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Application of Sliding Mode Control for Distributed Formation Trajectory Tracking of Multiple Quadrotor Uavs

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ABSTRACT
This paper proposes a distributed formation control scheme for a group of Quadrotors under limited communication constraints. Each Quadrotor only has access to local information from its neighbors, and the disconnections between the virtual leader and some followers may occur. To address this challenge, a distributed observer is designed to estimate the virtual leader's position using the desired positions of neighboring agents and its self. Then, a finite-time control law based on the terminal sliding mode control is developed for both position and attitude control, enabling each Quadrotor to accurately track the desired trajectory of the virtual leader while maintaining the desired formation shape. Theoretical analyses based on Lyapunov stability theory are provided to ensure the closed-loop stability of the system. Simulation results demonstrate the effectiveness of the proposed method, where four Quadrotors successfully track a virtual leader and maintain a square formation throughout the flight.

KEYWORDS: Multi-Quadrotor, Unmanded Aerial Vehicle (UAV), Distributed Formation Control, Terminal Sliding Mode Control

I. INTRODUCTION

In recent years, the formation control problem for multiple unmanned aerial vehicles (UAVs), particularly Quadrotors, has attracted significant attention from both academic and industrial communities due to a large range of important applications in surveillance, environmental monitoring, search and rescue, and precision agriculture[1] - [4].

The Quadrotor UAV is an underactuated system, respective to four independent control input while has six Degrees of Freedom (DoFs). Besides, the dynamics of the Quadrotor system is highly nonlinear and strongly coupled. The studies [5] - [7] in proposed a leader-follower formation scheme for multiple Quadrotors. Although the formation objective and the trajectory tracking to a leader can be achieved, the full connect between Quadrotor follower and leader must be ensured. In practical application, the disconnetion between leader and followers usually happen, which mean that each Quadrotor only can only receive limited local information from other Quadrotors. Therefore, the formation control problem for a group of Quadrotors becomes more challenges. To address these challenges, several formation control strategies based on consensus theory [8] - [14] have been proposed, which not require full connectivity among all agents. Although the studies in [8] - [11] not only address the distributed formation control problem for Multi-Quadrotors under limited communication constraints, but also achieve optimal trajectory tracking to a virtual leader. These approaches are offline methods, which offer limited practical value in real flight tasks, as Quadrotors typically operate in dynamically changing environments. As a result, their performance may degrade significantly when exposed to real-world uncertainties and disturbances. While the methods [12] - [14] are capable of achieving formation control in real-time, they do not consider important performance, such as ensuring trajectory tracking within a finite-time.

Motivated by the aforementioned discussions, this study proposes a distributed control strategy for a Multi-Quadrotor system, which not only enables each Quadrotor to track the leader within a finite time but also maintaine the desired formation shape. To achieve objective, a distributed state observer is introduced to estimate the position of the virtual leader, which address the challenge of the limited information exchange among Quadrotors within the team. After that, a finite-time terminal sliding control law is developed for both position and attitude control loops, enabling each Quadrotor to accurately track the desired trajectory in finite-time. Furthermore, robustness against noises, disturbances and uncertainties is also provided as a key advantage of the sliding mode control approach. The key contributions of this paper are listed as follows. Compared to [5] - [7], the proposed method introduces a distributed to estimate the position of the virtual leader using only local information from neighboring agents, effectively addressing the challenge of limited information exchange among Quadrotors. Unlike [8] - [11], the proposed finite-time controller enables each Quadrotor to accurately track the virtual leader's desired trajectory in real time, while guaranteeing the tracking errors convergence within a finite time and simultaneously maintaining the desired formation shape. Numerical simulations are conducted to verify the effectiveness of the proposed method.

The rest of this paper is organized as follows. Section 2 introduces the communication topology and presents the dynamic model of the Quadrotor UAVs. In Section 3, the distributed formation control scheme is developed, including the design of a distributed state observer and the finite-time controllers for both position and attitude loops. Simulation results demonstrate the effectiveness of the proposed method. Finally, Section 4 concludes the paper.

