Research on Distributed Real-Time Formation Tracking Control of High-Order Multi-UAV System

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This work was supported in part by the National Science Foundation of China under Grant 61663032.

ABSTRACT To address the problem of real-time formation tracking control of multi-UAV systems, a high-order distributed real-time formation tracking control protocol is designed based on previous research. Firstly, the dynamic models of the third-order formation motion control subsystem and second-order formation attitude control subsystem are established based on the mathematical model with autopilot, and the algebraic graph theory is introduced. Secondly, considering the influence of the mass of the obstacle on the formation, the mass of the obstacle was introduced into the repulsive potential field function to improve the obstacle avoidance efficiency of the UAV. Then, according to the state information between the leader and follower of the UAV, as well as between the follower and its neighbors, a third-order real-time formation tracking control protocol is designed combined with the potential field and consensus theory. Finally, the stability is proved using the Lyapunov theory. The 3D simulation results show that the formation-tracking control accuracy and obstacle avoidance efficiency are improved by this control protocol.

INDEX TERMS Consensus theory, formation tracking control, third-order integrator, the repulsive potential field function.

I. INTRODUCTION
Unmanned aerial vehicles (UAVs) are widely used in military application [1]. However, as mission requirements continue to increase, a single UAV cannot meet the requirements of combat missions owing to its susceptibility to limitations in the combat range and strike accuracy. Scholars have proposed the concept of multi-UAV cooperative operations [2], [3]. Among them, formation-tracking control is the focus of research in the field of cooperative control of multi-UAV systems.

Formation tracking control means that the UAV follows the moving target in real time, and simultaneously adapts to the constraints of the battlefield environment (such as obstacle avoidance) [4]. In recent years, scholars have mainly used multi-agent consensus to study the problem of formation-tracking control. Consensus implies that each UAV will eventually converge its state to the same value through information interaction [5]. For example, [6] designed a second-order formation control algorithm combining the potential field and second-order consensus theory to achieve consensus of position and velocity. Reference [7] proposed a second-order consensus algorithm that successfully solved the problem of consensus formation. Reference [8] added formation information to the standard consensus algorithm and combined it with particle swarm optimization algorithm to achieve formation consensus control. Reference [9] designed a linear quadratic regulator using theories of consensus and matrix conversion to achieve distributed optimization. Reference [10] proposed a new type of consensus control method and achieved control objectives, such as the formation and consensus of state under switching communication topologies. Reference [11] designed a distributed consensus control algorithm using a fuzzy wave-shaped neural network and consensus theory to realize formation consensus control. Reference [12] designed a distributed consensus algorithm with a better control effect than the existing results. Reference [13] designed a multi-agent distributed control algorithm to achieve fully distributed low-complexity control. Reference [14] designed a second-order consensus control protocol that can make the consensus error converge to zero, and the tracking error can be reduced arbitrarily. Reference
[15] designed a distributed formation tracking protocol based on the Riccati inequality, and the tracker can achieve a time-varying model. Reference [16] designed an attitude-tracking control protocol based on the fast terminal sliding mode, which achieved fast synchronization and attitude tracking. Reference [17] designed a second-order distributed time-varying formation-tracking controller with a switched-directed network, which has a good tracking effect. Reference [18] designed a second-order time-varying group tracking control protocol that can solve the problem of multi-target tracking control.

Formation avoidance control has become an important aspect of this research direction [19], [20]. Many obstacle avoidance control algorithms exist, such as the optimization method [21], neural network method [22], artificial potential field (APF) [23], and consensus algorithms [24]. Among them, the APF is widely used owing to its advantages of simple calculations and strong real-time performance. For example, [25] proposed a real-time obstacle avoidance control algorithm based on a dynamic network topology and APF, which can enable the aircraft to accurately avoid obstacles in real time. Reference [26] effectively prevented the collision of an aircraft with obstacles through a combination of the H∞ controller and APF. Reference [27] proposed an improved artificial potential field (IPAF) based on traditional APF and sliding mode control theory, which enables UAVs to safely avoid obstacles while tracking moving targets. Reference [28] successfully achieved the goal of obstacle avoidance through the combination of a virtual structure and APF. Reference [29] proposed an artificial potential field optimization algorithm in a 3D dynamic space, which improved the efficiency of obstacle avoidance.

From the above discussion, it is clear that the formation tracking control of low-order multi-agent systems was studied in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18]. The fixed track of the leader is preset, and offline tracking control of the follower to the leader is finally achieved in [6]–[18].

