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DISTRIBUTED EVENT-TRIGGERED COORDINATED CONTROL FOR QUAVS UNDER QUANTIZATION

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Abstract. *A distributed event-triggered (ET) coordinated control method is designed for quadrotor unmanned aerial vehicles (QUAVs) under quantization. The distributed disturbance observer is adopted to tackle the unknown external disturbance. On this basis, the distributed coordinated controller is designed. When the ET occurs, the distributed coordinated controller is quantized and updated to the actuator. Furthermore, the Lyapunov theorem is employed to analyze the stability of the whole closed-loop system. Finally, some experiment results based on the QUAVs are given to demonstrate the effectiveness of the proposed control method.*

Keywords: Distributed coordinated control, Event-triggered (ET), Quadrotor unmanned aerial vehicles (QUAVs), Quantization, Distributed disturbance observer

1. **Introduction.** In the last few years, due to the characteristics of simple structure, low cost, vertical takeoff, landing, and hover, the quadrotor unmanned aerial vehicle (QUAV) has been applied broadly in monitoring, road rescuing, and fire prevention [1]. One QUAV cannot satisfy the increasingly complex task due to its limited load capacity and short endurance time. By comparison, multiple QUAVs working together can transport more cargo and execute more complicated task than one single QUAV, such as the coordinated rescue, and strike [2]. Therefore, the coordinated control method has been developed rapidly and has a good development prospect in the military, chemistry, transportation and other industries.

In actual flight, QUAV is inevitably affected by the unknown external disturbance, which affects the stability of the system, and a serious disturbance even leads to the system out of control. To tackle this problem, the disturbance observer (DO) has been extensively studied [3-7]. In [3], the unknown external disturbance of the QUAV was estimated by the nonlinear DO. Furthermore, the controller was designed based on the output of the DO and the sliding mode control method. A fixed-time DO was presented to tackle the unknown external disturbance and the actuator faults in [4]. In [5], an extended state observer was designed with one parameter needed to be updated. A finite time DO was constructed to deal with the adverse effect of the unknown external disturbance in [6]. In [7], a finite-time extended state observer was designed to deal with the unknown external disturbance for networked QUAVs. In reviewing the above observations, how to improve the robustness of the QUAVs should be deeply researched.

The QUAVs need frequent communication during coordinated flights. To release the communication load, the event-triggered (ET) mechanism has attracted much attention in recent years [3,8-10]. In [8], a distributed ET controller was designed to deal with the coordinated control problem of QUAVs with unknown external disturbances. The

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attitude controller was designed with an ET mechanism including the unknown upper bound threshold in [9]. Furthermore, the quantization is also a typical way to release the communication load [5,10-12]. The appointed time controller for QUAVs in attitude loop with the quantization was designed in [5]. An adaptive fuzzy quantized control method was proposed by using the fuzzy logic system to deal with the trajectory tracking problem of QUAVs in [10]. Since frequent data transfers are required between QUAVs, how to release the communication load on the premise of stability of the system needs to be further studied.

To deal with the above problem, a distributed ET coordinated controller for QUAVs under quantization is designed to achieve the control objective with restricted communication resources and unknown external disturbances. To achieve the motivation, the distributed DO (DDO) is adopted to tackle the unknown external disturbance. Then, the distributed coordinated controller is designed. When the ET occurs, the controller is quantized and updated to the actuator only at the ET times. The contributions of this paper are shown as follows.

1) A novel DDO is constructed by using the information from the neighbors to estimate the unknown external disturbance.

2) To release the communication load, the ET mechanism and quantization are combined to not only reduce the number of communication, but also reduce the amount of data each communication occupies.

3) A real time flight experiment, which includes four QUAVs, is conducted to explain the superiority of the proposed controller. Compared with the literature, which only carries out the simulation, it is more convincing.

Inspired by the above literature, a distributed ET coordinated control method is designed for QUAVs under quantization. The remainder of this paper is organized as follows. Section 2 describes the problem statement and preliminaries. A distributed ET coordinated controller is designed based on the DDO in Section 3. The experiment results are given to demonstrate the effectiveness of the proposed control method in Section 4. Finally, Section 5 concludes this paper.