II. PROBLEM FORMULATION

2.1. Communication topology

Considering N Quadrotor UAVs labeled from 1 to N. The communication topology among the Quadrotors is described by a directed graph $G = (V, E, W)$, where $V = \{v_1, v_2, \dots, v_N\}$ represents a set of nodes, $E = \{e_{ij}\} \subseteq V \times V$ represents a set of edges, and $W = [w_{ij}] \in \boldsymbol{R}^{N\times N}$ represents an adjacency matrix with nonnegative weights. Each Quadrotor in the swarm represents a node in the communication topology. If there exists a connection between the i^{th} Quadrotor and the j^{th} Quadrotor, i.e., $(v_i, v_j) \in E$, then $w_{ij} > 0$; otherwise, $w_{ij} = 0$. The set of neighbors of the i^{th} Quadrotor is denoted as N_i, which includes all nodes j such that $(v_i, v_j) \in E$ or equivalently $w_{ij} > 0$. The Laplacian matrix is defined as $L = D - W$, where $D = diag(d_i) \in \boldsymbol{R}^{N\times N}, d_i = \sum w_{ij}$. Define $B = diag(b_i) \in \boldsymbol{R}^{N\times N}$, where b_i is the connection weight between the i^{th} Quadrotor and the virtual Quadrotor leader. If there exists a connection between the i^{th} Quadrotor and the virtual Quadrotor leader, i.e, $b_i > 0$; otherwise, $b_i = 0$. The messaging matrix is defined as $H = L + B$. A graph G is said to have a spanning tree if there exists a node, called the root, from which there are paths to all other nodes in the graph.

Assumption 1. It is assumed that the communication topology includes at least one spanning tree, ensuring that every Quadrotor is reachable from the virtual leader through a sequence of directed connections.

2.2. Quadrotor dynamics

Considering a group of multiple Quadrotor UAVs: a virtual leader and N followers. Each Quadrotor system is modeled as a rigid body equipped with four rotors, as shown in Figure 1.

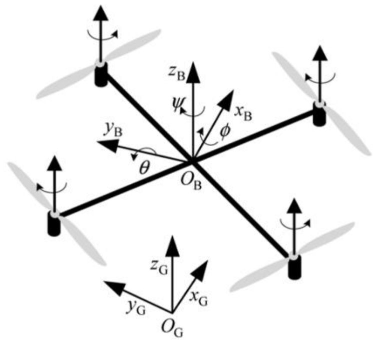

Figure 1. ***The Quadrotor system***

Define $p_i = [x_i, y_i, z_i]^T$ as the position vector of the i^{th} Quadrotor and $\eta_i = [\phi_i, \theta_i, \psi_i]^T$ as the attitude vector for the Euler angles of the i^{th} Quadrotor, where ϕ_i, θ_i and ψ_i represent the roll, pitch, and yaw angles, respectively. The vector $v_i = [v_{xi}, v_{yi}, v_{zi}]^T$ is defined as the linear velocity vector of the i^{th} Quadrotor of the $\Omega_i = [w_{xi}, w_{yi}, w_{zi}]^T$ is defined as the angular velocity vector of the i^{th} Quadrotor. According to [15], [16], the Quadrotor dynamics, including the position and attitude subsystem, can be expressed as follows

$$\begin{aligned} \dot{\boldsymbol{p}}_i &= \boldsymbol{v}_i \\ \dot{\boldsymbol{v}}_i &= -g\boldsymbol{e}_3 + \frac{\boldsymbol{u}_{Ti}}{\boldsymbol{m}_i}\boldsymbol{R}_{G2B}(\boldsymbol{\Omega}_i)\boldsymbol{e}_3 - \frac{\boldsymbol{J}_i}{\boldsymbol{m}_i}\boldsymbol{v}_i \\ \dot{\boldsymbol{\eta}}_i &= \boldsymbol{\Gamma}_i(\boldsymbol{\Omega}_i)\boldsymbol{\Omega}_i \\ \boldsymbol{I}_i\dot{\boldsymbol{\Omega}}_i &= -\boldsymbol{\Omega}_i \times (\boldsymbol{I}_i\boldsymbol{\Omega}_i) + \boldsymbol{\tau}_i \end{aligned} \quad (1)$$

where m_i is the mass of the i^{th} Quadrotor, $J_i = diag(J_{xi}, J_{yi}, J_{zi})$ is the diagonal aerodynamic matrix of the i^{th} Quadrotor, $I_i = diag(I_{xi},, I_{yi}, I_{zi})$ is the inertia matrix of the i^{th} Quadrotor, g is the gravity acceleration, $e_3 = [0,0,1]^T$, u_{Ti} is the total thrust, and $\tau_i = [\tau_{\phi i}, \tau_{\theta i}, \tau_{\psi i}]^T$ is the control torque. The rotation matrix $R_{G2B}(\Omega_i)$ and transformation matrix $\Gamma_i(\Omega_i)$ is the transformation matrix can be described as in [17]. In practical application, the control inputs