II. MODEL ESTABLISHMENT

A. DYNAMIC MODEL OF UAV SYSTEM

The kinematic model of UAVs with autopilot is often established in research on multi-UAV formation tracking control. Considering generality, it is assumed that the formation system is composed of \( n \) UAVs, and the 3D particle dynamics model of the \( i \)-th UAV is shown in Equation (1).

\[
\begin{align*}
\dot{\xi}_{ui} &= \xi_{ui} \cos \psi_{ui} \cos \theta_{ui} \\
\dot{\xi}_{ui} &= \xi_{ui} \sin \psi_{ui} \cos \theta_{ui} \\
\dot{\xi}_{ui} &= \xi_{ui} \sin \theta_{ui} \\
\dot{\psi}_{ui} &= -\frac{1}{\tau_{c}} \psi_{ui} + \frac{1}{\tau_{c}} \psi_{aic} \\
\dot{\psi}_{ui} &= -\frac{1}{\tau_{\phi}} \psi_{ui} + \frac{1}{\tau_{\phi}} \psi_{aic} \\
\dot{\theta}_{ui} &= -\frac{1}{\tau_{\theta}} \theta_{ui} + \frac{1}{\tau_{\theta}} \theta_{aic}
\end{align*}
\]

where \((\xi_{uix}, \xi_{uiy}, \xi_{uiz})\) is the position coordinate of UAV \( i \); \( \xi_{ui}, \psi_{ui}, \) and \( \theta_{ui} \) are the velocity, direction angle, and pitch angle of UAV \( i \), respectively; \( \psi_{aic}, \theta_{aic}, \) and \( \theta_{aic} \) are the reference inputs of the velocity, direction angle, and pitch angle, respectively; \( \tau_{c}, \tau_{\phi}, \) and \( \tau_{\theta} \) are all time constants; and \( i = \{1, 2, \ldots, n\} \). The dynamic mathematical model of the UAV \( i \) is transformed into a linear continuous formation motion control subsystem dynamic model based on a third-order integrator by obtaining a third-order derivative of \( \xi_{ui} \), as shown in Equation (2). The mathematical model of the heading angle and pitch angle is transformed into a linear continuous dynamic model of the formation attitude control subsystem based on the second-order integrator by obtaining the second-order derivatives of \( \psi_{ui} \) and \( \theta_{ui} \), as shown in Equations (3) and (4), respectively.

\[
\begin{align*}
\hat{\xi}_{ui}(t) &= \xi_{ui}(t) \\
\hat{\xi}_{ui}(t) &= \xi_{ui}(t) \\
\hat{\xi}_{ui}(t) &= \xi_{ui}(t) \\
\hat{\psi}_{ui}(t) &= \omega_{ui}(t) \\
\hat{\omega}_{ui}(t) &= \psi_{ui}(t) \\
\hat{\theta}_{ui}(t) &= \nu_{ui}(t) \\
\hat{\upsilon}_{ui}(t) &= \upsilon_{ui}(t)
\end{align*}
\]

where \( i = \{1, 2, \ldots, n\} \), \( \xi_{ui} = (\xi_{uix}, \xi_{uiy}, \xi_{uiz}) \), \( \xi_{ui} = (\xi_{uix}, \xi_{uiy}, \xi_{uiz}) \), \( \omega_{ui} = (\omega_{uix}, \omega_{uiy}, \omega_{uiz}) \), \( \upsilon_{ui} = (\upsilon_{ui}, \upsilon_{ui}, \upsilon_{ui}) \) are the state of positions, velocities, accelerations, and control inputs of the UAV \( i \), respectively. \( \psi_{ui}, \omega_{ui}, \) and \( \upsilon_{ui} \) are the states of heading angle, heading angular velocity, and control input, respectively. \( \theta_{ui}, \nu_{ui}, \) and \( \upsilon_{ui} \) are the

states of the pitch angle, pitch angular velocity, and control input, respectively. The maximum velocity and acceleration of the UAV are assumed to be $\xi_{ui\text{max}} = 5m/s$ and $\zeta_{ui\text{max}} = 5m/s^2$, respectively.

B. COMMUNICATION NETWORK TOPOLOGY MODEL OF THE UAV SYSTEM

Each UAV is regarded as a node, and the edges between nodes represent the communication between UAVs. $G_n = \{V_n, E_n, A_n\}$ is an undirected graph where $V_n = \{v_1, v_2, \ldots, v_n\}$ is the node set of the graph, $E_n \subset V_n \times V_n$ is the edge set of the graph, and $(v_i, v_j) \in E_n \Leftrightarrow (v_j, v_i) \in E_n$. $A_n = [a_{ij}] \in \mathbb{R}^{n \times n}$ is the adjacency matrix of the graph, $a_{ij}$ is the communication weight between two adjacent nodes, and $a_{ij} = 0$ is typically assumed. $a_{ij} > 0$ when $(v_i, v_j) \in E_n$; otherwise $a_{ij} = 0$. $L_n = [l_{ij}]_{n \times n} \in \mathbb{R}^{n \times n}$ is a Laplacian matrix where $l_{ij} = -a_{ij}, \forall i \neq j$, and $l_{ii} = \sum_{j=1,j\neq i}^{n} a_{ij}$.

III. AN ALGORITHM FOR DISTRIBUTED REAL-TIME FORMATION TRACKING CONTROL

The principle of the traditional APF was introduced in [6]; therefore, it is not repeated in this paper.