2. Problem Statement and Preliminaries.

2.1. The nonlinear model of QUAVs.

The dynamic model of the ith QUAV is modelled as [3]

$$\begin{cases} \dot{p}_i(t) = v_i(t) \\ \dot{v}_i(t) = \gamma_i(t) + B_i u_i(t) + w_i(t) \end{cases} \tag{1}$$

where $i = 1, 2, \dots, n$, $p_i = [p_{ix}, p_{iy}, p_{iz}]^{\mathrm{T}}$ and $v_i = [v_{ix}, v_{iy}, v_{iz}]^{\mathrm{T}}$ are the position and velocity of the ith QUAV, respectively. $\gamma_i = [-\zeta_{ix} v_{ix}/m_i, -\zeta_{iy} v_{iy}/m_i, -\zeta_{iz} v_{iz}/m_i - g]^{\mathrm{T}}$ is the nonlinear term, ζ_{ix}, ζ_{iy}, and ζ_{iz} are aerodynamic damping coefficients, m_i is the weight of the ith QUAV, g is the gravitational acceleration, $B_i = \frac{1}{m_i} I_3$, $u_i = [u_{ix}, u_{iy}, u_{iz}]^{\mathrm{T}}$ is the input of the ith QUAV, and $w_i = [w_{ix}, w_{iy}, w_{iz}]^{\mathrm{T}}$ is the unknown external disturbance of the ith QUAV.

2.2. Graph theory.

Suppose $G_g = (V_g, E_g, A_g)$ as an undirected and connected graph to describe the communication network. V_g, E_g, and $A_g = [a_{ij}]$ are vertexes, edges, and adjacency matrix, respectively. If the ith and jth vertexes can communicate with each other, then $a_{ij} = 1$; otherwise, $a_{ij} = 0$ [7]. $L_g = D_g - A_g$ is the Laplacian matrix, where $D_g = \mathrm{diag}\,(d_{1g}, d_{2g}, \dots, d_{ng})$ is the degree matrix with $d_{ig} = \sum_{j=1}^{n} a_{ij}$. As for the leader-follower system, an undirected graph is defined as $\bar{G}_g$. $B_g = \mathrm{diag}\,(b_{1g}, b_{2g}, \dots, b_{ng})$ is the leader adjacency matrix. If $b_{ig} = 1$, the ith follower can receive the data from the leader; otherwise, $b_{ig} = 0$ [2].

2.3. **Uniform quantizer.** Due to the limited communication resources of the system, a uniform quantization is modelled as [11]

$$q_u(u) = \begin{cases} u, & u_r - \dfrac{l}{2} \le u < u_r + \dfrac{l}{2} \\ 0, & -u_0 \le u < u_0 \\ -u, & -u_r - \dfrac{l}{2} \le u < -u_r + \dfrac{l}{2} \end{cases} \tag{2}$$

where $u_0 = l/2$ and $u_{r+1} = u_r + l$, $(r = 0, 1, 2, \ldots)$, l is the quantized interval, $q_u(u(t))$ is in the set of $U = \{0, \pm u_r\}$, and the quantized error satisfies $\Delta q_u \le l$.

To achieve the distributed ET coordinated controller, some Assumptions and Lemma are introduced.

Assumption 2.1. [3] *The reference trajectory of the leader* $p_l = [p_{lx}, p_{ly}, p_{lz}]^{\mathrm{T}}$, *and its derivatives* $\dot{p}_l$, *and* $\ddot{p}_l$ *are bounded.*

Assumption 2.2. [13] *The undirected graph* $\bar{G}_g$ *is connected. Furthermore,* $L_g + B_g$ *is a symmetric positive definite matrix.*

Assumption 2.3. [14] *The unknown external disturbance and its derivatives are bounded, and then there are two constants that satisfy* $\|w_i\| \le \psi_1$ *and* $\|\dot{w}_i\| \le \psi_2$.

Lemma 2.1. [15] *Suppose that there is a continuous positive function* $V(a)$ *satisfing* $\kappa_1(\|a\|) \le V(a) \le \kappa_2(\|a\|)$ *and* $\dot{V}(a) \le -\kappa_3 V(a) + \kappa_4$ *with bounded initial conditions, where* κ_1 *and* κ_2 *are class K functions,* κ_3 *and* κ_4 *are positive constants, then the solution is uniformly ultimately bounded.*

3. Distributed ET Coordinated Controller.

3.1. **Design of the DDO.** In this subsection, the DDO is developed to estimate the unknown external disturbance [16].