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$(u_{Ti}, \tau_{\phi i}, \tau_{\theta i}, \tau_{\psi i})$ can be gennerated by adjusting the speed of four rotors.From (1), the position and attitude dynamics [16] can be formulated as:

$$\begin{aligned} \ddot{x}_i &= -\frac{J_{xi}}{m_i}\dot{x}_i + \frac{1}{m_i}u_{xi} \\ \ddot{y}_i &= -\frac{J_{yi}}{m_i}\dot{y}_i + \frac{1}{m_i}u_{yi} \\ \ddot{z}_i &= -\frac{J_{zi}}{m_i}\dot{z}_i + \frac{1}{m_i}u_{zi} - g \end{aligned} \quad (2)$$

$$\begin{aligned} \ddot{\phi}_i &= -\frac{I_{yi} - I_{zi}}{I_{xi}}\dot{\theta}_i\dot{\psi}_i + \frac{1}{I_{xi}}\tau_{\phi i} \\ \ddot{\theta}_i &= -\frac{I_{xi} - I_{zi}}{I_{yi}}\dot{\phi}_i\dot{\psi}_i + \frac{1}{I_{yi}}\tau_{\theta i} \\ \ddot{\psi}_i &= -\frac{I_{yi} - I_{xi}}{I_{zi}}\dot{\phi}_i\dot{\theta}_i + \frac{1}{I_{zi}}\tau_{\psi i} \end{aligned} \quad (3)$$

where $u_{pi} = [u_{xi}, u_{yi}, u_{zi}]^T$ is the virtual position control input, which can be expressed as

$$\begin{aligned} u_{xi} &= u_{Ti}(\cos(\phi_i)\cos(\psi_i)\sin(\theta_i) + \sin(\phi_i)\sin(\psi_i)) \\ u_{yi} &= u_{Ti}(\cos(\phi_i)\sin(\psi_i)\sin(\theta_i) - \sin(\phi_i)\cos(\psi_i)) \\ u_{zi} &= u_{Ti}\cos(\phi_i)\cos(\theta_i) \end{aligned} \quad (4)$$

2.2. Problem statement

It is assumed that the position dynamics of the virtual leader is described as:

$$\begin{aligned} \dot{p}_0 &= v_0 \\ \dot{v}_0 &= u_0 \end{aligned} \quad (5)$$

where $p_0 = [x_0, y_0, z_0]^T$ and $v_0 = [\dot{x}_0, \dot{y}_0, \dot{z}_0]^T$ are the position and velocity vectors, respectively, and $u_0 = [u_{x0}, u_{yo}, u_{zo}]^T$ is the virtual position control input.

Assumption 2. It is assumed that the virtual position control input u_0 is bounded.

$$||\mathbf{u}_0|| \le \varepsilon_0 \quad (6)$$

Definition 1. Let $f_i = [f_{xi}, f_{yi}, f_{zi}]^T$ is the desired position deviation between the virtual leader and the i^{th} Quadrotor. The Multi-Quadrotor system with a virtual leader and N Quadrotor followers is said to achieve the formation trajectory tracking, if there exists a small constant $\varepsilon_i > 0$ such that:

$$\lim_{t\to\infty}||p_i(t) - f_i - p_0(t)|| \le \varepsilon_i \quad (7)$$

In this paper, the desired position deviation is considered to be constant. The control objective is to design a distributed formation control law that enables formation trajectory tracking with respect to a virtual leader while simultaneously maintaining the desired formation pattern among all agents.