A. IAPF

The repulsive potential field function was redefined based on Reference [6]. The attractive force of the target and the potential field force between the UAVs in [6] are used in this study to ensure that the UAVs can reach the target position smoothly and avoid inter-machine collisions. These are briefly introduced in this section. The resultant force is given by Equation (5).

$$F_{ui}(\xi_{ui}) = -\nabla U_{ui}(\xi_{ui}) = -\nabla U_{ui}(\xi_{ui}, \xi_{op}) - \nabla U_{op}(\xi_{ui}, \xi_{op}) = F_{atui}(\xi_{ui}, \xi_{op}) + F_{repui}(\xi_{ui}, \xi_{op}) + F_{atop}(\xi_{ui}, \xi_{op})$$

where $F_{atui}(\xi_{ui}, \xi_{op})$, $F_{repui}(\xi_{ui}, \xi_{op})$, $F_{atop}(\xi_{ui}, \xi_{op})$, and $F_{repui}(\xi_{ui})$ are the attractive force, repulsive force, potential field force between the UAVs, resultant force of the UAV, respectively; and $i, j = \{1, 2, \ldots, n\}$.

1) IMPROVED REPULSIVE POTENTIAL FIELD FUNCTION OF OBSTACLES

The dynamic gain factor of the repulsive force was introduced to enable the UAV to avoid static and dynamic obstacles autonomously and safely. This factor can automatically adjust the repulsive force in real time according to the mass of the obstacle, movement velocity of the dynamic obstacle, and distance deviation. The improved repulsive potential field function and repulsive force are shown in Equations (6) and (7), respectively.

$$U_{repui}(\xi_{ui}, \xi_{op}) = \frac{\beta_{ui}(m_o, \zeta_o, \Delta d_{opui})}{d_{opui}^2} \left[\frac{\|\xi_{ui} - \xi_{op}\|}{d_{max}} - \frac{2 \ln \|\xi_{ui} - \xi_{op}\|}{d_{opui}}\right]$$

$$F_{repui}(\xi_{ui}, \xi_{op}) = -\nabla U_{repui}(\xi_{ui}, \xi_{op}) = -\frac{\beta_{ui}(m_o, \zeta_o, \Delta d_{opui})}{d_{opui}^2} \left[\frac{\|\xi_{ui} - \xi_{op}\|}{d_{max}} + \frac{1}{\|\xi_{ui} - \xi_{op}\|^2}\right]$$

among them

$$\beta_{ui}(m_o, \zeta_o, \Delta d_{opui}) = \begin{cases} 1 + m_o e^{\zeta_o - \Delta d_{opui}}, & \zeta_o > 0 \\ 1 + m_o e^{-\Delta d_{opui}}, & \text{else} \end{cases}$$

$$m_o = \rho_o v_o$$

where $U_{repui}(\xi_{ui}, \xi_{op})$ is the repulsive potential field; $\nabla U_{repui}(\xi_{ui}, \xi_{op})$ is the gradient of $U_{repui}(\xi_{ui}, \xi_{op})$; $F_{repui}(\xi_{ui}, \xi_{op})$ is the repulsive force; $\zeta_o$ is the coordinate of the intersection of the line between the center of the obstacle and the UAV and the surface of the obstacle (the intersection below); $\|\xi_{ui} - \xi_{op}\|$ is the actual distance between the UAV and the intersection; $R_{uoi} = (d_{min}, d_{max})$ and $R_{uoi} = [0, d_{min}]$ are the scope of action of the repulsive potential field; $d_{min}$ and $d_{max}$ are the minimum and maximum distances of the impact of the repulsive potential field on the UAV, respectively; $\beta_{ui}(m_o, \zeta_o, \Delta d_{opui})$ is the dynamic gain factor of the repulsive force; $\Delta d_{opui}$ is the deviation between $\|\xi_{ui} - \xi_{op}\|$ and $d_{min}$; $\zeta_o$ is the velocity of the dynamic obstacle; $\rho_o$, $v_o$ and $m_o$ are the density, volume, and mass of the obstacle, respectively; and $i \in \{1, 2, \ldots, n\}$.

The attractive potential field function is modified by the segmentation principle, and the potential field function between the UAVs is defined in [6] to solve the problem of unreachable targets and collisions between UAVs in the traditional APF. The attractive potential field function and attractive force are given by Equations (11) and (12), respectively.

$$U_{atui}(\xi_{ui}, \xi_i) = \begin{cases} 0.5 \alpha_{ui1}(\rho_{ui}) \|\xi_{ui} - \xi_i\|^2, & \|\xi_{ui} - \xi_i\| < d_{uij} \\ 0.5 \alpha_{ui2}(\rho_{ui}) \|\xi_{ui} - \xi_i\|^2, & \|\xi_{ui} - \xi_i\| \geq d_{uij} \end{cases}$$

$$F_{atui}(\xi_{ui}, \xi_i) = -\nabla U_{atui}(\xi_{ui}, \xi_i)$$
shown in Equation (19).

\[
\begin{align*}
\mathbf{u}_{ui}(t) &= -\gamma_{u1} \sum_{j=1}^{n} a_{ij} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] - \gamma_{u2} \sum_{j=1}^{n} a_{ij} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] \\
&\quad - \gamma_{u3} \sum_{j=1}^{n} a_{ij} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] - \lambda_{i} \gamma_{u4} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] \\
&\quad + F_{ui}(\xi_{ui}, \xi_{i}) + \sum_{\alpha=1}^{m} F_{uopt}(\xi_{ui}, \xi_{op}) \\
&= \sum_{j \in N_{i}(t)} F_{uij}(\xi_{ui}, \xi_{uj})
\end{align*}
\]

