IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 29, 2020, accepted July 7, 2020, date of publication July 16, 2020, date of current version July 28, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3009751

Stochastic Robust Team Formation Tracking Design of Multi-VTOL-UAV Networked Control System in Smart City Under Time-Varying Delay and Random Fluctuation

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This work was supported by the Ministry of Science and Technology of Taiwan under Grant MOST 108-2221-E-007-099-MY3.

ABSTRACT In this study, the robust H_∞ event-triggered team formation tracking control design of multi-VTOL-UAVs in networked system is investigated. To describe the realistic networked system and UAV model, the intrinsic continuous Wiener random fluctuation, discontinuous Poisson random fluctuations, external disturbances and time-varying delays of wireless network are formulated in the proposed nonlinear stochastic jump diffusion system structure. By combining the event-triggered multi-UAV dynamic models and reference model into an augmented system, the robust H_∞ event-triggered multi-UAV networked team tracking problem can be transformed to a Hamilton-Jacobi inequality(HJI)-constraint optimization problem. Due to the difficulties in solving HJI-constraint optimization problem, for practical application, the T-S fuzzy techniques are adopted to efficiently approximate the nonlinear multi-UAVs system by a set of local linearized networked systems. Thus, the HJI-constraint optimization problem for the H_∞ event-triggered robust formation team tracking control can be transformed to a linear matrix inequality(LMI)-constraint optimization problem and can be easily solved by the convex optimization techniques. Finally, a simulation example is given to validate the effectiveness of the proposed event-triggered robust H_∞ team formation tracking control for the multi-VTOL-UAV system.

INDEX TERMS Unmanned aerial vehicle networked system, event-triggered control, stochastic control, virtual structure formation control, robust H_∞ fuzzy control.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have received a growing interest no matter in academic research or industrial field in recent years. Unlike the fixed-wing UAV, the vertical take-off and landing (VTOL) UAV uses multiple rotors to generate vertical thrust, which can force the UAV body hovering in the air or flying in the vertical motion like helicopter [1]. Thus, due to its high maneuverability and payload capacity, the quadrotor VTOL-UAV has given rise to interest nowadays. Physically, the quadrotor UAV is an under-actuated system with six degrees of freedom which contains three attitudes and three positions but only four independent control inputs. Although the under-actuated system can reduce the manufacturing difficulty of the system, the strong nonlinear coupling and static instability will make the quadrotor UAV control problem very difficult and challenging [2]–[4].

Recently, one of the emerging areas of UAVs is their involvement in smart cities. Since the UAV missions become more and more complex and challenging, various missions need to be completed by the team formation flight, such as agriculture application, battlefield reconnaissance, multi-target attacking and so on [5], [6]. Nowadays there are several formation control strategies, such as virtual-leader structure (V-S) approach [7], leader-follower (L-F) approach [8], and behavior-based method [9]. The idea of L-F approach

The associate editor coordinating the review of this manuscript and approving it for publication was Shuping He.

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is that one of the UAVs is selected as the leader to represent the team behavior and is asked to track the reference path, while other UAVs are the followers which are required to track the trajectory of the leader UAV with a team formation.

Despite L-F approach is the most earlier-developed and common-used method, the main drawback is that the entire formation only depends on one agent (leader). Thus, if the leader system is crashed during the guidance process, the whole UAV formation cannot be maintained [10]. Compared with the L-F approach, V-S approach can avoid aforementioned problems and becomes more robust. The concept of the V-S approach is that the virtual leader is at the central of the desired UAV formation shape to represent the movement of the team. In this situation, the virtual leader generates the formation reference point [11], and then each UAV in the formation has its own trajectory which is asked to track the reference path of the virtual leader with a certain distance. Hence, there are no interactions between the agents in the V-S approach [12]. The main cause of robustness is that the virtual leader will not suffer from the perturbation and can substantially reduce the possibility of formation failure in reality. Several experimental works of V-S control strategy can be found in [13], [14].

In recent years, advances in communication technologies have facilitated multi-agent control over communication networks [15], [16]. Most of control schemes within the networked control system (NCS) so far are based on the time-triggered communication which makes full use of the sampled data at every time instant. Under the time-triggered scheme of NCS, different transmission signals will occupy certain channel resources at the same bandwidth. However, in the real smart city [17], due to the limited communication bandwidth and the massive number of agents, it is necessary and important to consider the energy-waste and resource-saving problems. To overcome these power-saving problems, the event-triggered mechanism is proposed to replace the conventional time-triggered mechanism in networked-based control system. In the event-triggered mechanism, the event (energy constraint) will be executed and the controlled command will be transmitted only when the event-triggered condition is met, i.e., the controller will be updated only when it is necessary. As a result, event-triggered mechanism is regarded as an efficient way to reduce the load of the communication network. An event-triggered state-feedback approach is proposed in [18] and the event-triggered output-feedback control is developed by [19]. In [20], the authors proposed the general event-triggered controller with a fixed constant threshold in the mean-square error perspective which is the simplest triggering condition in all kinds of event-triggered schemes. There are other event-triggered schemes such as the triggering function related to the Lyapunov function from the perspective of energy [21]–[25].

In the previous studies, most of the researches about UAV networked control system have considered the external disturbance or noise as deterministic signals for the convenience of control design [27], [28]. However, in the real smart city, the UAV system will suffer from parametric fluctuations due to the rotors, rigid bodies, electrical circuits and communication channels or sensors. For example, there are continuous fluctuations from rotors or channel variations and discontinuous sudden voltage jumps from the sensors or electrical circuits [29]–[33]. Through Itô–Lévy integral [34], [35], these intrinsic fluctuations should be modeled by random processes, including continuous Wiener process and discontinuous Poisson process in the multi-UAV team tracking problem. Besides, there exist some external disturbances in multi-UAV system during flight process, such as the unpredictable aerodynamic perturbations or wireless interferences on the wireless network. Thus, the multi-UAV system in the smart city should be modeled as a stochastic nonlinear system from the practical point of view.

In this work, an event-triggered mechanism and a robust state feedback controller are designed simultaneously to ensure that the controlled multi-VTOL-UAV networked system could gradually track on their desired team path with the desired attitude despite intrinsic random fluctuation in the UAV system and external disturbance from the environment. Also, we can save the energy resources and release the load of communication bandwidth in the wireless network with the consideration of the time-varying delay in transmission channel. To deal with the stochastic event-triggered robust team tracking control problem with external disturbance, the H_∞ event-triggered robust team tracking control design is proposed to efficiently attenuate the effect of random fluctuation and external disturbance on the team formation tracking performance of the multiple VTOL-UAVs networked control system. Then, by using Itô-Lévy formula, the event-triggered nonlinear multi-UAV robust team tracking design problem is transformed to an equivalent Hamilton-Jacobi inequality (HJI)-constraint optimization problem. However, since HJI is a partial derivative inequality, it is difficult to be solved analytically and numerically. As a result, Takagi-Sugeno (T-S) fuzzy technique [38], [39] is adopted to efficiently approximate the nonlinear multi-UAV system to simplify the design procedure. T-S fuzzy model can interpolate several locally linearized systems by fuzzy bases to approximate the nonlinear multi-UAV system. Therefore, the HJI-constraint optimization problem for the H_∞ event-triggered robust formation team tracking control can be transformed to a linear matrix inequality (LMI)-constrained optimization problem which can be easily solved with the help of MATLAB LMI toolbox. In the simulation, a square-shape formation tracking task for four UAVs stochastic networked system is provided to validate the effectiveness of proposed H_∞ event-triggered robust formation team tracking control.

The contributions of this study are described as follows:

- To completely describe the more realistic multi-UAV team formation tracking system and complicated wireless network in smart city, the stochastic nonlinear event-triggered multi-UAV networked control system is firstly formulated with the consideration of time-varying delay, external disturbance, intrinsic continuous Wiener diffusion fluctuations and discontinuous Poisson jump fluctuation.

• Without using conventional time-triggered control for multi-UAV networked system in previous studies, the event-triggered mechanism is utilized for the multi-UAV team formation tracking control design to relieve the communication load and save the energy consumption for the UAV networked system in future smart city. Then, an augmented and shifted nonlinear multi-UAV tracking system is proposed to transform the complex multi-UAV team formation tracking control design to an equivalent stabilization control design of the augmented system.

• By constructing the error tracking dynamic and using T-S fuzzy model, the robust H_∞ stochastic event-triggered multi-UAV team formation tracking control could be designed by solving an LMI-constrained optimization scheme to efficiently achieve the dynamic virtual structure team formation tracking. As a result, the robust H_∞ stochastic event-triggered multi-UAV team formation tracking control design can be simply implemented for more practical applications.

The study is organized as follows. The VTOL-UAV networked control system description and the preliminaries are given in Section II. Section III is the problem formulation, including the conception of the virtual structure formation and the virtual structure formation team tracking of multi-UAV event-triggered networked control system. Also, the H_∞ team formation tracking control design is developed in this section. In Section IV, T-S fuzzy model is adopted to deal with the H_∞ event-triggered team tracking control problem. The co-design of the stochastic H_∞ robust team tracking controller and the event-triggered mechanism via the LMI approach is proposed in Section V. In Section VI, a simulation example is provided to illustrate the design procedure and performance validation of H_∞ team formation tracking performance of the stochastic multi-UAV networked team tracking control system. Finally, the concluding remarks are made in Section VII.

Notation: A^T: the transpose of matrix A; $A \geq 0 (A > 0)$: symmetric positive semi-definite (symmetric positive definite) matrix A; I_n: the n-dimensional identity matrix; $\|\boldsymbol{x}\|_2$: the Euclidean norm for the given vector $\boldsymbol{x} \in \mathbb{R}^n$; C^2: the class of functions $V(\boldsymbol{x})$ with twice continuous derivatives with respect to $\boldsymbol{x}$; $f_{\boldsymbol{x}}$:the gradient column vector of continuously differentiable function $\boldsymbol{f}(\boldsymbol{x})$ (i.e., $\frac{\partial f(\boldsymbol{x})}{\partial \boldsymbol{x}}$); $f_{\boldsymbol{xx}}$: the Hessian matrix with elements of second partial derivatives of twice continuously differentiable function $\boldsymbol{f}(\boldsymbol{x})$, (i.e., $\frac{\partial^2 f(\boldsymbol{x})}{\partial \boldsymbol{x}^2}$); $\boldsymbol{E}$: the expectation operator; $\mathcal{L}^2_{\mathcal{F}}(\mathbb{R}^+, \mathbb{R}^l)$: the space of nonanticipative stochastic processes $y(t) \in \mathbb{R}^l$ with respect to an increasing $\sigma-$ algebras $\mathcal{F}_t (t \geq 0)$ satisfying $\|\boldsymbol{y}(t)\|_{\mathcal{L}^2(\mathbb{R}^+;\mathbb{R}^l)} \triangleq \boldsymbol{E}\left\{\int_0^\infty \boldsymbol{y}^T(t)\boldsymbol{y}(t)dt\right\}^{\frac{1}{2}} < \infty$; The matrix $\begin{bmatrix} A & B \\ B^T & C \end{bmatrix}$ is represented as $\begin{bmatrix} A & B \\ * & C \end{bmatrix}$ for the simplicity.

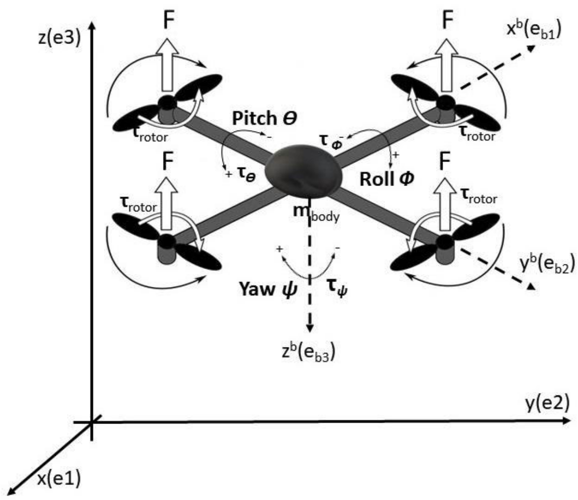


FIGURE 1. The ith VTOL-UAV dynamic model with the attitude and translation subsystem.