III. FORMATION CONTROL DESIGN

3.1. Distributed formation observer design

It should be noted that the issue of disconnection between the virtual leader and the followers can happen, and each Quadrotor can only receive limited local information from other Quadrotors. To overcome this challenge, this secsion introduces a distributed formation observer that can generate the desired position for each Quadrotor of the team using the information of its neighbors and itself. The distributed formation observer is designed as follows:

$$\begin{aligned} \dot{\hat{p}}_i &= \hat{v}_i - k_{1i}\sum_{j=1}^{N} w_{ij}(\hat{p}_i - f_i - \hat{p}_j + f_j) + b_i(\hat{p}_i - f_i - p_0) \\ \dot{\hat{v}}_i &= -k_{2i}\sum_{j=1}^{N} w_{ij}(\hat{v}_i - \hat{v}_j) + b_i(\hat{v}_i - v_0) \end{aligned} \quad (8)$$

where k_{1i} and k_{2i} as positive constants. The vectors $\hat{p}_i$ and $\hat{v}_i$ are the desired position and velocity of the i^{th} Quadrotor, respectively. It should be noted that $b_i = 0$ when the Quadrotor is disconnected from the leader. Define the estimation error $\zeta_i = [\zeta_{pi}^T, \zeta_{vi}^T]^T$ of the distributed observer for the i^{th} Quadrotor as

$$\begin{aligned} \zeta_{pi} &= [\zeta_{xi}, \zeta_{yi}, \zeta_{zi}]^T = \hat{p}_i - f_i - p_0 \\ \zeta_{vi} &= \dot{\zeta}_{pi} = [\dot{\zeta}_{xi}, \dot{\zeta}_{yi}, \dot{\zeta}_{zi}]^T = \hat{v}_i - v_0 \end{aligned} \quad (9)$$

Theorem 1. The estimation error is input-to-state stable (ISS) if k_{1i} and k_{2i} are large enough.

Proof.

Taking the time derivative of (9) using (5) and (8), the dyanmics of the estimation error can be formulated as follows:

$$\begin{aligned} \dot{\zeta}_{pi} &= \zeta_{vi} - k_{1i}\sum_{j=1}^{N} w_{ij}(\zeta_{pi} - \zeta_{pj}) + b_i\zeta_{pi} \\ \dot{\zeta}_{vi} &= -k_{2i}\sum_{j=1}^{N} w_{ij}(\zeta_{vi} - \zeta_{vj}) + b_i\zeta_{vi} - u_0 \end{aligned} \quad (10)$$

Define the esitmation errors as follows:

$$\begin{aligned} \zeta_p &= [\zeta_{p1}^T, \zeta_{p2}^T, \dots, \zeta_{pN}^T]^T \\ \zeta_v &= [\zeta_{p1}^T, \zeta_{p2}^T, \dots, \zeta_{pN}^T]^T \end{aligned} \quad (11)$$

The dynamics of the esitmation error can be rewritten as:

$$\frac{d}{dt}\begin{bmatrix}\zeta_p\\ \zeta_v\end{bmatrix} = \begin{bmatrix}-k_{1i}(H\otimes I_3) & I_{3N}\\ 0 & -k_{2i}(H\otimes I_3)\end{bmatrix}\begin{bmatrix}\zeta_p\\ \zeta_v\end{bmatrix} + \begin{bmatrix}0_{3N}\\ -I_{3N}\otimes u_0\end{bmatrix} \quad (12)$$

Under the **Assumption 1**, all the eigenvalues of H have positive real parts. Additionally, u_0 is bounded according to the **Assumption 2**. By choosing k_{1i} and k_{2i} are large enough, the estimation error is input-to-state stable (ISS).

3.2. Position control design

By employing the distributed formation observer, the desired position reference of each Quadrotor is estimated accurately. The formation control problem of the Multi-Quadrotor UAV system is reduced to a fundamental problem of trajectory tracking for each Quadrotor. Define the position tracking error for each Quadrotor as follows:

$$e_{pi1} = [e_{xi}, e_{yi}, e_{zi}]^T = p_i - \hat{p}_i \quad (13)$$
$$e_{pi2} = \dot{e}_{pi1} = [\dot{e}_{xi}, \dot{e}_{yi}, \dot{e}_{zi}]^T = v_i - \hat{v}_i$$