(19)

Let

\[
\begin{align*}
\mathbf{e}_{ui}(t) &= \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t), \\
\mathbf{e}_{i}(t) &= \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t), \\
\mathbf{e}_{ui}(t) &= \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t), \\
\mathbf{e}_{i}(t) &= \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t),
\end{align*}
\]

and substitute Equations (7), (12), and (16) into Equation (19) to obtain Equation (20).

\[
\begin{align*}
\mathbf{u}_{ui}(t) &= -\gamma_{u1} \sum_{j=1}^{n} a_{ij} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] - \gamma_{u2} \sum_{j=1}^{n} a_{ij} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] \\
&\quad - \gamma_{u3} \sum_{j=1}^{n} a_{ij} \left[ \mathbf{q}_{ui}(t) - \mathbf{q}_{ui}'(t) \right] - \lambda_{i} \gamma_{u4} \mathbf{e}_{i}(t) \\
&\quad + \sum_{\alpha=1}^{m} \nabla U_{uopt}(\xi_{ui}, \xi_{op}) \\
&= \sum_{j \in N_{i}(t)} \nabla U_{uij}(\xi_{ui}, \xi_{uj})
\end{align*}
\]

(20)

where \( \mathbf{e}_{ui}(t), \mathbf{e}_{i}(t), \mathbf{e}_{ui}(t), \mathbf{e}_{i}(t), \mathbf{e}_{ui}(t), \mathbf{e}_{i}(t), \mathbf{e}_{ui}(t), \mathbf{e}_{i}(t) \) and \( \mathbf{e}_{ui}(t), \mathbf{e}_{i}(t) \) are the tracking error of the formation position, velocity, and acceleration of the follower \( i \) and \( j \), respectively. \( \xi_{ui}(t), \xi_{uj}(t), \xi_{ui}'(t), \xi_{uj}'(t), \zeta_{ui}(t), \zeta_{uj}(t), \zeta_{ui}'(t), \zeta_{uj}'(t) \) and \( \zeta_{ui}(t), \zeta_{uj}(t) \) are the actual position, actual velocity, and actual acceleration of the follower \( i \) and \( j \). \( \xi_{ui}'(t) \) is the leader-centered formation center vector, \( \zeta_{ui}'(t) \) and \( \zeta_{uj}'(t) \) are the leader’s velocity and acceleration, respectively, \( \gamma_{u1}, \gamma_{u2}, \gamma_{u3}, \gamma_{u4} \) and \( \gamma_{u5} \) are control protocol parameters that are greater than zero. The meanings of the other symbols are the same as above and are not repeated here.

\textbf{Definition 1:} If a multi-UAV system can always satisfy

\[
\lim_{t \to \infty} \mathbf{e}_{ui}(t) = 0, \quad \lim_{t \to \infty} \mathbf{e}_{i}(t) = 0, \quad \lim_{t \to \infty} \left\| \mathbf{e}_{ui}(t) - \mathbf{e}_{i}(t) \right\| = 0, \quad \lim_{t \to \infty} \left\| \mathbf{e}_{ui}(t) - \mathbf{e}_{i}(t) \right\| = 0, \quad \lim_{t \to \infty} \left\| \mathbf{e}_{ui}(t) - \mathbf{e}_{i}(t) \right\| = 0
\]

for any initial state under the action of Equation (20), then the tracking error of the multi-UAV system can converge to zero. In other words, the follower can follow the leader in the form
of a formation, and the entire formation follows the leader to move to the target point.

The formation attitude tracking control protocol was designed based on the formation attitude control subsystem. The attitude angle of the follower quickly tracks that of the leader to ensure that the formation can perform various tasks better. This is shown in Equations (21) and (22).

\[
u_{\psi_1}(t) = -\gamma_{\psi_1} \sum_{j=1}^{n} a_{ij} [\psi_{ul}(t) - \psi'_{ul}(t)] - [\psi_{uj}(t) - \psi'_{ul}(t)]
- \gamma_{\psi_2} \sum_{j=1}^{n} a_{ij} [\omega_{ul}(t) - \omega'_{ul}(t)] - [\omega_{uj}(t) - \omega'_{ul}(t)]
- \lambda_1 \gamma_{\psi_1} \sum_{j=1}^{n} a_{ij} [\psi_{ul}(t) - \psi'_{ul}(t)] - \lambda_1 \gamma_{\psi_2} \sum_{j=1}^{n} a_{ij} [\omega_{ul}(t) - \omega'_{ul}(t)]
\]

\[
u_{\theta_1}(t) = -\gamma_{\theta_1} \sum_{j=1}^{n} a_{ij} [\theta_{ul}(t) - \theta'_{ul}(t)] - [\theta_{uj}(t) - \theta'_{ul}(t)]
- \gamma_{\theta_2} \sum_{j=1}^{n} a_{ij} [\nu_{ul}(t) - \nu'_{ul}(t)] - [\nu_{uj}(t) - \nu'_{ul}(t)]
- \lambda_1 \gamma_{\theta_1} \sum_{j=1}^{n} a_{ij} [\theta_{ul}(t) - \theta'_{ul}(t)] - \lambda_1 \gamma_{\theta_2} \sum_{j=1}^{n} a_{ij} [\nu_{ul}(t) - \nu'_{ul}(t)]
\]  