II. SYSTEM DESCRIPTION AND PRELIMINARIES

A. SYSTEM MODEL OF THE VTOL-UAV

In order to deal with the attitude and position tracking control in the quadrotor UAV system, we consider a translation subsystem with respect to the inertial frame and the attitude subsystem with respect to the body frame, respectively. By considering the velocity and acceleration of the translation subsystem, and the angular velocity and acceleration of the attitude subsystem, the quadrotor dynamic equations can be described as a dynamic system of twelve components, including the translation dynamic of quadrotor related to it's position motion and the attitude dynamic associated with it's angular motion. By the Euler method and the conception above, the dynamic system of the quadrotor UAV in Fig. 1 can be described as follows [45]:

$$
\begin{aligned}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= -\frac{f x}{m} x_2(t) + (\cos\phi_1(t)\sin\theta_1(t)\cos\psi_1(t) \\
&\quad + \sin\phi_1(t)\sin\psi_1(t))\frac{F(t)}{m} + v_x(t) \\
\dot{y}_1(t) &= y_2(t) \\
\dot{y}_2(t) &= -\frac{f y}{m} y_2(t) + (\cos\phi_1(t)\sin\theta_1(t)\sin\psi_1(t) \\
&\quad - \sin\phi_1(t)\cos\psi_1(t))\frac{F(t)}{m} + v_y(t) \\
\dot{z}_1(t) &= z_2(t) \\
\dot{z}_2(t) &= -\frac{f z}{m} z_2(t) - g + (\cos\phi_1(t)\cos\theta_1(t))\frac{F(t)}{m} + v_z(t) \\
\dot{\phi}_1(t) &= \phi_2(t) \\
\dot{\phi}_2(t) &= \frac{J_\theta - J_\psi}{J_\phi}\theta_2(t)\psi_2(t) - \frac{f_\phi}{J_\phi}\phi_2(t) + \frac{1}{J_\phi}\tau_\phi(t) + v_\phi(t)
\end{aligned}
$$

$$\begin{aligned}
\dot{\theta}_1(t) &= \theta_2(t)\\
\dot{\theta}_2(t) &= \frac{J_\psi - J_\phi}{J_\theta}\phi_2(t)\psi_2(t) - \frac{f_\theta}{J_\theta}\theta_2(t) + \frac{1}{J_\theta}\tau_\theta(t) + v_\theta(t)\\
\dot{\psi}_1(t) &= \psi_2(t)\\
\dot{\psi}_2(t) &= \frac{J_\phi - J_\theta}{J_\psi}\phi_2(t)\theta_2(t) - \frac{f_\psi}{J_\psi}\psi_2(t) + \frac{1}{J_\psi}\tau_\psi(t) + v_\psi(t)
\end{aligned} \tag{1}$$

where the attitude vector is denoted by $\Theta(t) = [\phi_1(t), \theta_1(t), \psi_1(t)]^T$ in the body frame associated with the unit vector basis (e_{b1}, e_{b2}, e_{b3}). The parameters $\phi_1(t), \theta_1(t), \psi_1(t)$ are Euler angles of rotation fixed to the body of a quadrator UAV. These three angles respectively represent roll angle ($-\frac{\pi}{2} < \phi_1(t) < \frac{\pi}{2}$), pitch angle ($-\frac{\pi}{2} < \theta_1(t) < \frac{\pi}{2}$), and yaw angle ($-\pi < \psi_1(t) < \pi$) related to the orientation of the quadrotor to be controlled by changing the rotational speed of four rotors. The position vector $\Xi(t) = [x_1(t), y_1(t), z_1(t)]^T$ represents the position of mass center of the quadrotor in the inertial frame associated with the unit vector basis (e_1, e_2, e_3). Specifically, $x_1(t), y_1(t), z_1(t) \in \mathbb{R}^1$ are the position states of UAV, which is on the Cartesian coordinate in respect of the inertial frame. $v_x(t), v_y(t), v_z(t)$ are the external disturbances of the UAV in the three translation dynamics. $v_\phi(t), v_\theta(t), v_\psi(t)$ are the external disturbances of the UAV caused by the unexpected rotation force in raw, pitch, and yaw dynamics, respectively. $f_x, f_y, f_z \in \mathbb{R}^+$ are the coefficients of the translation drag forces and $f_\phi, f_\theta, f_\psi \in \mathbb{R}^+$ represent the aerodynamic friction coefficient of the quadrotor. The total thrust $F(t) \in \mathbb{R}^1$ and the rotational forces $\tau_\phi(t), \tau_\theta(t), \tau_\psi(t) \in \mathbb{R}^1$ are produced by four rotors of the UAV. $m \in \mathbb{R}^+$ is the total mass of the UAV and g denotes the acceleration of gravity. $J_\phi, J_\theta, J_\psi \in \mathbb{R}^+$ are the moments of inertia of the UAV.

In the realistic situation, the quadrotor UAV system will unavoidably suffer from parametric fluctuations due to the rotors, rigid bodies, electrical circuits or sensors. To mimic the real quadrotor UAV system, the dynamical model of ith UAV in (1) should be modified by continuous and discontinuous intrinsic random fluctuations as follows:

$$\begin{aligned}
dx_i(t) = (f_i(x_i(t)) + g_i(x_i(t))u_i(t) + v_i(t))dt\\
+ \sigma(x_i(t))dW_i(t) + \Gamma(x_i(t))dN_i(t)
\end{aligned} \tag{2}$$

with

$$\begin{aligned}
f_i(x_i(t)) = [&x_2^i(t), -\frac{f_x^i}{m^i}x_2^i, y_2^i(t), -\frac{f_y^i}{m^i}y_2^i, z_2^i(t),\\
&-g-\frac{f_z^i}{m^i}z_2^i(t), \phi_2^i(t), \frac{J_\theta^i - J_\psi^i}{J_\phi^i}\theta_2^i(t)\psi_2^i(t) - \frac{f_\phi^i}{J_\phi^i}\phi_2^i(t),\\
&\theta_2^i(t), \frac{J_\psi^i - J_\phi^i}{J_\theta^i}\phi_2^i(t)\,\psi_2^i(t) - \frac{f_\theta^i}{J_\theta^i}\theta_2^i(t), \psi_2^i(t),\\
&\frac{J_\phi^i - J_\theta^i}{J_\psi^i}\phi_2^i(t)\theta_2^i(t) - \frac{f_\psi^i}{J_\psi^i}\psi_2^i(t)]^T
\end{aligned}$$

$$g_i(x_i(t)) = \begin{bmatrix}
0 & 0 & 0 & 0\\
\frac{1}{m^i}(\cos\phi_1^i(t)\sin\theta_1^i(t) \times \cos\psi_1^i(t) + \sin\phi_1^i(t) \times \sin\psi_1^i(t)) & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
\frac{1}{m^i}(\cos\phi_1^i(t)\sin\theta_1^i(t) \times \sin\psi_1^i(t) - \sin\phi_1^i(t) \times \cos\psi_1^i(t)) & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
\frac{1}{m^i}(\cos\phi_1^i(t)\cos\theta_1^i(t)) & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & \frac{1}{J_\phi^i} & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & \frac{1}{J_\theta^i} & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & \frac{1}{J_\psi^i}
\end{bmatrix}^T$$

$$\begin{aligned}
x_i(t) &= [x_1^i(t), x_2^i(t), y_1^i(t), y_2^i(t), z_1^i(t), z_2^i(t), \phi_1^i(t),\\
&\quad \phi_2^i(t), \theta_1^i(t), \theta_2^i(t), \psi_1^i(t), \psi_2^i(t)]^T\\
u_i(t) &= [F^i(t), \tau_\phi^i(t), \tau_\theta^i(t), \tau_\psi^i(t)]^T\\
v_i(t) &= [0, v_x^i(t), 0, v_y^i(t), 0, v_z^i(t), 0,\\
&\quad v_\phi^i(t), 0, v_\theta^i(t), 0, v_\Psi^i(t)]^T
\end{aligned}$$

for $i = 1, 2, \cdots, N$, where $x_i(t)$ denotes the state variable of the ith UAV, $u_i(t)$ denotes the control input, which is produced by the four rotors of the *ith* UAV. $v_i(t) \in \mathcal{L}_F^2(\mathbb{R}^+; \mathbb{R}^{12})$ denotes the finite energy external disturbance in the *ith* UAV system, which is produced by the unpredictable interference from the wireless network and the neighboring UAVs. $W_i(t) \in \mathbb{R}^1$ is the Wiener process which is continuous but non-differentiable, and $\sigma_i(x_i(t))dW_i(t)$ denotes the effect of continuous stochastic intrinsic fluctuation caused by the modeling uncertainty of the *ith* UAV. $N_i(t) \in \mathbb{R}^1$ denotes the Poisson counting process with jump intensity $\lambda_i > 0$, and $\Gamma_i(x_i(t))dN_i(t)$ denotes the effect of discontinuous abruptly random fluctuation caused by the sudden incident at time instant t such as the packet loss in network transmission or deformations of faults of mechanical elements during the flight. It is assumed that $W_i(t)$ and $N_i(t)$ are independent. The above two processes are defined on the complete filtration probability space $(\Omega, \mathcal{F}, \mathcal{F}_t, \mathcal{P})$, Ω is the sample space, $\mathcal{F}$ denotes the filtration, and P denotes the probability measure. $\mathcal{F} = \{\mathcal{F}_t : t \geq 0\}$ and $\mathcal{F}_t$ is an σ-algebra filtration generated by the Wiener process $W_i(s)$ and the Poisson counting processes $N_i(s)$, for $s < t$.

Remark 1: Some important properties of Wiener process and Poisson counting process are given as follows [34], [35]: (I) $E\{W_i(t)\} = E\{dW_i(t)\} = 0$. (II) $E\{dW_i(t)^T dW_j(t)\} = 0$, for $i \neq j$. $E\{dW_i(t)^T dW_j(t)\} = dt$, for $i = j$.

(III) $E\{dN_i(t)\} = \lambda_i dt$, *where the finite scalar number* $\lambda_i > 0$ *is the Poisson jump intensity.*

B. EVENT-TRIGGERED NETWORKED TEAM TRACKING CONTROL SYSTEM OF THE VTOL-UAV

We now introduce the event-triggered scheme for the ith UAV in the multi VTOL-UAV networked control system, where the sensor is clock-driven while the data transmission is event-driven. To begin with, we first make some definitions related to the time instant. The set $S_1 = \{0, h, 2h, \cdots, jh\}$ denotes the sampling sequence of the sensor under the time-triggered with sampling period $h \in \mathbb{R}^+$ and some $j \in \mathbb{N}$, i.e. they are discrete-time instants of all the sampled data from the sensors. The set $S_2 = \{0, t_1 h, t_2 h, \cdots, t_k h\} \subseteq S_1$, for some $t_k \in \mathbb{N}$ denotes the transmission sequence after the event-triggered mechanism, by which whether the sampled data would be transmitted or not and it is determined by the event-triggered condition. The transmission condition of the event-triggered mechanism can be described as [21]–[24]:

$$t_{k+1}h = t_k h + \min_{l>0, l\in\mathbb{N}} \{lh | E\{[x_i(i_k h) - x_i(t_k h)]^T \times \Phi[x_i(i_k h) - x_i(t_k h)]\} \geq \sigma E\{x_i^T(t_k h)\Phi x_i(t_k h)\}\} \tag{3}$$

where $\sigma \in [0, 1)$ is the proper threshold parameter, which represents the level of the event-triggered mechanism. $i_k h = t_k h + lh$, means the next sampled instant which should be decided to transmit or not, for some $l \in \mathbb{N}$. Φ is the positive definite event-triggered matrix which should be designed. $x_i(i_k h) - x_i(t_k h)$ is the threshold error between the states at the current sampling instant and the latest transmitted instant, $t_k h$ is the time instant at sensor successively transmitting data to the controller. Note that the parameters σ, Φ and h of the event-triggered scheme in (3) are related to the communication load of networked control system. When the event-triggered condition is satisfied, the new transmission $x_i(t_{k+1}h)$ occurs through the wireless network and it will be stored in the event-triggered mechanism for the next computation and decision (see Fig. 2). Especially, if $\sigma = 0$, it implies the scheme in (3) becomes the conventional time-triggered mechanism.