$$\begin{cases} \hat{w} = \xi + \mathrm{K}\dot{e}_p \\ \dot{\xi} = -\mathrm{K}\bar{L}\left(\gamma + Bu + \hat{w} - \ddot{\bar{p}}_l\right) \end{cases} \tag{3}$$

where $\hat{w} = \left[\hat{w}_1^{\mathrm{T}}, \hat{w}_2^{\mathrm{T}}, \ldots, \hat{w}_n^{\mathrm{T}}\right]^{\mathrm{T}}$ is the output of the DDO, $\hat{w}_i = [\hat{w}_{ix}, \hat{w}_{iy}, \hat{w}_{iz}]^{\mathrm{T}}$, $\xi = \left[\xi_1^{\mathrm{T}}, \xi_2^{\mathrm{T}}, \ldots, \xi_n^{\mathrm{T}}\right]^{\mathrm{T}}$ is the auxiliary variable, $\xi_i = [\xi_{ix}, \xi_{iy}, \xi_{iz}]^{\mathrm{T}}$, $\mathrm{K} = \mathrm{diag}(\mathrm{K}_1, \mathrm{K}_2, \ldots, \mathrm{K}_n)$ is the gain of the DDO, $\mathrm{K}_i = \mathrm{diag}(\mathrm{K}_{ix}, \mathrm{K}_{iy}, \mathrm{K}_{iz}) > 0$, $\bar{L} = (L_g + B_g) \otimes I_3$ with $\otimes$ as the Kronecker product, $\gamma = \left[\gamma_1^{\mathrm{T}}, \gamma_2^{\mathrm{T}}, \ldots, \gamma_n^{\mathrm{T}}\right]^{\mathrm{T}}$, $B = \mathrm{diag}(B_1, B_2, \ldots, B_n)$, $u = \left[u_1^{\mathrm{T}}, u_2^{\mathrm{T}}, \ldots, u_n^{\mathrm{T}}\right]^{\mathrm{T}}$, $\bar{p}_l = 1_n \otimes p_l$, $e_p = \left[e_{1p}^{\mathrm{T}}, e_{2p}^{\mathrm{T}}, \ldots, e_{np}^{\mathrm{T}}\right]^{\mathrm{T}}$ is the tracking error, and $e_{ip} = [e_{ipx}, e_{ipy}, e_{ipz}]^{\mathrm{T}}$ is defined as

$$e_{ip} = \sum_{i=1}^{N} a_{ij}(p_i(t) - p_j(t) - M_{ij}) + b_{ig}(p_i(t) - p_l(t) - M_i) \tag{4}$$

where M_{ij} is the desired distance between the ith and jth QUAV, and M_i is the desired distance between the ith QUAV and the leader.

Defining the estimate error $\tilde{w} = w - \hat{w}$ and differentiating it yield

$$\dot{\tilde{w}} = \dot{w} - \dot{\hat{w}} = \dot{w} - \mathrm{K}\bar{L}\tilde{w} \tag{5}$$

where $\tilde{w} = \left[\tilde{w}_1^{\mathrm{T}}, \tilde{w}_2^{\mathrm{T}}, \ldots, \tilde{w}_n^{\mathrm{T}}\right]^{\mathrm{T}}$, $\tilde{w}_i = [\tilde{w}_{ix}, \tilde{w}_{iy}, \tilde{w}_{iz}]^{\mathrm{T}}$, and $w = \left[w_1^{\mathrm{T}}, w_2^{\mathrm{T}}, \ldots, w_n^{\mathrm{T}}\right]^{\mathrm{T}}$.

3.2. **Design of the distributed ET coordinated controller.** The distributed ET coordinated controller is designed based on the DDO and the backstepping method. Then, we define

$$\left\{\begin{array}{l} z_1 = e_p \\ z_2 = v - \alpha \end{array}\right. \tag{6}$$

where $z_1 = \left[z_{11}^{\mathrm{T}}, z_{21}^{\mathrm{T}}, \ldots, z_{n1}^{\mathrm{T}}\right]^{\mathrm{T}}$, $z_{i1} = [z_{i1x}, z_{i1y}, z_{i1z}]^{\mathrm{T}}$, $z_2 = \left[z_{12}^{\mathrm{T}}, z_{22}^{\mathrm{T}}, \ldots, z_{n2}^{\mathrm{T}}\right]^{\mathrm{T}}$, $z_{i2} = [z_{i2x}, z_{i2y}, z_{i2z}]^{\mathrm{T}}$, $v = \left[v_1^{\mathrm{T}}, v_2^{\mathrm{T}}, \ldots, v_n^{\mathrm{T}}\right]^{\mathrm{T}}$, $\alpha = \left[\alpha_1^{\mathrm{T}}, \alpha_2^{\mathrm{T}}, \ldots, \alpha_n^{\mathrm{T}}\right]^{\mathrm{T}}$ is the virtual control law, and $\alpha_i = [\alpha_{ix}, \alpha_{iy}, \alpha_{iz}]^{\mathrm{T}}$.