Let

\[e_{\psi_1}(t) = \psi_{ul}(t) - \psi'_{ul}(t), \quad e_{\omega_1}(t) = \omega_{ul}(t) - \omega'_{ul}(t),\]

\[e_{\psi_2}(t) = \psi_{uj}(t) - \psi'_{ul}(t), \quad e_{\omega_2}(t) = \omega_{uj}(t) - \omega'_{ul}(t),\]

\[e_{\theta_1}(t) = \theta_{ul}(t) - \theta'_{ul}(t), \quad e_{\nu_1}(t) = \nu_{ul}(t) - \nu'_{ul}(t),\]

\[e_{\theta_2}(t) = \theta_{uj}(t) - \theta'_{ul}(t), \quad e_{\nu_2}(t) = \nu_{uj}(t) - \nu'_{ul}(t),\]

Equations (21) and (22) can be rewritten as Equations (23) and (24), respectively.

\[
u_{\psi_1}(t) = -\gamma_{\psi_1} \sum_{j=1}^{n} a_{ij} [e_{\psi_1}(t) - e_{\psi_2}(t)] - \gamma_{\psi_2} \sum_{j=1}^{n} a_{ij} [e_{\omega_1}(t) - e_{\omega_2}(t)] - \lambda_1 \gamma_{\psi_1} e_{\psi_1}(t) - \lambda_1 \gamma_{\psi_2} e_{\psi_2}(t)
\]

\[
u_{\theta_1}(t) = -\gamma_{\theta_1} \sum_{j=1}^{n} a_{ij} [e_{\theta_1}(t) - e_{\theta_2}(t)] - \gamma_{\theta_2} \sum_{j=1}^{n} a_{ij} [e_{\nu_1}(t) - e_{\nu_2}(t)] - \lambda_1 \gamma_{\theta_1} e_{\theta_1}(t) - \lambda_1 \gamma_{\theta_2} e_{\theta_2}(t)
\]

where \(e_{\psi_1}(t), e_{\psi_2}(t), e_{\omega_1}(t), e_{\omega_2}(t), e_{\theta_1}(t), e_{\theta_2}(t), e_{\nu_1}(t)\) and \(e_{\nu_2}(t)\) are the tracking errors of the heading angle, heading angular velocity, pitch angle, and pitch angular velocity of the followers \(i\) and \(j\), respectively. \(\psi_{ul}(t), \psi_{uj}(t), \omega_{ul}(t), \omega_{uj}(t), \theta_{ul}(t), \theta_{uj}(t), \nu_{ul}(t)\) and \(\nu_{uj}(t)\) are the actual heading angle, actual heading angular velocity, actual pitch angle, and actual pitch angular velocity of the followers \(i\) and \(j\), respectively. \(\psi'_{ul}(t), \omega'_{ul}(t), \theta'_{ul}(t)\) and \(\nu'_{ul}(t)\) are the leader’s heading angle, heading angular velocity, pitch angle, and pitch angular velocity, respectively. \(\gamma_{\psi_1}, \gamma_{\psi_2}, \gamma_{\omega_1}, \gamma_{\omega_2}, \gamma_{\theta_1}, \gamma_{\theta_2}, \gamma_{\nu_1}\) and \(\gamma_{\nu_2}\) are all control protocol parameters greater than zero. The meanings of other symbols are the same as the above, and are not repeated here.

**IV. ANALYSIS OF STABILITY, CONSENSUS, AND PERFORMANCE OF COLLISION AVOIDANCE AND OBSTACLE AVOIDANCE**

The following assumptions and theorem are first proposed before the proof:

**Assumptions 1:** The formation system consists of \(n\) UAVs, one of which is the leader, and the other \(n - 1\) are followers, and there are \(m\) obstacles in the flight environment. The communication between UAVs is good. Each UAV can measure the volume and density of an obstacle by using an onboard detector. A directed spanning tree exists in a fixed communication-network topology. \(V_u(t)\) is defined as the total energy function of the system and is a finite value that satisfies \(V_u(t) \leq V_0\).

**Theorem 1:** If the total system energy function is bounded under Assumption 1 and Equation (20), the tracking error of the real-time formation tracking control system can converge to zero.

**Theorem 2:** If the total system energy function is bounded under the action of Assumption 1 and Equations (23) and (24), the tracking error of the real-time formation attitude tracking control system can converge to zero.