Remark 2: Different from the conventional continuous-time event-triggered mechanism, the event-triggered mechanism in (3) evaluates the constraint at each time instants kh, for $k \in \mathbb{N}$, *with sample period* $h > 0$. *Thus, the minimum triggered time interval is greater than one sample period h and the Zeno effect is excluded, i.e., there are no infinite triggered instants in any finite time interval.*

Consider the network-induced round trip delay τ_{t_k} from sensor to controller and controller to actuator at the time instant t_k, i.e., $\tau_{t_k} = \tau_{sc}(t_k h) + \tau_{ca}(t_k h)$, where $\tau_{sc}(t_k h)$ and $\tau_{ca}(t_k h)$ denote the sensor-to-controller delay and controller-to-actuator delay, respectively (see Fig. 2). Assume $0 \leq \tau_{t_k} \leq \overline{\tau}$, where $\overline{\tau}$ denotes the upper bound of the network-induced delay. Since both controllers and actuators are event-triggered, the control input to the actuator should

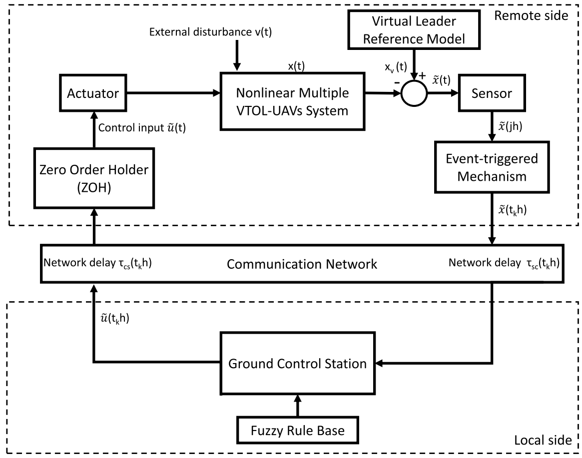


FIGURE 2. **The event-triggered scheme for the quadrotor networked tracking control system.**

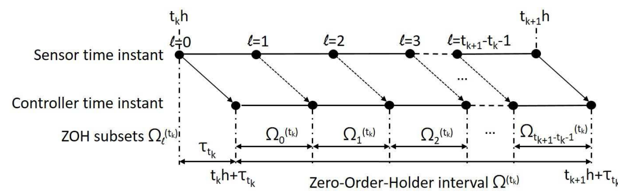


FIGURE 3. **Subsets of the zero-order-holder,** l **is the positive integer related to the time of the current sampling, i.e.,** $i_k h = t_k h + lh$.

be generated by a zero-order-holder (ZOH) with the holding time $t \in \Omega^{(t_k)} \equiv [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t_{(k+1)}})$, in which the sampling instants are contained between the current transmitted instant $t_k h$ and the future transmitted instant $t_{k+1}h$. $t_k h + \tau_{t_k}$ is the time instant at which the control signal reaches the ZOH.

Remark 3: The function of the ZOH at the actuator stores the last transmitted control signal and keeps the control input of the plant until the next trigger updating has occurred.

In order to analyze the stability of the event-based UAV networked team tracking control system, we need to make a detailed timing analysis. As shown in Fig. 3, the holding interval $\Omega^{(t_k)} \equiv [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t_{(k+1)}})$ can be partitioned into several subsets, i.e., $\Omega^{(t_k)} = \bigcup_{l=0}^{t_{k+1}-t_k-1} \Omega_l^{(t_k)}$. The subset $\Omega_l^{(t_k)}$is defined as

$$\Omega_l^{(t_k)} = [i_k h + \tau_{i_k}, i_k h + h + \tau_{i_{(k+1)}}), \tag{4}$$

where $i_k h = t_k h + lh$, for $l = 0, 1, 2, \ldots, t_{k+1} - t_k - 1$. In order to provide an unified framework for $x_i(i_k h)$, i.e., $i_k h = t - (t - i_k h)$, a piecewise delay function $\eta(t)$ is defined as [46]:

$$\eta(t) \equiv t - i_k h, t \in \Omega_l^{(t_k)} \tag{5}$$

which denotes the time-varying delay in the control signal. From the scope of the subset $\Omega_l^{(t_k)}$, it is clear that $\eta(t)$ is a linear differentiable function satisfying [41]

$$\dot{\eta}(t) = 1, \; 0 \leq \eta(t) \leq \overline{\eta} = h + \overline{\tau}, t \in \Omega_l^{(t_k)} \tag{6}$$

where $\overline{\eta}$ is the sum of maximum allowable upper delay bound $\overline{\tau}$ and one sampling period h. As a result, we can obtain a trade-off between the sampling period and the allowable delay upper bound when $\overline{\eta}$ is specified. Then, by considering the network-induced delay, the ith quadrotor UAV event-triggered networked control system can be formulated as the following stochastic nonlinear diffusion jump system:

$$\begin{aligned} dx_i(t) &= (f_i(x_i(t)) + g_i(x_i(t))u_i(t) + v_i(t))dt \\ &\quad + \sigma_i(x_i(t))dW_i(t) + \Gamma_i(x_i(t))dN_i(t), \\ x_i(s) &= \varsigma_i(s), \\ u_i(t) &= \hat{u}_i(x_i(t_kh), x_v(t_kh)) \\ &\quad t \in [t_kh + \tau_{t_k}, t_{k+1}h + \tau_{t(k+1)}), \\ &\quad \forall i = 1, 2, \cdots, N,\ k \in \mathbb{N} \cup \{0\} \\ &\quad \forall -\overline{\eta} \le s \le 0 \end{aligned} \tag{7}$$

where $x_v(t_kh)$ denotes the reference state to be tracked at $t = t_kh$, $\hat{u}_i(x_i(t_kh), x_v(t_kh))$ is the control input after ZOH for the *ith* UAV in the event-triggered multi-UAV team formation tracking networked system and will be designed in the sequel and $\varsigma_i(s)$ denotes known continuous function in (7) to describe the state value of ith UAV from $-\overline{\eta}$ to 0.

III. PROBLEM FORMULATION

In this work, we employ a virtual leader structure to deal with the multi-UAV team formation tracking control. Fig. 2 shows a framework of the proposed event-triggered scheme for the multi-quadrotor team tracking control system through wireless network. Compared with other types of UAV formation such as Leader-Follower, the best advantage of virtual leader formation is that not only the leader can affect the followers, but also the follower information can feedback to the leader, which could make the formation more robust and flexible. The detail of our approach is described as follows.

A. FORMATION TEAM TRACKING DESIGN OF MULTI-UAV VIRTUAL LEADER STRUCTURE

For a connected N-UAV team formation networked control system, the formation structure can be constructed by two parts: One is the real members of all N UAVs as the followers; the other is the virtual leader UAV in the central of the followers' formation shape and it's path is defined by a reference model via the software. The formation pattern is settled in such a way that each follower UAV will track a trajectory specified by the state of virtual leader. The dynamic of each follower UAV with event-triggered team tracking control is represented as (7) and $u_i(t)$ is the control input after ZOH to be designed to track the virtual leader with a team formation shape to maintain the location and attitude of the ith UAV in the team. The state of virtual leader is generated by the reference model. The advantage of the virtual structure is that such a team formation shape of UAVs could simplify the team tracking design procedure. Therefore the desired trajectory of virtual leader including position, velocity and attitude (including roll, pitch and yaw angles) of multi-UAV team could be generated by the following virtual leader reference model:

$$dx_v(t) = (A_rx_v(t) + r(t))dt \tag{8}$$

where $x_v(t) \in \mathbb{R}^{12}$ denotes the reference state including the desired position, velocity, and row, pitch, yaw angles, $r(t) \in \mathbb{R}^{12}$ denotes the bounded reference input vector and the matrix A_r denotes a specific asymptotically stable matrix.

Remark 4: It is obvious that at the steady state of the reference model, $x_v(t) = -A_r^{-1}r(t)$. If we choose $A_r = -I$, the desired trajectory $x_v(t)$ is equivalent to the reference input $r(t)$ at the steady state. If this is the case, $x_v(t)$ will converge to $r(t)$ at the steady state. In this situation $r(t)$ can be considered as the desired target of the virtual leader.

As shown in Fig. 4, 4 UAVs are assumed to maintain a square formation during the flight, which will be used to illustrate in the simulation example in the sequel. The virtual leader in Fig. 4 represents the movement of the overall UAV team structure and is requested to be the same as the reference path, velocity and attitude generated by reference model in (8). By the above reference information of the virtual leader, the followers will be controlled to track the virtual leader to maintain the formation on the desired path, velocity and attitude despite intrinsic random fluctuation, external disturbance and arbitrary reference input signal from the robust H_∞ tracking perspective. Since the external disturbances such as weather conditions or channel interferences during the flight tracking process of multi-UAV team formation networked control system are unpredictable and the reference input $r(t)$ is arbitrary and unknown to the followers, the following robust H_∞ tracking control strategy is considered to efficiently attenuate the effect of external disturbances $\bar{v}(t) = [r^T(t), v_1^T(t), \ldots, v_N^T(t)]^T$ on the tracking performance of the stochastic event-triggered multi-UAV team formation networked control system:

$$J_\infty(\{u_i\}_{i=1}^N) = \sup_{\substack{\bar{v}(t)\in\mathcal{L}^2_{\mathcal{F}_t} \\ (\mathbb{R}^+,\mathbb{R}^{12(N+1)})}} \frac{\begin{aligned} &E[\int_0^{t_f} \sum_{i=1}^N (x_i(t) - x_v(t) - e_{di})^T \\ &\times Q_i(x_i(t) - x_v(t) - e_{di})dt \\ &- \sum_{i=1}^N (x_i(0) - x_v(0) - e_{di})^T \\ &\times P_i(x_i(0) - x_v(0) - e_{di}) \end{aligned}}{E\{\int_0^{t_f} \bar{v}^T(t)\bar{v}(t)dt\}} \tag{9}$$

where $Q_i \in R^{12\times 12}$ denotes the positive definite tracking error weighting matrix on the ith UAV. $x_i(t) - x_v(t)$ denotes the tracking error between the ith UAV to the virtual leader. e_{di} is the desired formation between the ith UAV and the virtual leader UAV. If $x_i(t) - x_v(t) - e_{di} \to 0$, then $x_i(t) \to x_v(t) + e_{di}$. i.e., the UAV team can maintain the formation structure $e_d = [0^T, e_{d1}^T, \ldots, e_{dN}^T]^T$ around the virtual leader $x_v(t)$. $\sum_{i=1}^N (x_i(0) - x_v(0) - e_{di})^T P_i(x_i(0) - x_v(0) - e_{di})$ is the effect of the initial conditions on the team tracking of UAVs with some

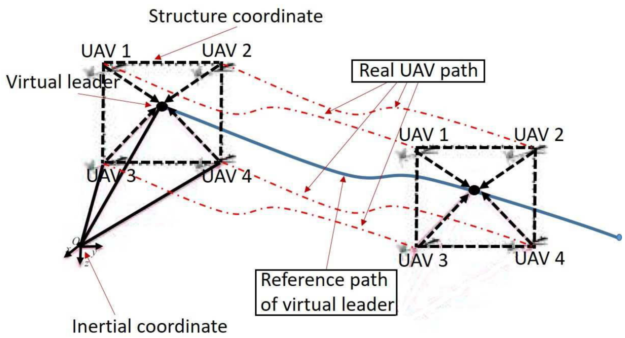


FIGURE 4. The virtual structure team formation of the multi-UAVs networked control system to track the desired trajectory. The example considers four follower-UAVs. The black dot is the virtual leader at the central of the UAV team formation shape, and the dynamic of virtual leader is given by the reference model in (8).

positive definite matrices $\{P_i\}_{i=1}^N$ and should be excluded in the H_∞ tracking performance in (9), t_f denotes the terminal time of tracking control process. In (9), our objective is to design the specific controllers $\{u_i(t)\}_{i=1}^N$ for each UAV so that the worst-case effect of external disturbance $\bar{v}(t)$ on the reference team formation tracking performance could be below a prescribed disturbance attenuation level ρ^2 for the UAVs team tracking system from the energy perspective. i.e., we aim to design the specific controllers $\{u_i^*(t)\}_{i=1}^N$ such that $J_\infty(\{u_i^*(t)\}_{i=1}^N) \leq \rho^2$.

