange. The control performance has shown that it can reach and maintain the consensus following the leader agent's trajectories when one agent is faulty. The effectiveness of the proposed approach has been exemplified by means of the formation control problem in a second-order MAS representing a fleet of UAVs subject to wind turbulence in which the performance of the desired final formation has been verified. A comparison between the classical formation control and the proposed strategy has been provided demonstrating the robustness of the proposed approach based on $\mathscr{H}_\infty$.

APPENDIX
NOTATION, BASIC GRAPH THEORY, AND LEMMAS

Given a matrix X, X^T denotes its transpose, $X > 0 (< 0)$ denotes a symmetric positive (negative) definite matrix. $\|.\|$ denotes the Euclidean norm. For simplicity, the symbol $*$ within a symmetric matrix represents the symmetric entries. The Hermitian part of a square matrix X is denoted by $\text{He}\{X\} := X + X^T$. The symbol $\otimes$ denotes the Kronecker product, which for real matrices A, B, C, and D with appropriate dimensions, satisfies the following properties [65]:

1) $(A + B) \otimes C = A \otimes C + B \otimes C$;
2) $(A \otimes B)^T = A^T \otimes B^T$;
3) $(A \otimes B)(C \otimes D) = (AC) \otimes (BD)$.

Lemma 2 [66]: For a given symmetric matrix $\begin{bmatrix} S_1 & S_2 \\ S_2^T & S_3 \end{bmatrix} < 0$ *the following statements are equivalent*:

1) $S_1 < 0$, $S_3 - S_2^T S_1^{-1} S_2 < 0$,
2) $S_3 < 0$, $S_1 - S_2^T S_3^{-1} S_2 < 0$.

A directed graph $\mathcal{G}$ is a pair $(\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{\mathbf{v}_1, \ldots, \mathbf{v}_N\}$ is a non-empty finite node set and $\mathcal{E} = \{(i, j) : i, j \in \mathcal{V}\} \subseteq \mathcal{V} \times \mathcal{V}$ is an edge set of ordered pairs of N nodes (total agents). The neighbors of node i are denoted as $j \in \mathcal{N}_i$. The adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N \times N}$ associated with the graph $\mathcal{G}$ is defined such that $a_{ii} = 0$, $a_{ij} > 0$ if and only if $(i, j) \in \mathcal{E}$ and $a_{ij} = 0$ otherwise. The Laplacian matrix $\mathcal{L} = [\mathcal{L}_{ij}] \in \mathbb{R}^{N \times N}$ of the graph $\mathcal{G}$ is defined as $\mathcal{L}_{ii} = \sum_{j \neq i} a_{ij}$ and $\mathcal{L}_{ij} = -a_{ij}$, $i \neq j$.

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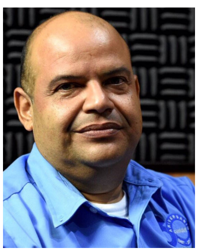

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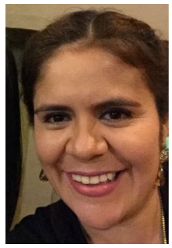

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