**Proof of Theorem 1:** Firstly, a suitable positive semidefinite total energy function is constructed as shown in Equation (25).

\[
V_u(t) = \frac{1}{2} \sum_{i=1}^{n} [\Theta_{ul}(t) + e^T \xi(t) \Theta_{ul}(t)] + \sum_{i=1}^{n} [U_{ul}(e_{\xi_1}(t)) + \sum_{j=1}^{n} U_{uij}(e_{\xi_1}(t)) + U_{fix}(e_{\xi_1}(t))]
\]
where

\[ \Theta_{ui}(t) = \gamma_{u1} \sum_{j=1}^{n} a_{ij}(e_{\xi_i}(t) - e_{\xi_j}(t))^T e_{\xi_i}(t) \]
\[ + \gamma_{u2} \sum_{j=1}^{n} a_{ij}(e_{\zeta_i}(t) - e_{\zeta_j}(t))^T e_{\zeta_i}(t) \]
\[ + \lambda_i\gamma_{u4} e_{\zeta_i}(t)^T e_{\zeta_i}(t) \]  \tag{26} \]

Equation (27) can be obtained by taking the derivative of \( V_u(t) \):

\[ \dot{V}_u(t) = \frac{1}{2} \sum_{i=1}^{n} \{ \dot{\Theta}_{ui}(t) + 2e_{\xi_i}(t)^T \dot{\bar{e}}_{\xi_i}(t) + 2 \sum_{j=1}^{n} [\dot{U}_{uii}(e_{\xi_j}(t)) \]
\[ + \sum_{o=1}^{m} \dot{U}_{uwi}(e_{\xi_i}(t)) \]}
\[ + \frac{1}{2} \sum_{j=1}^{n} [\dot{U}_{uij}(e_{\xi_i}(t))] \}
\[ = \frac{1}{2} \sum_{i=1}^{n} \{ 2\gamma_{u1} \sum_{j=1}^{n} a_{ij}(e_{\xi_i}(t) - e_{\xi_j}(t))^T \dot{e}_{\xi_i}(t) \]
\[ + 2\gamma_{u2} \sum_{j=1}^{n} a_{ij}(e_{\zeta_i}(t) - e_{\zeta_j}(t))^T \dot{e}_{\zeta_i}(t) \]
\[ - e_{\zeta_i}(t)^T \dot{e}_{\zeta_i}(t) + 2\lambda_i\gamma_{u4} e_{\zeta_i}(t)^T \dot{e}_{\zeta_i}(t) \]
\[ + 2e_{\xi_i}(t)^T u_{ui}(t) \]
\[ + 2 \sum_{i=1}^{m} \{ \nabla U_{uii}(e_{\xi_i}(t)) \]
\[ + \sum_{o=1}^{m} \nabla U_{uwi}(e_{\xi_i}(t)) \} + \frac{1}{2} \sum_{j=1}^{n} \nabla U_{uij}(e_{\xi_j}(t)) \} \]
\[ = \gamma_{u1} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{\xi_i}(t) - e_{\xi_j}(t))^T e_{\xi_i}(t) \]
\[ + \gamma_{u2} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{\zeta_i}(t) - e_{\zeta_j}(t))^T e_{\zeta_i}(t) \]
\[ + \lambda_i\gamma_{u4} e_{\zeta_i}(t)^T e_{\zeta_i}(t) \] \]
FIGURE 4. The error curves of velocity component: a) the velocity of the X-axis in [6]; b) the velocity of the X-axis of this paper; c) the velocity of the Y-axis in [6]; d) the velocity of the Y-axis of this paper; e) the velocity of the Z-axis in [6]; f) the velocity of the Z-axis of this paper.

\[
\begin{align*}
    &+ \sum_{i=1}^{n} e_{xi}^T(t)u_{ai}(t) \\
    &+ \sum_{i=1}^{n} \nabla U_{ai}(e_{xi}(t)) \\
    &+ \sum_{i=1}^{n} \sum_{a=1}^{m} \nabla U_{aiop}(e_{xi}(t)) \\
    &+ \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \nabla U_{ij}(e_{xi}(t)) \\
    &= \gamma_{u1} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{xi}(t) - e_{xj}(t))^T e_{xi}(t) \\
    &+ \gamma_{u2} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{xi}(t) - e_{xj}(t))^T e_{xj}(t) \\
    &- \gamma_{u1} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{xi}(t) - e_{xj}(t))^T e_{xj}(t)
\end{align*}
\]
FIGURE 5. The error curves of acceleration component: a) the acceleration of the X-axis in [6]; b) the acceleration of the X-axis of this paper; c) the acceleration of the Y-axis in [6]; d) the acceleration of the Y-axis of this paper; e) the acceleration of the Z-axis in [6]; f) the acceleration of the Z-axis of this paper.
where $t > 0$, it can be concluded that UA $V_s$ satisfies $\lim_{t \to \infty} \dot{V}_s(t) = 0$. Similarly, when $t_1 > 0$, at this time, the potential energy between the UAVs satisfies $U_{aij}(\xi_{aij}(t_1)) \to \infty$, and the relationship is as follows:

$$V_a(t_1) = U_a(\xi_a(t_1)) + \frac{1}{2} e^T \xi_a(t_1) e_\xi(t_1) + \frac{1}{2} \gamma_{aij} e^T \xi_a(t_1) \Lambda e_\xi(t_1)$$

$$\geq U_a(\xi_a(t_1))$$

$$\geq U_{aij}(\xi_{aij}(t_1))$$

It is clear that the result of this equation is obviously in contradiction with $V_a(t) \leq V_0$, so the original assumptions are invalid; that is, there will be no collision between the UAVs in the system. Similarly, obstacle avoidance can also be proven by contradiction, which is omitted here to save space.