B. THE VIRTUAL LEADER TEAM TRACKING DESIGN OF MULTI-UAV EVENT-TRIGGERED NETWORKED CONTROL SYSTEM

In order to investigate the H_∞ team tracking performance of the stochastic multi-UAV dynamic system, we first aggregate the states of all followers and the virtual leader, then convert the original team formation tracking system into a team formation tracking error dynamic system to simplify the design procedure. At first, the augmented states and control input by (7) and (8) are given as:

$$\begin{aligned}\bar{x}(t) &= [x_v^T(t), x_1^T(t) - x_v^T(t), x_2^T(t) - x_v^T(t),\\ &\quad x_3^T(t) - x_v^T(t), \cdots, x_N^T(t) - x_v^T(t)]^T\\ \bar{u}(t) &= [u_1^T(t), u_2^T(t), \cdots, u_N^T(t)]^T \end{aligned}\tag{10}$$

By the time instant defined in (3), the set $S_1 = \{jh \mid j \in N\}$ represents the sampled instants. Let $x_1(jh), x_2(jh), \ldots, x_N(jh)$ denote the sampled state of the N controlled UAVs and $x_v(jh)$ denote the sampled states of the virtual leader reference. Moreover, these sampled states are augmented as a packet $\bar{x}(jh)$ and then transmitted to the event-triggered mechanism in Fig. 2 at the jth sampling instant. After the decision from the event-triggered mechanism, the signal $\bar{x}(t_k h)$ is transmitted to the local side through the network. To simplify the discrete state $\bar{x}(t_k h)$, the threshold error between the augmented state at the current instant $i_k h$ and the one at the last transmitted instant $t_k h$ is defined as

$$e_k(t) \triangleq \bar{x}(i_k h) - \bar{x}(t_k h),\ t \in \Omega_l^{(t_k)} \tag{11}$$

Then, from (5) and (11)

$$\bar{x}(t_k h) = \bar{x}(t - \eta(t)) - e_k(t),\ t \in \Omega_l^{(t_k)}, \quad 0 < \eta(t) \leq \bar{\eta} \tag{12}$$

(12) is the feedback state information transmitted to the ground control station through the network. Besides, the nonlinear tracking control input $\bar{u}(t)$ in (10) of the event-triggered multi-UAV networked team tracking control system is given as

$$\begin{aligned}\bar{u}(t) &= \bar{K}(\bar{x}(t_k h)) = \bar{K}(\bar{x}(t - \eta(t)) - e_k(t)),\\ &\qquad t \in [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t_{(k+1)}})\end{aligned}\tag{13}$$

where $\bar{K}(\cdot)$ is the nonlinear state-feedback function to be designed.

Remark 5: In (12), the value of the controller $\bar{K}(\bar{x}(t_k h))$ at $t \in [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t_{(k+1)}})$ depends on the information $\bar{x}(t_k h)$ at $t = t_k h$. As a result, the time-varying delay is not used in designing the controller. On the other hand, It is worth to point out that the piecewise delay function $\eta(t)$ is introduced to simplify the design. By using the piecewise delay function $\eta(t)$, the controller $\bar{u}(t)$ can be designed as the form $\bar{K}(\bar{x}(t - \eta(t)) - e_k(t))$ which is associated with two variables $\bar{x}(t - \eta(t))$, $e_k(t)$. In this situation, the design conditions are more flexible.

Thus the event-triggered stochastic UAV networked team formation tracking error dynamic system in consideration of the networked-induced delay is derived as follows:

$$\begin{aligned}d\bar{x}(t) &= [\bar{f}(\bar{x}(t)) + \bar{g}(\bar{x}(t))\bar{u}(t) + H\bar{v}(t)]dt\\ &\quad + \sum_{i=1}^N [\bar{\sigma}_i(\bar{x}(t))dW_i(t) + \bar{\Gamma}_i(\bar{x}(t))dN_i(t)]\end{aligned}\tag{14}$$

where $\bar{u}(t)$ is defined in (13) and

$$\begin{aligned}\bar{v}(t) &= [r(t), v_1(t), \cdots, v_N(t)]^T\\ \bar{f}(\bar{x}(t)) &= [(A_r x_v(t))^T, f_1(x_1(t))^T - (A_r x_v(t))^T,\\ &\qquad \cdots, f_N(x_N(t))^T - (A_r x_v(t))^T]^T\\ \bar{\sigma}_1(\bar{x}(t)) &= [0,\ \sigma_1^T(x_1(t)), 0, \cdots, 0]^T\\ &\vdots\\ \bar{\sigma}_i(\bar{x}(t)) &= [0, 0, \cdots, \sigma_i^T(x_i(t)), \cdots, , 0]^T\\ &\vdots\\ \bar{\sigma}_N(\bar{x}(t)) &= [0, 0, \cdots, 0, \sigma_N^T(x_N(t))]^T\\ \bar{\Gamma}_1(\bar{x}(t)) &= [0,\ \Gamma_1^T(x_1(t), 0, \cdots, 0]^T\\ &\vdots\\ \bar{\Gamma}_i(\bar{x}(t)) &= [0, 0, \cdots, \Gamma_i^T(x_i(t)), \cdots, 0]^T\\ &\vdots\\ \bar{\Gamma}_N(\bar{x}(t)) &= [0, 0, \cdots, 0, \Gamma_N^T(x_N(t))]^T\end{aligned}$$

$$\overline{g}(\overline{x}(t)) = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & g_1(x_1(t)) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & g_N(x_N(t)) \end{bmatrix}$$

$$H = \begin{bmatrix} I & 0 & \cdots & 0 \\ -I & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -I & 0 & \cdots & I \end{bmatrix}$$

In order to arrange N UAVs in a virtual structure formation, the formation structure of the UAV team as $e_d = [0^T, e_{d1}^T, \ldots, e_{dN}^T]^T$ and the shifted error state is defined as:

$$\widetilde{x}(t) = \overline{x}(t) - e_d \tag{15}$$

where $\widetilde{x}(t)$ denotes the desired tracking error state of all UAVs in the virtual formation structure of team tracking process.

Then, we get the following shifted nonlinear multi-UAV networked team formation system:

$$d\widetilde{x}(t) = [\tilde{f}(\widetilde{x}(t)) + \tilde{g}(\widetilde{x}(t))\tilde{u}(t) + H\overline{v}(t)]dt + \sum_{i=1}^{N}[\tilde{\sigma}_i(\widetilde{x}(t))dW_i(t) + \tilde{\Gamma}_i(\widetilde{x}(t))dN_i(t)] \tag{16}$$

where $\tilde{f}(\widetilde{x}(t)) = \overline{f}(\widetilde{x}(t) + e_d)$, $\tilde{g}(\widetilde{x}(t)) = \overline{g}(\widetilde{x}(t) + e_d)$, $\widetilde{u}(t) = \widetilde{K}(\widetilde{x}(t-\eta(t)) - e_k(t)) = \overline{K}(\widetilde{x}(t-\eta(t)) - e_k(t) + e_d)$, $\tilde{\sigma}_i(\widetilde{x}(t)) = \overline{\sigma}_i(\widetilde{x}(t) + e_d)$, $\tilde{\Gamma}_i(\widetilde{x}(t)) = \overline{\Gamma}_i(\widetilde{x}(t) + e_d)$, $e_k(t) = \widetilde{x}(i_k h) - \widetilde{x}(t_k h)$, $t \in \Omega_l^{(t_k)}$. For the simplicity of notation, and the transmission condition of the event-triggered mechanism for the multi-UAV networked team tracking system in Fig. 2 can be reformulated as:

$$\begin{aligned} t_{k+1}h = t_k h + \min_{l>0, l\in\mathbb{N}} \{lh | E\{e_k(t)^T \Phi e_k(t)\} \\ \geq \sigma E\{[\widetilde{x}(t-\eta(t)) - e_k(t)]^T \Phi [\widetilde{x}(t-\eta(t)) - e_k(t)]\} \end{aligned} \tag{17}$$

where $i_k h = t_k h + lh$. The transmission condition depends on the tracking error of the latest transmission instant $\widetilde{x}(t_k h) = \widetilde{x}(t-\eta(t)) - e_k(t)$, and the variation of the tracking error between the current sampling instant and the latest transmission instant, i.e., $\widetilde{x}(i_k h) - \widetilde{x}(t_k h) = e_k(t)$. (17) is similar to the event-triggered in (3) but with one UAV state being replaced by the shifted tracking error of the multi-UAV team.

Thus, the origin $\widetilde{x}(t) = 0$ of the nonlinear multi-UAV networked team tracking error dynamic system in (16) is at the desired steady state (target of the desired team formation) e_d of the augmented nonlinear multi-UAV networked team tracking dynamic system in (14), i.e., the multi-UAV team formation tracking problem in (14) with the desired tracking target e_d is transformed an equivalent stabilization problem at the origin $\widetilde{x}(t) = 0$ of the shifted nonlinear multi-UAV networked team tracking error dynamic system in (16). This origin shift makes the design procedure of virtual leader formation tracking problem of multi-UAV team much simpler.

With the help of the shifted event-triggered multi-UAV networked team tracking system in (16) and (17), the H_∞ robust team formation tracking strategy in (9) can be reformulated as the following equivalent H_∞ stabilization problem of the shifted multi-UAV networked team tracking system in (16):

$$J_\infty(\widetilde{u}(t)) = \sup_{\bar{v}(t)\in L_F^2(\mathbb{R}^+;\mathbb{R}^{12(N+1)})} \frac{E\{\int_0^{t_f}[\widetilde{x}(t)\overline{Q}\widetilde{x}(t)]dt - V(\widetilde{x}(0))\}}{E\{\int_0^{t_f}[\bar{v}^T(t)\bar{v}(t)]dt\}} \tag{18}$$

where $\overline{Q} = diag\{0, Q_1, \cdots, Q_N\}$, $V(\widetilde{x}(0))$ is the positive function of initial used to represent the effect of the initial condition. In the robust H_∞ event-triggered multi-UAV team formation tracking design, our goal is to design a specific controller $\widetilde{u}(t)$ to achieve the H_∞ team formation tracking performance in (18) under a prescribed disturbance attenuation level ρ^2, i.e. $J_\infty(\widetilde{u}(t)) \leq \rho^2$ in (18).

Remark 6: By the augmented multi-UAV networked system in (10) and (14) and the shifted multi-UAV networked system in (15) and (16), the complex H_∞ team formation control problem of N UAVs in (9) to track the desired reference model becomes the robust H_∞ stabilization problem in (18) of the shifted multi-UAV networked team tracking system in (16).

Before the design of event-triggered H_∞ team formation tracking control of multi-UAV system, the following lemmas are necessary.

Lemma 1 [34]: Consider the Lyapunov function $V(\cdot) \in C^2$ with $V(\cdot) \geq 0$ and $V(0) = 0$. For the stochastic nonlinear system in (16), the Itô–Lévy formula of $V(\widetilde{x}(t))$ is given as follows:

$$\begin{aligned} dV(\widetilde{x}(t)) = [V_{\widetilde{x}}^T[\widetilde{f}(\widetilde{x}(t)) + \widetilde{g}(\widetilde{x}(t))\widetilde{u}(t) + H\bar{v}(t)] \\ + \sum_{i=1}^{N}\frac{1}{2}\tilde{\sigma}_i^T(\widetilde{x}(t))V_{\widetilde{x}\widetilde{x}}\tilde{\sigma}_i(\widetilde{x}(t))]dt + \sum_{i=1}^{N}[V_{\widetilde{x}}^T \\ \times \widetilde{\sigma}_i(\widetilde{x}(t))dW_i(t) + \{V(\widetilde{x}(t) + \widetilde{\Gamma}_i(\widetilde{x}(t))) \\ - V(\widetilde{x}(t))\}dN_i(t)] \end{aligned} \tag{19}$$

Lemma 2 [42], [43]: For any arbitrary matrix A and B (or vector) with appropriate dimension, the following inequality holds for any $\beta > 0$:

$$A^T B + B^T A \leq \beta^{-1} A^T A + \beta B^T B \tag{20}$$

Then the main theorem of the event-triggered H_∞ team tracking control design for the nonlinear stochastic multi-UAV networked control system is given as follows:

Theorem 1: Consider the stochastic nonlinear event-triggered multi-UAV networked team tracking system in (16) with the event-triggered mechanism in (17). If one could specify a nonlinear tracking controller $\widetilde{u}(t) = \widetilde{K}(\widetilde{x}(t-\eta(t)) - e_k(t))$ and the event-triggered weighting matrix $\Phi = \Phi^T > 0$ such that the following HJI-constraint has a positive solution $V(\widetilde{x}(t)) > 0$ with $V(0) = 0$ and $V(\cdot) \in C^2$

$$\tilde{x}^T(t)\bar{Q}\tilde{x}(t) + V_{\tilde{x}}^T\tilde{f}(\tilde{x}(t)) + V_{\tilde{x}}^T\tilde{g}(\tilde{x}(t))\tilde{u}(t) + \frac{1}{4\rho^2}V_{\tilde{x}}^T HH^T V_{\tilde{x}} + \sum_{i=1}^{N}\frac{1}{2}\tilde{\sigma}_i^T(\tilde{x}(t))V_{\tilde{x}\tilde{x}}\tilde{\sigma}_i(\tilde{x}(t)) + \sum_{i=1}^{N}\lambda_i\{V(\tilde{x}(t)+\tilde{\Gamma}_i(\tilde{x}(t))) - V(\tilde{x}(t))\} \leq 0 \quad (21)$$

then the robust event-triggered H_∞ team tracking control performance (18) of the multi-UAV networked team tracking system under the event-triggered mechanism in (17) is guaranteed for a prescribed attenuation level ρ^2 for the arbitrary external disturbance $\bar{v}(t) \in \mathcal{L}^2_{\mathcal{F}}(\mathbb{R}^+; \mathbb{R}^{12(N+1)})$.