Then, a terminal sliding surface is constructed as follows:

$$s_{pi} = e_{pi2} + \alpha_{pi}|e_{pi1}|^{\beta_{pi}}\, sign(e_{pi}) \quad (14)$$

where $\alpha_{pi} > 0$ and $0 < \beta_{pi} < 1$. The finite-time position control input $u_{pi} = [u_{px,i}, u_{py,i}, u_{pz,i}]^T$ is designed as follows:

$$u_{pi} = J_i v_i - m\Big([0,0,g]^T + \alpha_{pi}\beta_{pi}|e_{pi1}|^{\beta_{pi}-1}e_{pi2} - k_{pi1}s_{pi} - k_{pi2}sat(s_{pi})\Big) \quad (15)$$

where k_{pi1} and k_{pi2} are positive constant, and $sat(.)$ is described as:

$$sat(x) = \begin{cases} sign(x) & if\ |x| > 1\\ x & otherwises\end{cases} \quad (16)$$

Choosing the Lyapunov function as follows:

$$V_{pi} = \frac{1}{2}s_{pi}^T s_{pi} \quad (17)$$

Taking the time derivative of (19) using (17), we have:

$$\dot{V}_{pi} = s_{pi}^T\dot{s}_{pi} = s_{pi}^T\Big(-[0,0,g]^T - \frac{J_i}{m}v_i + \frac{1}{m}u_{pi} + \alpha_{pi}\beta_{pi}|e_{pi1}|^{\beta_{pi}-1}e_{pi2} - \ddot{\hat{p}}_i\Big) = -k_{pi1}s_{pi}^T s_{pi} - (k_{pi2}s_{pi}sat(s_{pi}) - \ddot{\hat{p}}_i) \le 0 \quad (18)$$

By choosing $k_{pi1} > 0$ and $k_{pi2} \ge ||\ddot{\hat{p}}_i||$, based on the Lyapunov stability theory, the position dynamics in (2) with the virtual position control law in (14) is asymptotically stable. Once the virtual position control input is determined, the desired attitude reference $\eta_{di} = [\phi_{di}, \theta_{di}, \psi_{di}]^T$ can be obtained from (4) as follows:

$$u_{Ti} = \sqrt{u_{xi}^2 + u_{yi}^2 + u_{zi}^2}$$
$$\phi_{di} = arcsin\left(\frac{u_{xi}\sin(\psi_{di}) - u_{yi}\cos(\psi_{di})}{u_{Ti}}\right) \quad (19)$$
$$\theta_{di} = \arctan\left(\frac{u_{xi}\cos(\psi_{di}) + u_{yi}\sin(\psi_{di})}{u_{zi}}\right)$$

where ϕ_{di}, θ_{di}, and ψ_{di} are the desired references of the roll, pitch and yaw angles, respectively. In practical application, the desired yaw reference ψ_{di} is usually set to zero.

3.3. Attitude control design

It is noted that there is a strong coupling between the position and attitude dynamics via the rotation matrix in [17]. Firstly, the dynamics of attitude subsystem in (3) is rewritten as:

$$\ddot{\eta}_i = F(\eta_i, \dot{\eta}_i) + I_i^{-1}\tau_i \quad (20)$$

Where:

$$F(\eta_i, \dot{\eta}_i) = \left[-\frac{I_{yi}-I_{zi}}{I_{xi}}\dot{\theta}_i\dot{\psi}_i \quad -\frac{I_{xi}-I_{zi}}{I_{yi}}\dot{\phi}_i\dot{\psi}_i \quad -\frac{I_{yi}-I_{xi}}{I_{zi}}\dot{\phi}_i\dot{\theta}_i\right]^T$$

The attitude tracking error is defined as

$$e_{\eta i1} = [e_{\phi i}, e_{\theta i}, e_{\psi i}]^T = \eta_i - \eta_{di} \quad (21)$$
$$e_{\eta i2} = \dot{e}_{\eta i1} = [\dot{e}_{\phi i}, \dot{e}_{\theta i}, \dot{e}_{\psi i}]^T = \dot{\eta}_i - \dot{\eta}_{di}$$

Then, a terminal sliding surface is constructed as follows

$$s_{\eta i} = e_{\eta i2} + \alpha_{\eta i}|e_{\eta i1}|^{\beta_{\eta i}}sign(e_{\eta i}) \quad (22)$$

where $\alpha_{\eta i} > 0$ and $0 < \beta_{\eta i} < 1$. Based on the terminal sliding surface in (22) and the attitude