**Proof of Theorem 2**: A suitable positive semidefinite total energy function is constructed as shown in Equation (29).

$$V_\psi(t) = \frac{1}{2} \sum_{i=1}^{n} [\Theta_{\psi,i}(t) + e^T_{aij}(t) e_{aij}(t)]$$

where

$$\Theta_{\psi,i}(t) = \gamma_{\psi,i} \sum_{j=1}^{n} a_{ij} (e_{\psi,j}(t) - e_{\psi,j}(t))^T e_{\psi,j}(t)$$

$$+ \lambda_{aij} e^T_{aij}(t) e_{aij}(t)$$

Equation (31) can be obtained by taking the derivative of $V_\psi(t)$:

$$\dot{V}_\psi(t) = \frac{1}{2} \sum_{i=1}^{n} [\dot{\Theta}_{\psi,i}(t) + 2e^T_{aij}(t) \dot{e}_{aij}(t)]$$

$$= \frac{1}{2} \sum_{i=1}^{n} [2\gamma_{\psi,i} \sum_{j=1}^{n} a_{ij} (e_{\psi,j}(t) - e_{\psi,j}(t))^T \dot{e}_{\psi,j}(t)]$$
FIGURE 7. The curves of velocity component: a) the velocity of the X-axis in [6]; b) the velocity of the X-axis of this paper; c) the velocity of the Y-axis in [6]; d) the velocity of the Y-axis of this paper; e) the velocity of the Z-axis in [6]; f) the velocity of the Z-axis of this paper.

\[ + 2\lambda_i \gamma_3 e_{\psi_i}(t) \dot{e}_{\psi_i}(t) + 2e_{\psi_i}(t)u_{\psi_i}(t) \]

\[ = \gamma_1 \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{\psi_i}(t) - e_{\psi_j}(t))^T e_{\psi_i}(t) \]

\[ + \gamma_3 \sum_{i=1}^{n} \lambda_i e_{\psi_i}(t)e_{\psi_i}(t) + \sum_{i=1}^{n} e_{\psi_i}(t)u_{\psi_i}(t) \]

\[ = \gamma_1 \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}(e_{\psi_i}(t) - e_{\psi_j}(t))^T e_{\psi_i}(t) \]

\[ + \gamma_3 \sum_{i=1}^{n} \lambda_i e_{\psi_i}(t)e_{\psi_i}(t)\]
TABLE 1. Obstacle information.

| Obstacle | Number | $\xi_0$ | $R_o$ | $\rho_o$ |
|----------|--------|---------|-------|---------|
| Sphere   | 1      | (220, 220, 130) | 25    | 0.9     |
|          | 2      | (220, 220, 60)  | 20    | 0.6     |
|          | 3      | (330, 15, 89)   | 10    | 0.1     |
|          | 4      | (15, 368, 80)   | 10    | 0.1     |
| Hemisphere | 1    | (350, 450, 0)   | 35    | 0.1     |
|          | 2      | (450, 350, 0)   | 35    | 0.1     |
| Cylinder | 1      | (100, 166, 0)   | 45    | 0.1     |
|          | 2      | (166, 100, 0)   | 45    | 0.1     |

TABLE 2. The initial position of each UAV and the position of the target point.

| Name            | Number           | $\xi_{wi}$ | $\xi_{w}$ | $\Psi_{wi}$ | $\Theta_{wi}$ |
|-----------------|------------------|------------|-----------|-------------|--------------|
| UAVL            | (30, 40, 50)     | (40, 40, 50)| 0         | 0           |
| UAVF1           | (18, 61, 20)     | (18, 61, 20)| -0.7      | 0           |
| UAVF2           | (18, 61, 20)     | (18, 61, 20)| -0.7      | 0           |
| UAVF3           | (50, 29, 40)     | (50, 29, 40)| -0.7      | 0           |
| UAVF4           | (50, 29, 40)     | (50, 29, 40)| -0.7      | 0           |

TABLE 3. The initial state of each UAV.

| Name   | $\xi_{wi}$ | $\xi_{w}$ | $\Psi_{wi}$ | $\Theta_{wi}$ |
|--------|------------|-----------|-------------|--------------|
| UAVL   | (30, 40, 50)| (40, 40, 50)| 0         | 0           |
| UAVF1  | (18, 61, 20)| (18, 61, 20)| -0.7      | 0           |
| UAVF2  | (18, 61, 20)| (18, 61, 20)| -0.7      | 0           |
| UAVF3  | (50, 29, 40)| (50, 29, 40)| -0.7      | 0           |
| UAVF4  | (50, 29, 40)| (50, 29, 40)| -0.7      | 0           |

Because $L$ and $\Lambda$ are both positive semi-definite matrices, where $\Lambda = \text{diag}(\lambda_1, \lambda_2, \cdots, \lambda_n)$, and both $\gamma_2$ and $\gamma_4$ are greater than zero, it can be concluded that $V_\psi(t) \leq 0$, that is, $V_\psi(t)$ is bounded. When $t \to \infty$, $V_\psi(t) \to 0$, it is easy to know $e_{\psi}(t) = 0$. Similarly, $\lim_{t \to \infty} e_\psi(t) = 0$ can be obtained.