Proof: Please refer to Appendix A. □

IV. ROBUST H_∞ TEAM TRACKING CONTROL DESIGN OF STOCHASTIC EVENT-TRIGGERED MULTI-UAV NETWORKED CONTROL SYSTEM VIA T-S FUZZY MODEL

In general, in order to deal with the robust H_∞ event-triggered team tracking control problem for stochastic nonlinear multi-UAV networked control system, we need to solve the nonlinear partial differential HJI in (21). However, HJI in (21) is difficult to be solved analytically and directly. Therefore, a T–S fuzzy model is introduced to approximate the nonlinear stochastic system by interpolating several local linear stochastic systems through fuzzy bases. Under the assumption that the state variables are accessible and bounded, the mth rule of the T-S fuzzy model for the stochastic nonlinear event-triggered multi-UAV shifted team tracking dynamic system in (16) can be described as [39]

Plant Rule m :

If $\varpi_{i,1}(t)$ *is* $G_{m,1}, \cdots,$ *and* $\varpi_{i,g}(t)$ *is* $G_{m,g}$,

Then

$$d\tilde{x}_i(t) = (A_{im}\tilde{x}_i(t) + B_{im}\tilde{u}_i(t) + v_i(t) - r(t))dt + C_{im}\tilde{x}_i(t)dW_i(t) + D_{im}\tilde{x}_i(t)dN_i(t),$$
$$\text{for } m = 1, 2, \ldots, L, \text{ and } i = 1, 2, \ldots, N \quad (22)$$

where $\tilde{x}_i(t) = x_i(t) - x_v(t) - e_{di}$, L is the number of the fuzzy rules. $A_{im}, B_{im}, C_{im}, D_{im}$ are the local linearization matrices with appropriate dimensions, $\tilde{u}_i(t)$ is ith control input in $\tilde{u}(t)$, $\varpi_{i,1}(t), \varpi_{i,2}(t), \cdots, \varpi_{i,g}(t)$ are the premise variables related to the state of the ith UAV in the virtual structure and $G_{m,1}, G_{m,2}, \cdots, G_{m,g}$ are the fuzzy sets and g is the number of the premise variables of the each UAV. Then we define the grade of membership function of mth rule $\mu_m(\varpi_i(t))$ as

$$\mu_m(\varpi_i(t)) = \prod_{s=1}^{g} G_{m,s}(\varpi_{i,s}(t)) \geq 0 \quad \text{for } m = 1, 2, \cdots, L, \quad (23)$$

where $G_{m,s}(\varpi_{i,s}(t))$ is the membership grade of $\varpi_{i,s}(t)$ in $G_{m,s}$. $\varpi_i(t) = [\varpi_{i,1}(t), \cdots, \varpi_{i,g}(t)]$. It is obviously that $\sum_{m=1}^{L}\mu_m(\varpi_i(t)) \geq 0$ and the mth interpolation functions of the ith UAV can be inferred as follows

$$\bar{h}_m(\varpi_i(t)) = \frac{\mu_m(\varpi_i(t))}{\sum_{m=1}^{L}\mu_m(\varpi_i(t))} \geq 0 \quad (24)$$

which satisfies the following property

$$\sum_{m=1}^{L}\bar{h}_m(\varpi_i(t)) = 1 \quad (25)$$

Based on T-S fuzzy model (22)-(25), the overall nonlinear event-triggered multi-UAV team tracking system in (16) can be represented by

$$d\tilde{x}(t) = \sum_{m=1}^{L}h_m(\varpi(t))[\bar{A}_m\tilde{x}(t) + \bar{B}_m\tilde{u}(t) + H\bar{v}(t)]dt + \sum_{i=1}^{N}\{\bar{C}_{im}\tilde{x}(t)dW_i(t) + \bar{D}_{im}\tilde{x}(t)dN_i(t)\},$$
$$k \in \mathbb{N}, t \in [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t(k+1)}) \quad (26)$$

where

$$\begin{aligned}
\bar{A}_m &= diag\{A_r, A_{1m}, A_{2m}, \cdots, A_{Nm}\}\\
\bar{B}_m &= diag\{0, B_{1m}, B_{2m}, \cdots, B_{Nm}\}\\
\bar{C}_{1m} &= diag\{0, C_{1m}, 0, \cdots, 0\}\\
&\vdots\\
\bar{C}_{im} &= diag\{0, 0, \cdots, C_{im}, \cdots, 0\}\\
&\vdots\\
\bar{C}_{iN} &= diag\{0, 0, \cdots, C_{Nm}\}\\
\bar{D}_{1m} &= diag\{0, D_{1m}, 0, \cdots, 0\}\\
&\vdots\\
\bar{D}_{im} &= diag\{0, 0, \cdots, D_{im}, \cdots, 0\}\\
&\vdots\\
\bar{D}_{Nm} &= diag\{0, 0, , \cdots, D_{Nm}\}\\
h_m(\varpi(t)) &= diag\{I_{12}, \bar{h}_m(\varpi_1(t))I_{12}, \cdots, \bar{h}_m(\varpi_N(t))I_{12}\}
\end{aligned}$$

By the similar way, the fuzzy model of the event-based controller for the ith UAV in the multi-UAV team tracking system can be described as follows:

Control Rule n :

If $\varpi_{i,1}(t_k h)$ *is* $G_{n,1}, \ldots,$ *and* $\varpi_{i,g}(t_k h)$ *is* $G_{n,g}$

Then

$$\tilde{u}_i(t) = \bar{K}_{in}[x_i(t_k h) - x_v(t_k h) - e_{di}], k \in \mathbb{N},$$
$$t \in [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t(k+1)})$$
$$\text{for } n = 1, 2, \ldots, L, \text{ and } i = 1, 2, \ldots, N \quad (27)$$

By combining the definitions of (5) and (11), the control signal of multi-UAV team tracking system in (16) is generated after the zero-order holder:

$$\begin{aligned}\tilde{u}(t) &= \widetilde{K}(\widetilde{x}(t-\eta(t)) - e_k(t)) \\ &= \sum_{n=1}^{L} h_n(\varpi(\bar{t}_k))[\bar{K}_n(\widetilde{x}(t-\eta(t)) - e_k(t))], \\ &\quad k \in \mathbb{N}, t \in [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t(k+1)}) \end{aligned} \tag{28}$$

where $\bar{K}_n = diag\{0, \bar{K}_{1n}, \cdots, \bar{K}_{Nn}\}$ denotes the fuzzy control matrices to be designed, $h_n(\varpi(\bar{t}_k) = diag\{I_{12}, \bar{h}_n(\varpi_1(\bar{t}_k), \cdots, \bar{h}_n(\varpi_N(\bar{t}_k))\}$ is the augmented interpolation function and $\bar{t}_k = t_k h$ is the delay time instant that ground control station receives the state information.

Remark 7: Due to the networked induced delay, the ground control station receives the delayed state information and the fuzzy controller depends on the delayed state information. This fact implies that the firing mechanisms of the plant and controller are asynchronous [47].

Then by combining the T-S fuzzy model of the multi-UAV team tracking system and the fuzzy controller above, the overall stochastic nonlinear event-triggered multi-UAV shifted team tracking dynamic system in (16) can be rewritten as follows:

$$\begin{aligned} d\widetilde{x}(t) &= \sum_{m=1}^{L} h_m(\varpi(t)) \sum_{n=1}^{L} h_n(\varpi(\bar{t}_k))\{[\bar{A}_m \widetilde{x}(t) \\ &\quad + \bar{B}_m \bar{K}_n(\widetilde{x}(t-\eta(t)) - e_k(t)) + H\bar{v}(t)]dt \\ &\quad + \sum_{i=1}^{N}[\bar{C}_{im}\widetilde{x}(t)dW_i(t) + \bar{D}_{im}\widetilde{x}(t)dN_i(t)]\}, \\ &\quad k \in \mathbb{N}, t \in [t_k h + \tau_{t_k}, t_{k+1}h + \tau_{t(k+1)}) \end{aligned} \tag{29}$$

Remark 8: In this design, the fuzzy approximation error is state dependent and very complex. It can be merged into the random fluctuations and its effect can be efficiently attenuated by the proposed robust H_∞ team formation tracking control.

V. H∞ FUZZY EVENT-TRIGGERED TEAM TRACKING CONTROL DESIGN OF STOCHASTIC MULTI-UAV NETWORKED SYSTEM WITH TIME-VARYING DELAY

After using the T-S fuzzy model in (29) to approximate stochastic nonlinear event-triggered multi-UAV team tracking system in (16), we are now going to transform the complicated HJIs in (21) into a set of LMIs. To begin with, we select the Lyapunov function for the event-triggered multi-UAV shifted team tracking error dynamic system in (16) as $V(t) = \tilde{x}^T(t)P\tilde{x}(t)$, where P is a positive definite symmetric matrix $P = P^T > 0$. Then, we have following theorem:

Theorem 2: In the stochastic event-triggered multi-UAV shifted team tracking error dynamic system (29), for the given scalars $1 > \sigma \geq 0, \rho > 0, \bar{\eta} > 0$ and the event-triggered scheme in (17), if we can find some matrices $W = diag\{W_0, W_1, \cdots, W_N\}$ with $W_j > 0$, for $j = 0, \cdots, N$, $\bar{Y}_n = diag\{0, \bar{Y}_{1n}, ...\bar{Y}_{Nn}\}$, for $n = 1, \cdots, L$, $\Phi = \Phi^T > 0, \alpha > 0$ with appropriate dimension as the solutions of the following bilinear matrix inequalities (BMIs):

$$\begin{bmatrix} \Xi_{11}^m & \begin{matrix}\bar{B}_m\bar{Y}_n - \alpha I \\ +(\bar{\eta}+2)W\end{matrix} & -\bar{B}_m\bar{Y}_n & 2W \\ * & \Xi_{22} & -\sigma W\Phi W & -\bar{\eta}W \\ * & * & (\sigma-1)W\Phi W & 0 \\ * & * & * & -\alpha I \end{bmatrix} \leq 0, \quad for\ m, n = 1, 2, \ldots, L \tag{30}$$

where $\Xi_{11}^m = W\bar{Q}W + W\bar{A}_m^T + \bar{A}_m W + \frac{1}{\rho^2}HH^T + \sum_{i=1}^{N}[W\bar{C}_{im}^T W^{-1}\bar{C}_{im}W + \lambda_i(W\bar{D}_{im}^T + \bar{D}_{im}W + W\bar{D}_{im}^T W^{-1}\bar{D}_{im}W)] - 4W + \alpha I$, $\Xi_{22} = -2\bar{\eta}W + \alpha I + \sigma W\phi W$, then the fuzzy controller gains can be constructed as $\bar{K}_n = \bar{Y}_n W^{-1}, n = 1, 2, \ldots, L$ and the robust H_∞ team tracking control performance in (18) of the multi-UAV system (16) under the discrete event-triggered scheme in (17) can be guaranteed under a prescribed attenuation level ρ^2 for an arbitrary external disturbance $\bar{v}(t) \in \mathcal{L}^2_{\mathcal{F}}(\mathbb{R}^+; \mathbb{R}^{12(N+1)})$.

Proof: Please refer to Appendix B. □

Remark 9: Due to the fact $\alpha > 0$, $\Phi > 0$ and $1 > \sigma \geq 0$, the diagonal terms (3,3) and (4,4) in (30) must be negative definite. Moreover, there have design variables $-4W < 0$ and $-2\bar{\eta}W < 0$ in (1,1) block and (2,2) block, respectively. Thus, it is able to solve (30) in Theorem 2 by Matlab LMI TOOLBOX and the proposed two-step design procedure in the sequel.