Differentiating z_1 yields

$$\dot{z}_1 = \bar{L}\left(v - \dot{\bar{p}}_l\right) = \bar{L}\left(z_2 + \alpha - \dot{\bar{p}}_l\right) \tag{7}$$

Then, the virtual control law is designed as

$$\alpha = -\bar{L}^{-1} k_1 z_1 + \dot{\bar{p}}_l \tag{8}$$

where $k_1 = \mathrm{diag}(k_{11}, k_{21}, \ldots, k_{n1})$ and $k_{i1} = \mathrm{diag}(k_{i1x}, k_{i1y}, k_{i1z}) > 0$ are the designed parameters.

Substituting (8) into (7), we obtain

$$\dot{z}_1 = -k_1 z_1 + \bar{L} z_2 \tag{9}$$

Differentiating z_2 yields

$$\dot{z}_2 = \gamma + Bu + w - \dot{\alpha} \tag{10}$$

Then, the controller is designed as

$$\bar{u} = -B^{-1}\left(\gamma + \hat{w} - \dot{\alpha} + k_2 z_2 + \bar{L}^{\mathrm{T}} z_1\right) \tag{11}$$

where $\bar{u} = \left[\bar{u}_1^{\mathrm{T}}, \bar{u}_2^{\mathrm{T}}, \ldots, \bar{u}_n^{\mathrm{T}}\right]^{\mathrm{T}}$, $\bar{u}_i = [\bar{u}_{ix}, \bar{u}_{iy}, \bar{u}_{iz}]^{\mathrm{T}}$, $k_2 = \mathrm{diag}(k_{12}, k_{22}, \ldots, k_{n2})$ and $k_{i2} = \mathrm{diag}(k_{i2x}, k_{i2y}, k_{i2z}) > 0$ are the designed parameters.

To release the communication load, the ET mechanism based on the quantization is defined as

$$u_{iq}(t) = q_u\left(\bar{u}_{iq}\left(t_k^i\right)\right) \tag{12}$$

$$t_{k+1}^i = \inf\left\{t \in R, |H_{iq}| \geq \chi_{iq}\right\} \tag{13}$$

where $q = x, y, z$, $H_{iq} = \bar{u}_{iq}(t) - \bar{u}_{iq}\left(t_k^i\right)$, t_k^i is the ET time, and $\chi_{iq} > 0$ is the fixed threshold.

In $\left[t_k^i, t_{k+1}^i\right)$, we can obtain $|E_{iq}| \leq \chi_{iq}$. And there exists a time-varying function satisfying $\Gamma_{iq}\left(t_k^i\right) = 0$, $\Gamma_{iq}\left(t_{k+1}^i\right) = \pm 1$, and $|\Gamma_{iq}| \leq 1$. Then, we obtain

$$u = \bar{u} + \Gamma\chi + \Delta q_u \tag{14}$$

where $\Gamma = \mathrm{diag}(\Gamma_1, \Gamma_2, \ldots, \Gamma_n)$, $\Gamma_i = \mathrm{diag}(\Gamma_{ix}, \Gamma_{iy}, \Gamma_{iz})$, $\chi = \left[\chi_1^{\mathrm{T}}, \chi_2^{\mathrm{T}}, \ldots, \chi_n^{\mathrm{T}}\right]^{\mathrm{T}}$, $\chi_i = [\chi_{ix}, \chi_{iy}, \chi_{iz}]^{\mathrm{T}}$, $\Delta q_u = \left[\Delta q_{1u}^{\mathrm{T}}, \Delta q_{2u}^{\mathrm{T}}, \ldots, \Delta q_{nu}^{\mathrm{T}}\right]^{\mathrm{T}}$ is the quantization error, and $\Delta q_{iu} = \left[\Delta q_{iux}, \Delta q_{iuy}, \Delta q_{iuz}\right]^{\mathrm{T}}$.