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dynamics in (20), a finite-time position control input is designed as follows

$$\boldsymbol{\tau_i = -I_i\Big(F(\eta_i,\dot{\eta}_i) + \alpha_{\eta i}\beta_{\eta i}|e_{\eta i1}|^{\beta_{\eta i}-1}e_{\eta i2} - k_{\eta i1}s_{\eta i} - k_{\eta i2}sat(s_{\eta i}) + \ddot{\eta}_{di}\Big)} \quad (23)$$

where $k_{\eta i1}$ and $k_{\eta i2}$ are positive constants. Choosing the Lyapunov function as follows

$$\boldsymbol{V_{\eta i} = \frac{1}{2}s_{\eta i}^T s_{\eta i}} \quad (24)$$

Similar to the position control design, based on the Lyapunov stability theory, the attitude dynamics in (3) with the attitude control law in (22) is asymptotically stable.

IV. SIMULATION RESULT

In this section, a formation simulation built in Matlab software is provided to verify the effectiveness of the proposed method. In this flight simulation, four Quadrotors are adopted to follow the trajectory path oquadrotorstual leader while maintaining a square formation. The desired position deviations are set up as $f_1 = [4.0, 0.0, 0.0]^T, f_2 = [0.0, 4.0, 0.0]^T, f_3 = [-4.0, 0.0, 0.0]^T$, and $f_4 = [0.0, -4.0, 0.0]^T$. The predefined trajectory path of the virtual leader is configured as $p_0 = [\sin(0.5t), \cos(0.5t), 3.0]^T$. The communication tocology is given with $w_{12} = w_{23} = w_{34} = w_{41} = 1$ and $b_1 = 1$. It is assumed that the Quadrotor 2, 3, and 4 disconnect with the virtual leader, respective to $b_2 = b_3 = b_4 = 0$. Four Quadrotor systems are modeled with the same parameters as $m_i = 1.7\ (kg), g = 9.8\ (m/s^2)$, $J_i = 10^{-4}diag([5.67, 5.67, 5.67])(Ns), I_i = 10^{-3}diag([4.0, 4.0, 8.4])(kgm^2)$.

The control parameters are chosen as $\alpha_{pi} = \alpha_{\eta i} = 2$, $\beta_{pi} = \beta_{\eta i} = 0.5$, $k_{p1i} = 5.0$, $k_{\eta 1i} = 5.0$, $k_{p2i} = 0.5$, and $k_{\eta 2i} = 0.1$. The formation tracking errors of both position and attitude control loops are shown Figure 2. After 4 seconds, both tracking errors asymptotically converge to a bounded region around zero. Figure 3 shows the position and attitude responses of four Quadrotor. It is easy to observer that four Quadrotors achieve the formation trajectory tracking following a virtual leader. This is further illustrated in Figure 4, which shows the 3D trajectories of the Quadrotor formation while maintaining the desired formation shape throughout the tracking process. We see that the proposed controllers can accuracy track the trajactory of the virtual leader while maintaining the desired formation shape even in cases where Quadrotor 2, 3, and 4 lose connection with the virtual leader.