In fact the inequalities in (30) are BMIs which are still complicated to be solved, and therefore we employ a two-step procedure to solve the event-triggered H_∞ robust team tracking control problem. The reason is that the diagonal components in (30) have some unsolvable coupled-variables such as $\sigma W\Phi W$ which can not be dealt by the Schur complement. Since all the diagonal terms in (30) should be negative definite if (30) holds, we first solve the term $\Xi_{11}^m \leq 0$ in (30) to obtain the variable W and α, then by substituting W into the BMI in (30) as an LMI, the solvable LMI for $\bar{Y}_n$ and Φ can be obtained. The two-step procedure for solving BMIs in (30) is given in the following:

Step 1: The inequality (30) implies that $\Xi_{11}^m \leq 0$, i.e.

$$\begin{aligned} &W\bar{Q}W + W\bar{A}_m^T + \bar{A}_m W + \frac{1}{\rho^2}HH^T \\ &\quad + \sum_{i=1}^{N}[W\bar{C}_{im}^T W^{-1}\bar{C}_{im}W + \lambda_i(W\bar{D}_{im}^T + \bar{D}_{im}W \\ &\quad + W\bar{D}_{im}^T W^{-1}\bar{D}_{im}\, W) - 4W + \alpha I \leq 0 \end{aligned} \tag{31}$$

By Schur complement, (31) is equivalent to the following LMI:

$$\begin{bmatrix} \widetilde{\Xi}_{1,1}^{m,n} & \widetilde{\Xi}_{1,2}^{m,n} \\ * & \widetilde{\Xi}_{2,2}^{m,n} \end{bmatrix} \leq 0 \tag{32}$$

where $\widetilde{\Xi}_{1,1}^{m,n} = W\bar{A}_m^T + \bar{A}_m W + \sum_{i=1}^{N}\lambda_i(W\bar{D}_{im}^T + \bar{D}_{im}W) + \alpha I - 4W$, $\widetilde{\Xi}_{1,2}^{m,n} = [H, W\bar{Q}^{\frac{1}{2}}, W\bar{C}_{1m}^T, \cdots, W\bar{C}_{Nm}^T, W\bar{D}_{1m}^T, \cdots, W\bar{D}_{Nm}^T], \widetilde{\Xi}_{2,2}^{m,n} = diag\{-\rho^2, -I,$

$-W, \cdots, -W, -\frac{1}{\lambda_1}W, \cdots, -\frac{1}{\lambda_N}W\}$. By solving the LMI in (32) for W and α, it will be used in the rest of the design procedure.

Step 2: Substituting W and α obtained from LMIs in (32) into the BMI in (30), (30) become LMIs and the design variables $\bar{Y}_n$, Φ can be obtained by solving the LMIs in (30). Moreover, the corresponding fuzzy control gains can be constructed as $\bar{K}_n = \bar{Y}_n W^{-1}$.

Thus, the optimal H_∞ team tracking control problem of the multi-UAV networked system can be formulated as the following LMIs-constrained optimization problem to achieve the optimal H_∞ event-triggered team tracking performance:

$$\rho_0^2 = \min_{W,\{\bar{Y}_n\}_{n=1}^L,\Phi} \rho^2$$
$$\text{subject to } W = W^T > 0, \Phi > 0, \text{(30) and (32)}. \tag{33}$$

By solving the EVP in (33), we can achieve the optimal H_∞ team tracking performance in (18) to optimally suppress the effect of external disturbance and continuous and discontinuous intrinsic random fluctuation as possible, and efficiently save the energy and communication load of the networked device under the event-triggered weighting matrix Φ at the same time.

Remark 10: For the proposed LMIs-constrained optimization problem in (33), the design variables are α, W, $\{\bar{Y}_n\}_{n=1}^L$ and Φ. According to the dimensions of these design variables, the computation complexity in (33) is $O((n(n+1))^{2.75}L^{1.5})$ where n is the dimension of variable W, L is the number of fuzzy IF-THEN rules [42].

Remark 11: Since the upper bound of induced delay $\overline{\eta} > 0$ and threshold parameter of event-triggered mechanism σ are considered in the LMI constraints in (30)*, the feasibility of* (30) *depends on these two prescribed parameters. Mathematically, the LMIs will be more feasible if these parameters are decreased. In this situation, however, the designed fuzzy sample controller becomes much conservative. For example, if $\sigma = 0$, the designed fuzzy sample controller becomes the conventional time-triggered controller and it will increase the energy consumption and bandwidth load in the wireless networked system. On the other hand, with the consideration of small $\overline{\eta}$ in* (30)*, the designed fuzzy sample controller can only be applied to the networked system with great channel quality. As a result, the trade-off of these two parameters in designing the controller should be carefully treated by the designer.*

VI. SIMULATION RESULT

In this section, we provide a simulation example to validate the effectiveness of the proposed robust event-triggered H_∞ virtual structure formation team tracking control strategy for the 4-VTOL-UAV networked control system as shown in Fig. 4 with stochastic jump diffusions, time-varying delays and external disturbances. The stochastic shifted team tracking error dynamic model of the 4 VTOL-UAVs is shown in (16) with the event-triggered mechanism in (17), and the parameters of 4 VTOL-UAVs in networked control system are given as follows [44]: $m = 2kg$ is the mass of each UAV. The coefficients of the translation drag forces $f_x = f_y = f_z = 0.01Ns/m$ and aerodynamic friction coefficients $f_\phi = f_\theta = f_\psi = 0.012Ns/m$. $g = 9.8m/s^2$ denotes the acceleration of gravity. $J_\phi = J_\theta = J_\psi = 0.013Ns^2/rad$ are the moments of inertia of each UAV. In this simulation example, the virtual structure of UAV team is set as a square-shape structure. As a result, we respectively set the initial positions of four UAVs at (+0.2,+0.2,0),(-0.2,+0.2,0),(-0.2,-0.2,0),(+0.2,-0.2,0) on the ground. Obviously, the virtual leader reference is initially at the origin

To construct the T-S fuzzy model of each UAV, the premise variables of each UAV are defined as $\varpi_{i,1} = \phi_1^i$, $\varpi_{i,2} = \theta_1^i$ for $i = 1, 2, 3, 4$ in (22) and (27), and they are used to interpolate the nonlinear UAV system by a set of local linear UAV systems. For each premise variable, the operation points are chosen as $-\pi/9, 0, \pi/9$ and the grade of membership function is selected as trapezoidal function. Based on the above setting, each UAV has 9 fuzzy rules and there are totally 6561 fuzzy rules for the whole multi-UAV networked team tracking control system.

By using MATLAB system identification toolbox, the dynamic model of the *qth* rule within 6561 rules of the fuzzy-based nonlinear stochastic shifted multi-VTOL-UAV event-triggered team tracking networked system is written as follows:

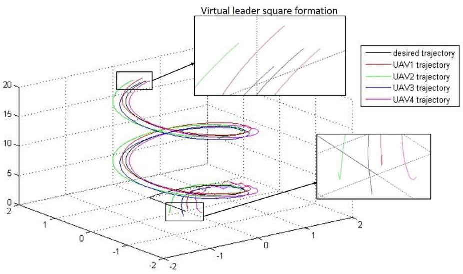
$$d\tilde{x}(t) = [A_q\tilde{x}(t) + B_qK_q(\tilde{x}(t-\eta(t)-e_k(t)) + H\bar{v}(t)]dt + \sum_{i=1}^{N}[\bar{C}_i\tilde{x}(t)dW_i(t) + \bar{D}_i\tilde{x}(t)dN_i(t)] \tag{34}$$

where A_q and B_q are matrices by generated by MATLAB system identification toolbox and $\{\bar{C}_i, \bar{D}_i\}_{i=1}^4$ are matrices of random process:

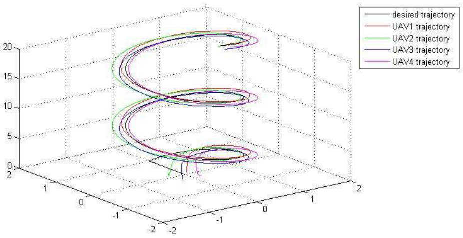
$$\bar{C}_1 = diag\{0, C, 0, 0, 0\}, \bar{D}_1 = diag\{0, D, 0, 0, 0\}$$
$$\bar{C}_2 = diag\{0, 0, C, 0, 0\}, \bar{D}_2 = diag\{0, 0, D, 0, 0\}$$
$$\bar{C}_3 = diag\{0, 0, 0, C, 0\}, \bar{D}_3 = diag\{0, 0, 0, D, 0\}$$
$$\bar{C}_4 = diag\{0, 0, 0, 0, C\}, \bar{D}_4 = diag\{0, 0, 0, 0, D\}$$

with $C = diag\{0, 0.2, 0, 0.2, 0, 0.2, 0, 0.2, 0, 0.2, 0, 0.2\}$ and $D = diag\{0, 0.2, 0, 0.2, 0, 0.2, 0, 2, 0, 2, 0, 2\}$. Besides, the Poisson jump intensities are set as $\{\lambda_i = 0.1\}_{i=1}^4$ and the external disturbances are set to be Gaussian noises with zero means and unit variance. If the event-triggered threshold parameter $\sigma = 0.1$ and the sampling period $h = 0.01$sec are set, then from (6) and [41], $\overline{\eta} = 0.0869\ s$, which means the maximum allowable upper delay bound $\overline{\tau} = 0.0769s$,i.e., the time-varying delay from the sensor to the controller is set within $0 \leq \tau_{t_k} \leq 0.0769$.

In this simulation, we tend to make the UAV team tracking on a desired spiral upward path and the initial position of the



(a) H_∞ event-triggered team formation tracking control scheme with $h = 0.01\sigma = 0.1$.



(b) H_∞ periodic time-triggered team formation tracking control scheme
with $h = 0.01$.

FIGURE 5. The 3D formation tracking flight trajectory of the 4-UAV team. (a) the trajectory is under event-triggered scheme $\sigma = 0.1$. (b) the trajectory is under periodic time-triggered scheme.

UAV team is set as the square formation. The virtual leader reference input vector in (8) is given as follows:

$$r(t) = [x_d(t), \dot{x}_d(t), y_d(t), \dot{y}_d(t), z_d(t), \dot{z}_d(t), \phi_d(t), \dot{\phi}_d(t), \theta_d(t), \dot{\theta}_d(t), \psi_d(t), \dot{\psi}_d(t)]$$

with the reference position: $x_d(t) = sin(0.5t)$, $y_d(t) = \cos(0.5t)$, $z_d(t) = 0.8t$, respectively. Besides, the reference attitude of ϕ_d, θ_d and ψ_d are given as follows:

$$\begin{aligned} \phi_d &= \frac{1}{2}\arcsin(d_x \sin(\psi_d) - d_y \cos(\psi_d)), \\ \theta_d &= \frac{1}{2}\arcsin(\frac{d_x \cos(\psi_d) + d_y \sin(\psi_d)}{\cos(\phi_d)}), \\ \psi_d(t) &= 0. \end{aligned}$$

where $d_x = 10(x - x_d) + 5(x - x_d)^{'}, d_y = 10(y - y_d) + 5(y - y_d)^{'}$. Moreover, the asymptotically stable matrix is chosen as $A_r = -I$ in (8). The reason why we define such complicated reference attitude is that we tend to simulate the real behavior of the multiple UAVs during the team flight, i.e., when UAV leads to the changes in the x position and y position, it needs to change the roll or pitch attitude to cause the translation motion. However, the yaw attitude is set to zero in this case.