3.3. **Stability analysis.**

Theorem 3.1. *Consider the nonlinear model (1) of the QUAVs under Assumptions 2.1, 2.2, and 2.3. If the uniform quantizer is designed as (2), the DDO is designed as (3), the distributed coordinated controller is designed as (11), and the ET mechanism is designed as (12), (13), all the closed-loop signals are bounded, and there is no Zeno Behavior.*

Proof: Consider the Lyapunov function candidate as

$$V = \frac{1}{2} z_1^{\mathrm{T}} z_1 + \frac{1}{2} z_2^{\mathrm{T}} z_2 + \frac{1}{2} \tilde{w}^{\mathrm{T}} \tilde{w} \tag{15}$$

Differentiating V yields

$$\begin{aligned} \dot{V} &= z_1^{\mathrm{T}} \dot{z}_1 + z_2^{\mathrm{T}} \dot{z}_2 + \tilde{w}^{\mathrm{T}} \dot{\tilde{w}} \\ &= z_1^{\mathrm{T}}\left(-k_1 z_1 + \bar{L} z_2\right) + z_2^{\mathrm{T}}\left(\tilde{w} - k_2 z_2 - \bar{L}^{\mathrm{T}} z_1 + B\Gamma\chi + B\Delta q_u\right) + \tilde{w}^{\mathrm{T}}\left(\dot{w} - \mathrm{K}\bar{L}\tilde{w}\right) \end{aligned}$$

$$= -z_1^{\mathrm{T}} k_1 z_1 + z_2^{\mathrm{T}} \tilde{w} - z_2^{\mathrm{T}} k_2 z_2 + z_2^{\mathrm{T}} B\Gamma\chi + z_2^{\mathrm{T}} B\Delta q_u + \tilde{w}^{\mathrm{T}} \dot{w} - \tilde{w}^{\mathrm{T}} \mathrm{K}\bar{L}\tilde{w} \tag{16}$$

According to Young's inequality, we obtain

$$z_2^{\mathrm{T}} \tilde{w} \le \frac{a_1}{2} z_2^{\mathrm{T}} z_2 + \frac{1}{2a_1} \tilde{w}^{\mathrm{T}} \tilde{w} \tag{17}$$

$$z_2^{\mathrm{T}} B\Gamma\chi \le \frac{a_2}{2} z_2^{\mathrm{T}} z_2 + \frac{1}{2a_2} \chi^{\mathrm{T}} \Gamma B B \Gamma \chi \tag{18}$$

$$z_2^{\mathrm{T}} B\Delta q_u \le \frac{a_3}{2} z_2^{\mathrm{T}} z_2 + \frac{1}{2a_3} \Delta q_u^{\mathrm{T}} B B \Delta q_u \tag{19}$$

$$\tilde{w}^{\mathrm{T}} \dot{w} \le \frac{a_4}{2} \tilde{w}^{\mathrm{T}} \tilde{w} + \frac{1}{2a_4} \psi_2^2 \tag{20}$$

where a_1, a_2, a_3, and a_4 are positive constants to be designed.

Thus, we obtain

$$\begin{aligned} \dot{V} &\le -z_1^{\mathrm{T}} k_1 z_1 - z_2^{\mathrm{T}} \left(k_2 - \left(\frac{a_1}{2} + \frac{a_2}{2} + \frac{a_3}{2} \right) I_{3n} \right) z_2 - \tilde{w}^{\mathrm{T}} \left(\mathrm{K}\bar{L} \left(\frac{1}{2a_1} + \frac{a_4}{2} \right) I_{3n} \right) \tilde{w} + \Delta \\ &= -kV + \Delta \end{aligned} \tag{21}$$

where $k = \min\Big(\lambda_{\min}(k_1), \lambda_{\min}\left(k_2 - \left(\frac{a_1}{2} + \frac{a_2}{2} + \frac{a_3}{2}\right) I_{3n}\right), \lambda_{\min}\Big(\mathrm{K}\bar{L} - \left(\frac{1}{2a_1} + \frac{a_4}{2}\right) I_{3n}\Big)\Big)$ and $\Delta = \frac{1}{2a_2}\chi^{\mathrm{T}}\Gamma B B \Gamma\chi + \frac{1}{2a_3}\Delta q_u^{\mathrm{T}} B B \Delta q_u + \frac{1}{2a_4}\psi_2^2$.