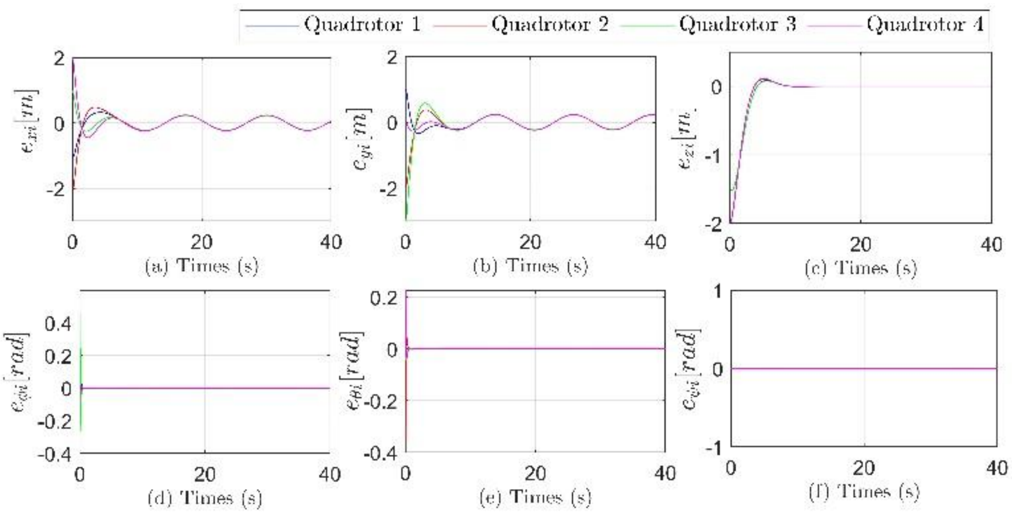

Figure 2. The position and attitude formation tracking errors

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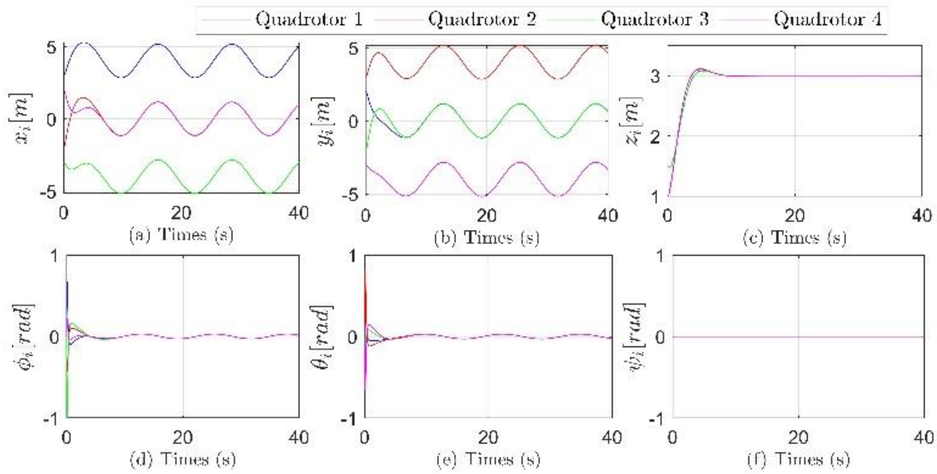

Figure 3. The position and attitude responses

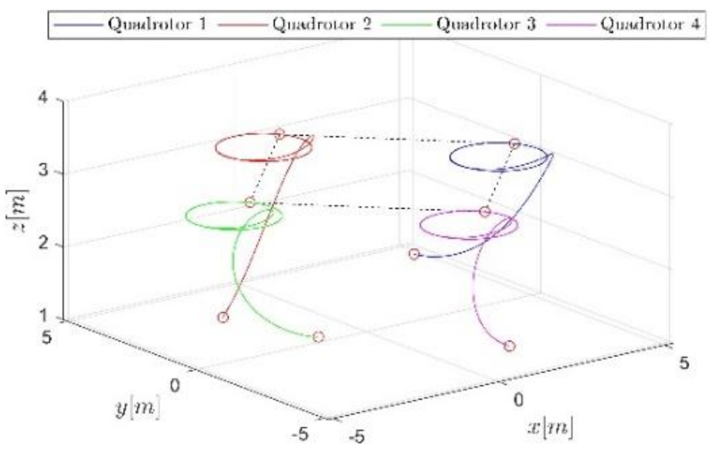

Figure 4. The 3D trajectory of four Quadrotors

V. CONCLUSION

This paper presents a distributed formation control scheme for a group of Quadrotor UAVs. It is worth noting that disconnections between the virtual leader and some followers may occur, and each Quadrotor has access only to limited local information from neighboring agents. To overcome this challenge, a distributed observer is proposed to estimate the position of the virtual leader by using its desired position and the desired position of neighbors. Then, a finte-time control law based terminal sliding mode control is developed for both position and attitude control loop, enabling each Quadrotor can accurately track to the virtual leader while maintain the desired formation shape. Theoretical analyses based on Lyapunov stability theory are provided to guarantee the stability of the closed-loop system. Finally, a formation flight simulation is conducted to verify the effectiveness of the proposed method. In this simulation, four Quadrotors successfully track a virtual leader while maintaining a square formation throughout the flight.

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