The H_∞ team formation tracking control strategy in (18) is used to design the event-triggered multiple VTOL-UAVs networked control system. Since the tracking of position and attitude of each UAV are more significant than the tracking of velocity and angle velocity, the following weighting matrices

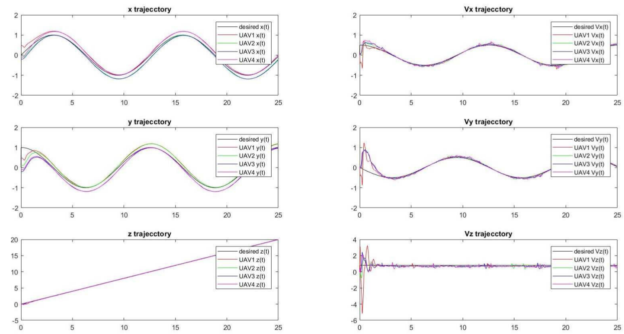


FIGURE 6. The position and the velocity tracking trajectory of the virtual structure UAV formation team. The effect of random fluctuation due to Wiener process and Poisson process in Fig. 8 and external disturbance are effectively attenuated by the proposed H_∞ team formation tracking control strategy.

of UAV are given as:

$$Q_i = diag\{1, 0.001, 1, 0.001, 1, 0.001, 1, 0.001, 1, 0.001, 1, 0.001\}, \quad for\ i = 1, 2, 3, 4.$$

By solving the LMIs-constrained optimization problem in (33), we have the optimal disturbance attenuation level $\rho^* = 3.2105$ and the corresponding fuzzy controller in (28). The result in Fig. 5 (a) shows the actual 3-D UAV team formation flight trajectory under the proposed H_∞ event-triggered team tracking scheme. In the result of Fig. 5 (a), the four UAVs can well track on the trajectory of the virtual leader while maintaining the square team formation structure despite external disturbances and intrinsic continuous Wiener fluctuation and discontinuous Poisson fluctuation. Compared with the result in Fig. 5 (b) with the traditional periodically time-triggered scheme with $\sigma = 0$, we can see that the trajectory in Fig. 5 (a) oscillates more substantially during the transient stage. It means that the team formation tracking performance in event-triggered scheme will be slightly degraded due to the saving of communication loading and energy waste. However, the multi-UAV team can finally finish the team tracking task of spiral upward maneuvering flight in a square shape formation under such a severe situation. The UAV team tracking trajectories in Figs. 6, 7 are separated into twelve components of each UAV state. The simulation result in Fig. 6 includes the position x, y, z and the velocity v_x, v_y, v_z of the four UAVs while simulation result in Fig. 7 includes the angular ϕ, θ, ψ and the angular velocity v_ϕ, v_θ, v_ψ of the four UAVs. We can see the effect of time-varying delay in Fig. 7 especially on v_ψ. The continuous Wiener process and the discontinuous Poisson counting process of the four UAVs are described in Fig. 8(a) and Fig. 8(b), respectively.

Fig. 9 shows the released instants of the stochastic UAV team formation tracking system under the event-triggered scheme in (17), i.e., if the event-triggered condition is met, sensor will release a signal $\widetilde{x}(t_k h)$ to the controller to generate a control signal $\widetilde{u}(t_k h)$ to actuator, otherwise the actuator would use the last control signal and sensor would not release signal. Released interval is defined as the interval between

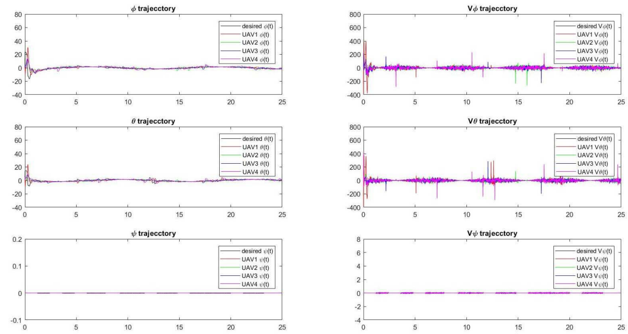
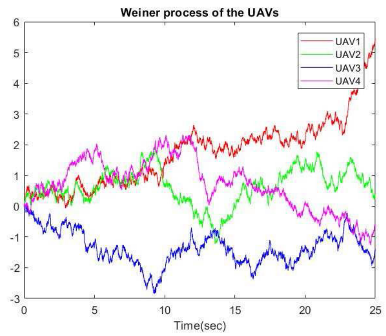
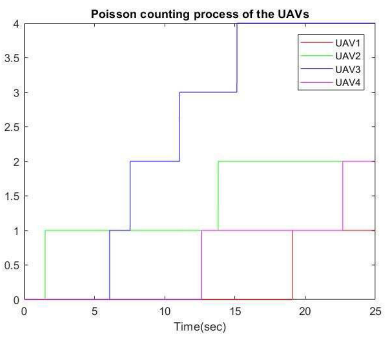


FIGURE 7. The angular and angular velocity tracking trajectory of the virtual structure multi-UAV formation team. The effect of the intrinsic fluctuations (Wiener process and Poisson process in Fig. 8) and time-varying delay can be observed in the simulation, especially on V_ψ.



(a) Wiener process of the four UAVs.



(b) Poisson counting process of the four UAVs.

FIGURE 8. The stochastic random process of the UAV formation team tracking system, including continuous Wiener process in (a) and the discontinuous Poisson process in (b).

two released sequential instants and we can see that the maximum released interval is $0.38s$ in our case. Compared with the periodically time-triggered scheme, the stochastic event-triggered multi-UAV team tracking strategy we proposed can save 67% of energy and communication loading. It means that our method only costs 33% of the consumption of energy and communication resource. In summary, the proposed robust H_∞ event-triggered team tracking control strategy will make the formation tracking performance of multi-UAV team within a desired disturbance attenuation level but it can save lots of energy and communication loading which become more and more important in the future application for the multi-UAV networked control system in smart city.

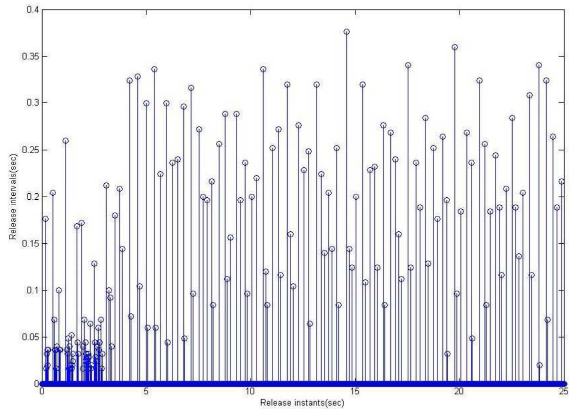


FIGURE 9. The released instants and the released intervals of the proposed event-triggered scheme for the multi-UAV team formation tracking system. The maximum released interval is 0.38 sec. Due to the transient response at the beginning, the control signal needs to be released more times than the sequels.

VII. CONCLUSION

In this study, the stochastic H_∞ virtual structure team tracking control strategy embedded with event-triggered mechanism is proposed for the formation design problem of multi-UAV networked system in future smart city. To describe the uncertainties, interference and delay in networked system, the intrinsic random fluctuation, time-varying delay and unknown external disturbances from the environment are considered in the proposed nonlinear stochastic multi-UAV networked system. To make the multiple UAVs track a fixed virtual structure formation, a shifted team tracking dynamic system is constructed to simplify the design procedure. Therefore, the event-triggered team tracking control problem can be transformed to an HJI-constrained optimization problem. However, for practical application, it is still difficult to be solved analytically and numerically. Thus, T-S fuzzy method is applied such that the HJI-constrained optimization problem can be replaced by the LMI-constraint optimization problem and the H_∞ event-triggered team tracking problem of the multi-VTOL-UAV system can be solved efficiently with the help of MATLAB LMI toolbox. In the simulation result, the 4-VTOL-UAVs networked system successfully achieve the square-shape formation tracking with a robust H_∞ team tracking performance and the communication load and energy consumption are greatly reduced than the traditional periodically time-triggered scheme. In the future, along with the increasing of mission complexity, the number of UAVs in the team formation system may increase substantially. In this case, a large amount UAVs in the network team tracking control system can not be controlled through one controller due to the large computational complexity. Thus, the centralized control is not workable for a large UAVs networked team tracking control system. Moreover, under the framework of networked control design, the UAVs team tracking control system not only suffers from channel interference but also receives malicious signal from the attacker. Hence, the future works will focus on the decentralized control design of UAVs networked team tracking system and fault-tolerant control design of UAVs networked team tracking control system under malicious attack.

APPENDIX A
PROOF OF THEOREM 1

Define a positive function $V(\tilde{x}(t)) \geq 0$ with $V(0) = 0$, $V(\cdot) \in C^2$, we have

$$E\{\int_0^{t_f} dV(\tilde{x}(t)) + V(\tilde{x}_0) - \lim_{t\to t_f} V(\tilde{x}(t))\} = 0 \tag{35}$$

Then, by using Itô–Lévy formula in Lemma 1 with the fact that $E[dW_i(t)] = 0$ and $E[dN_i(t)] = \lambda_i dt, for\ i = 1, \cdots, N$, (35) can be written as:

$$\begin{aligned}
&E\{V(\tilde{x}_0) - \lim_{t\to t_f} V(\tilde{x}(t)) + \int_0^{t_f} [V_{\tilde{x}}^T \tilde{f}(\tilde{x}(t)) + V_{\tilde{x}}^T \\
&\times \tilde{g}(\tilde{x}(t))\tilde{u}(t) + V_{\tilde{x}}^T H\bar{v}(t) + \sum_{i=1}^N \frac{1}{2}\tilde{\sigma}_i^T(\tilde{x}(t))V_{\tilde{x}\tilde{x}}\tilde{\sigma}_i(\tilde{x}(t)) \\
&+ \sum_{i=1}^N \lambda_i[V(\tilde{x}(t) + \tilde{\Gamma}_i(\tilde{x}(t))) - V(\tilde{x}(t))]]dt\} = 0
\end{aligned} \tag{36}$$

By (35) and (36), the numerator of robust H_∞ tracking performance in (18) can be written as:

$$\begin{aligned}
&E\{\int_0^{t_f} \tilde{x}^T(t)\bar{Q}\tilde{x}(t)\} \\
&= E\{\int_0^{t_f} \tilde{x}^T(t)\bar{Q}\tilde{x}(t)dt + \int_0^{t_f} dV(\tilde{x}(t))\} \\
&\quad + E\{V(\tilde{x}_0)\} - E\{\lim_{t\to t_f} V(\tilde{x}(t))\} \\
&\leq E\{V(\tilde{x}_0) + E\{\int_0^{t_f} \tilde{x}^T(t)\bar{Q}\tilde{x}(t) + V_{\tilde{x}}^T\tilde{f}(\tilde{x}(t)) \\
&\quad + V_{\tilde{x}}^T\tilde{g}(\tilde{x}(t))\tilde{u}(t) + V_{\tilde{x}}^T H\bar{v}(t) \\
&\quad + \sum_{i=1}^N \frac{1}{2}\tilde{\sigma}_i^T(\tilde{x}(t))V_{\tilde{x}\tilde{x}}\tilde{\sigma}_i(\tilde{x}(t)) \\
&\quad + \sum_{i=1}^N \lambda_i[V(\tilde{x}(t) + \tilde{\Gamma}_i(\tilde{x}(t))) - V(\tilde{x}(t))]dt\}
\end{aligned} \tag{37}$$

By applying Lemma 2, the term $V_{\tilde{x}}^T H\bar{v}(t)$ in (37) can be relaxed as

$$\begin{aligned}
V_{\tilde{x}}^T H\bar{v}(t) &= \frac{1}{2}V_{\tilde{x}}^T H\bar{v}(t) + \frac{1}{2}\bar{v}^T(t)H^T V_{\tilde{x}} \\
&\leq \frac{1}{4\rho^2}V_{\tilde{x}}^T HH^T V_{\tilde{x}} + \rho^2\bar{v}^T(t)\bar{v}(t)
\end{aligned} \tag{38}$$

By substituting (38) into (37), the following inequality holds:

$$\begin{aligned}
&E\{\int_0^{t_f} \tilde{x}^T(t)\bar{Q}\tilde{x}(t)\} \\
&\quad \leq E\{V(\tilde{x}_0) + \int_0^{t_f} \tilde{x}^T(t)\bar{Q}\tilde{x}(t) + V_{\tilde{x}}^T\tilde{f}(\tilde{x}(t)) \\
&\qquad + V_{\tilde{x}}^T\tilde{g}(\tilde{x}(t))\tilde{u}(t) + \frac{1}{4\rho^2}V_{\tilde{x}}^T HH^T V_{\tilde{x}} \\
&\qquad + \rho^2\bar{v}^T(t)\bar{v}(t) + \sum_{i=1}^N \frac{1}{2}\tilde{\sigma}_i^T(\tilde{x}(t))V_{\tilde{x}\tilde{x}}\tilde{\sigma}_i(\tilde{x}(t)) \\
&\qquad + \sum_{i=1}^N \lambda_i[V(\tilde{x}(t) + \tilde{\Gamma}_i(\tilde{x}(t))) - V(\tilde{x}(t))]]dt\}
\end{aligned} \tag{39}$$

As a result, if the HJI in (21) is satisfied, i.e.,

$$\begin{aligned}
&\tilde{x}^T(t)\bar{Q}\tilde{x}(t) + V_{\tilde{x}}^T\tilde{f}(\tilde{x}(t)) + V_{\tilde{x}}^T\tilde{g}(\tilde{x}(t))\tilde{u}(t) \\
&\quad + \frac{1}{4\rho^2}V_{\tilde{x}}^T HH^T V_{\tilde{x}} + \sum_{i=1}^N \frac{1}{2}\tilde{\sigma}_i^T(\tilde{x}(t))V_{\tilde{x}\tilde{x}}\tilde{\sigma}_i(\tilde{x}(t)) \\
&\quad + \sum_{i=1}^N \lambda_i\{V(\tilde{x}(t) + \tilde{\Gamma}_i(\tilde{x}(t))) - V(\tilde{x}(t))\} \leq 0
\end{aligned} \tag{40}$$

then we can obtain the following inequality:

$$E\{\int_0^{t_f} \tilde{x}^T(t)\bar{Q}\tilde{x}(t)dt\} \leq E\{V(\tilde{x}_0) + \rho^2\int_0^{t_f} \bar{v}^T(t)\bar{v}(t)dt\}, \tag{41}$$

i.e., the robust H_∞ tracking performance in (18) is satisfied with $J_\infty(\tilde{u}(t)) \leq \rho^2$. Q.E.D.