To ensure the system's stability, the designed parameters should satisfy $k_2 - \left(\frac{a_1}{2} + \frac{a_2}{2} + \frac{a_3}{2}\right) I_{3n} > 0$ and $\mathrm{K}\bar{L} - \left(\frac{1}{2a_1} + \frac{a_4}{2}\right) I_{3n} > 0$. By Lemma 2.1, the whole closed-loop signals are uniformly ultimately bounded. Otherwise, H is reset to zero at the ET instant, and we can obtain

$$\frac{d}{dt}\|H\| \le \frac{\left\|H^{\mathrm{T}}\right\| \left\|\dot{H}\right\|}{\|H\|} = \|\dot{\bar{u}}\| \tag{22}$$

where $H = \left[H_1^{\mathrm{T}}, H_2^{\mathrm{T}}, \ldots, H_n^{\mathrm{T}}\right]^{\mathrm{T}}$ and $H_i = [H_{ix}, H_{iy}, H_{iz}]^{\mathrm{T}}$.

Involving (21), one has $\dot{\bar{u}}$ is bounded. Furthermore, there is a constant $\Theta_{iq} > 0$, and $q = x, y, z$ satisfies $|\dot{\bar{u}}_{iq}| \le \Theta_{iq}$. We can obtain $\lim_{t \to t_{k+1}^i} |H_{iq}| = \chi_{iq}$ in the ET time. Thus, one has $t_{k+1}^i - t_k^i \ge \chi_{iq}/\Theta_{iq} > 0$, and there is no Zeno Behavior.

4. **Experiment Results.** Some flight experiments are implemented to verify the validity of the proposed control method. The platform and communication topology are shown in Figures 1 and 2, respectively. The initial position of the QUAVs is $(0, 0, 0)$ m, $(-1.158, 1.781, 0.101)$ m, $(-1.153, 0.867, 0.099)$ m, and $(-1.243, -1.232, 0.083)$ m. The parameters of the QUAV are $m_i = 0.3$ kg, $g = 9.8$ m/s^2, and $\xi_{ix} = \xi_{iy} = \xi_{iz} = 1.2$ Nm·s^2/rad. The reference trajectory of the leader is $p_{lx} = \sin(t)$ m, $p_{ly} = \cos(t)$ m, $p_{lz} = 1$ m, and the desired distances are $M_1 = [1, -1, 0]$ m, $M_{12} = [0, 1, 0]$ m, and $M_3 = [1, 1, 0]$ m. Furthermore, the designed parameters are $k_{i1} = \mathrm{diag}(1.25, 1.25, 1)$, $k_{i2} = \mathrm{diag}(2.5, 2.5, 2.5)$, $l = 0.005$, $\chi_{ix} = 0.001$, $\chi_{iy} = 0.001$, $\chi_{iz} = 0.001$, and $\mathrm{K}_i = \mathrm{diag}(0.5, 0.5, 0.5)$. The control parameters of the PID controller in attitude are $k_{iP\phi} = k_{iP\theta} = 5$, $k_{iP\mathrm{X}} = 2.8$, $k_{iPR\phi} = k_{iPR\theta} = 0.08$, $k_{iI\phi} = k_{iD\phi} = k_{iI\theta} = k_{iD\theta} = k_{iI\mathrm{X}} = k_{iD\mathrm{X}} = 0$, $k_{iIR\phi} = k_{iIR\theta} = 0.03$, $k_{iDR\phi} = k_{iDR\theta} = 0.001$, $k_{iDR\mathrm{X}} = 0$, and $k_{iPR\mathrm{X}} = k_{iIR\mathrm{X}} = 0.3$, where ϕ, θ, X are the roll, pitch, and yaw angle.