APPENDIX B
PROOF OF THEOREM 2

In Theorem 1, the stochastic nonlinear event-triggered multi-UAV shifted dynamic system (16) will achieve the H_∞ team tracking performance if the constrained HJI in (21) is satisfied. By the T-S fuzzy model in (22) with the Lyapunov function $V(\tilde{x}(t)) = \tilde{x}^T(t)P\tilde{x}(t)$ and positive matrix P, we can rewrite the terms in (21) as follows:

$$V_{\tilde{x}}^T\tilde{f}(\tilde{x}(t)) = \sum_{m=1}^L h_m(\varpi(t))\tilde{x}^T(t)\left[\bar{A}_m^T P + P\bar{A}_m\right]\tilde{x}(t) \tag{42}$$

$$\begin{aligned}
&V_{\tilde{x}}^T\tilde{g}(\tilde{x}(t))\bar{K}(\tilde{x}(t-\eta(t))) \\
&\quad = \sum_{m=1}^L h_m(\varpi(t))\sum_{n=1}^L h_n(\varpi(\bar{t}_k))\{\tilde{x}^T(t)P\bar{B}_m\bar{K}_n \\
&\qquad \times \tilde{x}(t-\eta(t)) + \tilde{x}^T(t-\eta(t))\bar{K}_n^T\bar{B}_m^T P\tilde{x}(t) \\
&\qquad - \tilde{x}^T(t)P\bar{B}_m\bar{K}_n e_k(t) - e_k^T(t)\bar{K}_n^T\bar{B}_m^T P\tilde{x}(t)\}
\end{aligned} \tag{43}$$

$$\begin{aligned}
&\frac{1}{2}\tilde{\sigma}_i^T(\tilde{x}(t))V_{\tilde{x}\tilde{x}}\tilde{\sigma}_i(\tilde{x}(t)) \\
&\quad = (\sum_{m=1}^L h_m(\varpi(t))\bar{C}_{im}\tilde{x}(t))^T P(\sum_{k=1}^L h_k(\varpi(t))\bar{C}_{im}\tilde{x}(t))
\end{aligned}$$

$$\leq \sum_{m=1}^{L} h_m(\varpi(t))\tilde{x}^T(t)\left[\bar{C}_{im}^T P\bar{C}_{im}\right]\tilde{x}(t),\ \forall i=1,\cdots,N \tag{44}$$

$$\begin{aligned}\lambda_i\{V(\tilde{x}(t)+\tilde{\Gamma}_i(\tilde{x}(t)))-V(\tilde{x}(t))\}\\ =\lambda[(\tilde{x}(t)+\sum_{m=1}^{L}h_m(\varpi(t))\bar{D}_{im}\tilde{x}(t))^T P(\tilde{x}(t)\\ +\sum_{k=1}^{L}h_k(\varpi(t))\bar{D}_{ik}\tilde{x}(t))-\tilde{x}^T(t)P\tilde{x}(t)]\\ \leq \sum_{m=1}^{L}h_m(\varpi(t))\tilde{x}^T(t)\lambda_i[\bar{D}_{im}^T P+P\bar{D}_{im}\\ +\bar{D}_{im}^T P\bar{D}_{im}]\tilde{x}(t),\ \forall i=1,\cdots,N\end{aligned} \tag{45}$$

By the Newton-Leibniz formula [38] for the event-triggered team shifted tracking dynamic system in (26), we have:

$$\tilde{x}(t)-\tilde{x}(t-\eta(t)) = \int_{t-\eta(t)}^{t} d\tilde{x}(s) \tag{46}$$

$$\begin{aligned}\times\alpha(\int_{t-\eta(t)}^{t} d\tilde{x}(s))^T PP\int_{t-\eta(t)}^{t} d\tilde{x}(s)\\ =\alpha(\tilde{x}(t)-\tilde{x}(t-\eta(t))^T PP(\tilde{x}(t)-\tilde{x}(t-\eta(t))\end{aligned} \tag{47}$$

where $\alpha>0$ is the scalar design variable.

From the event-triggered mechanism in (17), we note that the control signal between the two transmitted sequential instants must satisfy the following inequality:

$$\begin{aligned}E\{[\tilde{x}(t-\eta(t))-e_k(t)]^T\sigma\Phi[\tilde{x}(t-\eta(t))-e_k(t)]\\ -e_k(t)^T\Phi e_k(t)\}>0,\\ for\ t\in[t_k h+\tau_{t_k}, t_{j+1}h+\tau_{t(k+1)}),\ k\in\mathbb{N}\end{aligned} \tag{48}$$

By (46), (47) and inequality (48), (39) can be written as:

$$\begin{aligned}E\{\int_0^{t_f}\tilde{x}^T(t)\bar{Q}\tilde{x}(t)dt\}\\ \leq E\{V(\tilde{x}(0))-V(\tilde{x}(t_f))+\int_0^{t_f}[\sum_{k=0}^{T}\sum_{m=1}^{L}\sum_{n=1}^{L}\chi_k(t)\\ \times h_m(\varpi(t))h_n(\varpi(\bar{t}_k))\tilde{x}^T(t)(\bar{Q}+\bar{A}_m^T P+P\bar{A}_m\\ +\frac{1}{\rho^2}PHH^T P+\sum_{i=1}^{N}\{\bar{C}_{im}^T P\bar{C}_{im}+\lambda_i[\bar{D}_{im}^T P+P\bar{D}_{im}\\ +\bar{D}_{im}^T P\bar{D}_{im}]\})\tilde{x}(t)+\tilde{x}^T(t)P\bar{B}_m\bar{K}_n\tilde{x}(t-\eta(t))\\ +\tilde{x}^T(t-\eta(t))\bar{K}_n^T\bar{B}_m^T P\tilde{x}(t)-\tilde{x}^T(t)P\bar{B}_m\bar{K}_n e_k(t)\\ -e_k^T(t)\bar{K}_n^T\bar{B}_m^T P\tilde{x}(t)]+2(-2\tilde{x}(t)+\bar{\eta}\tilde{x}(t-\eta(t)))^T\\ \times P(\tilde{x}(t)-\tilde{x}(t-\eta(t))-\int_{t-\eta(t)}^{t} d\tilde{x}(s))\\ +\alpha(\tilde{x}(t)-\tilde{x}(t-\eta(t))^T PP(\tilde{x}(t)-\tilde{x}(t-\eta(t))\\ -\alpha(\int_{t-\eta(t)}^{t} d\tilde{x}(s))^T PP\int_{t-\eta(t)}^{t} d\tilde{x}(s)\\ +s[\tilde{x}(t-\eta(t))-e_k(t)]^T\sigma\Phi[\tilde{x}(t-\eta(t))-e_k(t)]\\ -e_k(t)^T\Phi e_k(t)]dt+E\{\int_0^{t_f}\rho^2\bar{v}^T(t)\bar{v}(t)dt\}\\ =E\{\int_0^{t_f}\sum_{k=0}^{T}[\sum_{m=1}^{L}\sum_{n=1}^{L}\chi_j(t)h_m(\varpi(t))h_n(\varpi(\bar{t}_k))\xi_k^T(t)\\ \times\Xi_{m,n}\xi_k(t)]dt\}+E\{\rho^2\int_0^{t_f}\bar{v}^T(t)\bar{v}(t)dt+V(\tilde{x}(0))\}\end{aligned} \tag{49}$$

with

$$\xi_k(t)=[\tilde{x}^T(t),\tilde{x}^T(t-\eta(t)),e_k^T(t),\int_{t-\eta(t)}^{t} d\tilde{x}^T(s)]^T$$

$$\Xi_{m,n}=\begin{bmatrix}\Xi_{11}^m & \begin{matrix}P\bar{B}_m\bar{K}_n-\alpha PP\\ +(\bar{\eta}+2)P\end{matrix} & -P\bar{B}_m\bar{K}_n & 2P\\ * & \Xi_{22} & -\sigma\Phi & -\bar{\eta}P\\ * & * & (\sigma-1)\Phi & 0\\ * & * & * & -\alpha PP\end{bmatrix}$$

$$\chi_k(t)=\begin{cases}1, & t\in[t_j h+\tau_{t_j}, t_{j+1}h+\tau_{t(j+1)})\\ 0, & otherwise\end{cases} \tag{50}$$

where $\Xi_{11}^m=\bar{Q}+\bar{A}_m^T P+P\bar{A}_m+\frac{1}{\rho^2}PHH^T P+\sum_{i=1}^{N}\{\bar{C}_{im}^T P\bar{C}_{im}+\lambda_i[\bar{D}_{im}^T P+P\bar{D}_{im}+\bar{D}_{im}^T P\bar{D}_{im}]\}-4P+\alpha PP$, $\Xi_{22}=-2\bar{\eta}P+\sigma\Phi+\alpha PP$.

From the matrix structure of $\Xi_{m,n}$, $\Xi_{m,n}$ is independent from index k. Thus, if the following matrix inequalities hold:

$$\begin{aligned}\Xi_{m,n}\leq 0\\ for\ m,n=1,\cdots,L\end{aligned} \tag{51}$$

then we immediately have the following inequality:

$$E\{\int_0^{t_f}\tilde{x}^T(t)Q\tilde{x}(t)dt\}\leq E\{V(\tilde{x}_0)+\rho^2\int_0^{t_f}\bar{v}^T(t)\bar{v}(t)dt\} \tag{52}$$

which shows the event-triggered multi-UAV system will achieve the robust H_∞ team formation tracking performance in (18) under a prescribed level ρ^2.

However, due to the cross-couple terms in $\Xi_{m,n}$, the matrix inequality $\Xi_{m,n}\leq 0$ can not be solved by current convex techniques. Thus, the following relaxing condition is developed to deal with this problem. Define the positive matrix P as $P=diag\{P_0,P_1,\cdots,P_N\}$ with $P_i>0$, for $i=0,1,\cdots,N$. Then, by pre-multiplying and post-multiplying $\bar{W}=diag\{W,W,W,W\}$ with $W=P^{-1}$ to (51), we have

$$\begin{aligned}\bar{\Xi}_{m,n}\leq 0\\ for\ m,n=1,\cdots,L\end{aligned} \tag{53}$$

where

$$\bar{\Xi}_{m,n}=\begin{bmatrix}\bar{\Xi}_{11}^m & \begin{matrix}\bar{B}_m\bar{Y}_n-\alpha I\\ +(\bar{\eta}+2)W\end{matrix} & -\bar{B}_m\bar{Y}_n & 2W\\ * & \bar{\Xi}_{22} & -\sigma W\Phi W & -\bar{\eta}W\\ * & * & (\sigma-1)W\Phi W & 0\\ * & * & * & -\alpha I\end{bmatrix}, \tag{54}$$

$\bar{\Xi}_{11}^m = W\bar{Q}W + W\bar{A}_m^T + \bar{A}_mW + \frac{1}{\rho^2}HH^T + \sum_{i=1}^{N}\{W\bar{C}_{im}^T W^{-1}\bar{C}_{im}W + \lambda_i[W\bar{D}_{im}^T + \bar{D}_{im}W + W\bar{D}_{im}^T W^{-1}\bar{D}_{im}W]\} - 4W + \alpha I$, $\bar{\Xi}_{22} = -2\bar{\eta}W + \sigma W\Phi W + \alpha I$, $\bar{Y}_{in} = \bar{K}_{in}W_i$ and $\bar{Y}_n = diag\{0, \bar{Y}_{1n}, \bar{Y}_{2n}, \ldots, \bar{Y}_{Nn}\} = \bar{K}_nW$.

As a results, the matrix inequalities in (51) are transformed to the more relaxed BMIs in (53), i.e., the robust H_∞ team formation tracking performance in (18) is achieved under a prescribed level ρ^2 if the BMIs in (30) hold. The proof is done

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