The trajectories of four QUAVs in the actual flight experiment are shown in Figure 3. Although QUAVs take off from different positions and the initial tracking errors are large, every QUAV can track its desired trajectory. On this basis, the desired formation is achieved. Thus, the presented distributed ET coordinated control method with quantization can realize the desired formation. Furthermore, the ET instants and intervals are shown in Figure 4. Although the ET instants are few from 16 s to 23 s, 28 s to 33 s, and

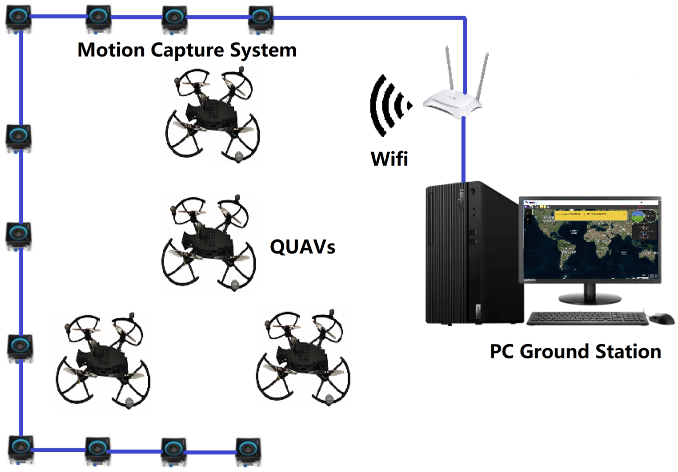

FIGURE 1. Platform

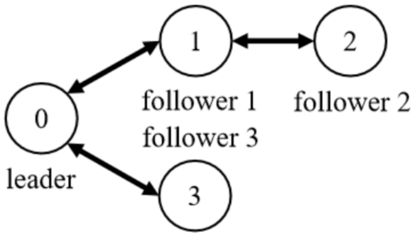

FIGURE 2. Communication topology

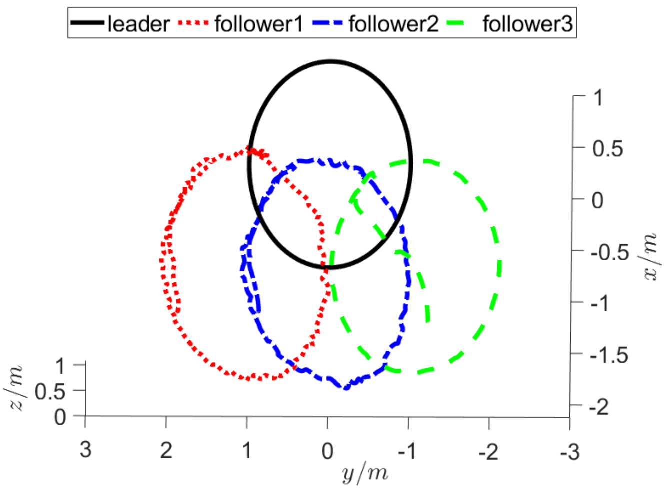

FIGURE 3. Trajectories of all QUAVs

0 s to 5 s in the first, second, and third subfigures, the satisfactory tracking errors are obtained in Figure 3. Furthermore, the communication efficiency is increased by 89.7%. Thus, the communication load is released on the premise of stability of the system.

Based on the flight experiments above, the distributed ET coordinated control method with quantization can realize the control objective of the QUAVs.

5. **Conclusions.** The distributed ET coordinated control method has been presented for QUAVs under quantization. The DDO was developed to tackle the unknown external disturbance. On this basis, the distributed coordinated controller was designed, quantized, and then updated to the actuator in the ET instant. Moreover, the Lyapunov method was

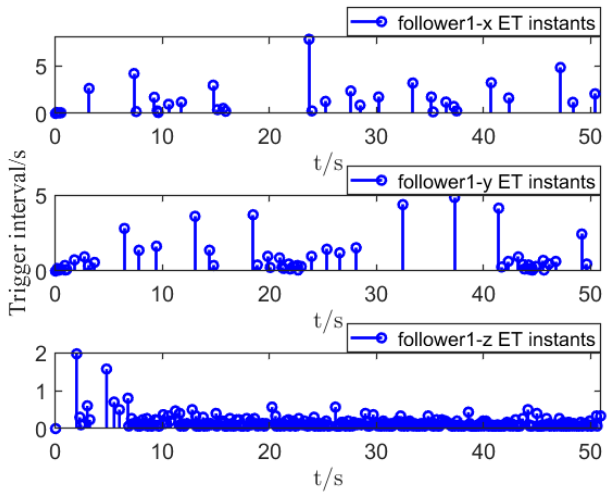

FIGURE 4. ET instants and intervals

employed to guarantee the stability of all closed-loop signals. Finally, the experiments were given to demonstrate the effectiveness of the proposed method. Furthermore, the distributed coordinated control problem with switching formation for QUAVs will be studied in the future.

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