It is worth noting that the methods for proving the pitch angle and heading angle are the same, and the analysis process of the pitch angle can refer to the heading angle, which will not be repeated here.

V. SIMULATION ANALYSIS

A. INITIALIZATION OF PARAMETERS

The algorithm in this section was simulated using the MATLAB platform. In this study, a formation system composed of five ($n = 5$) UAVs as an example. The algorithms proposed in [6] and this study were simulated and compared in this section to verify the effectiveness of the proposed algorithm. Sphere numbers 3 and 4 are used to simulate dynamic obstacles, which move from positions (330, 15, 89) and (15, 368, 80) to positions (15, 330, 89) and (368, 15, 80) at velocity $\xi_0 = 5m/s$. The radius and density of static spheres 1 and 2 were set to 25 and 0.9, 20 and 0.6, respectively, to verify the influence of $m_o$ on obstacle avoidance, the rest of the spheres were the same. The geometric center of each obstacle, radius of the hemisphere, sphere, and cylinder, and density are listed in Table 1. The mass of the obstacle can be calculated by combining the data in Table 1 and the relational expressions $m_{os} = (4\rho_{os}\pi R_{os}^3)/3$, $m_{oh} = (2\rho_{oh}\pi R_{oh}^3)/3$, and $m_{oc} = \rho_{oc}\pi L_{oc}^3/3$, where $m_{os}$, $m_{oh}$ and $m_{oc}$ are the masses of the sphere, hemisphere, and cylinder, respectively; $R_{os}$, $R_{oh}$ and $R_{oc}$ are the radius of the sphere, the hemisphere, and the cylinder; $L_{oc}$ is the height of the cylinder, and $L_{oc} = 180$; $\rho_{os}$, $\rho_{oh}$ and $\rho_{oc}$ are the density of sphere, hemisphere, and cylinder, respectively; and $\pi$ is pi. The expected formation based on the square is presented in this section, and the distance between two adjacent UAVs on each side is 30m. The directed topology of a UAV is shown in Figure 1. The mass of the UAV was assumed as $m_{ui} = 1$. The adjacency matrices are given by Equation (32).

$$
\xi_{ui} = -\sqrt{2}d_{ui}/4, -\sqrt{2}d_{ui}/4, d_{ui}/2, d_{ui}/2)
$$

The control protocols in Reference [6] and this study were simulated. The formation tracking tracks of UAVs are shown in Figure 2. The relative distance change curves for the followers are shown in Figure 3. The error curves of the velocity components of the UAVs are shown in Figure 4. The error curves of the acceleration components of the UAVs are shown in Figure 5. The error curves for the heading and pitch angles are shown in Figure 6. The curves of the velocity components of the UAVs are shown in Figure 7.

As shown in Figures 2 and 3, the follower does not maintain a stable formation to follow the leader under the
TABLE 4. Algorithm parameters.

| Parameter | Value  | Parameter | Value          |
|-----------|--------|-----------|----------------|
| γ_u₁      | 0.65   | γ_v²      | 0.000005       |
| γ_u₂      | 0.65   | γ_θ₁      | 0.5            |
| γ_u₃      | 0.000001| γ_θ₂      | 0.000005       |
| γ_u₄      | 1      | γ_θ₃      | 1              |
| γ_u₅      | 0.000001| γ_θ₄      | 0.000005       |
| γ_v¹      | 0.5    | τ_c       | 2              |
| γ_v²      | 0.000005| τ_ϕ       | 0.8            |
| γ_v₃      | 1      | τ_θ       | 0.8            |

control protocol of Reference [6], and does not converge to its corresponding target position. In contrast, in this study, the follower can achieve autonomous formation, autonomous obstacle avoidance, formation recovery, and real-time tracking of the leader under the action of the control protocol. It can be seen from Figure 4 that the error of the velocity component between the follower and leader does not converge to zero quickly under the control protocols of [6]. This indicates that the follower velocity does not track the leader. The follower can realize velocity-tracking control under the action of the control protocol in this study. It can be seen from Figure 5 that the error of the acceleration component between the follower and leader does not converge to zero quickly under the control protocols of [6]. This indicates that the follower acceleration does not track the leader. In this study, the follower can realize acceleration tracking control under the action of the control protocol. It can be observed from Figure 6 that the errors of the heading angle and pitch angle can converge to zero quickly under the action of the control protocol in this study. As shown in Figure 7, the change in the velocity component of the UAV when avoiding obstacles with a large mass is not too severe under the control protocols in [6]. This does not reflect the impact of obstacles of different masses on the UAV obstacle avoidance. The velocity change of the UAV was more drastic when obstacles with larger masses were avoided under the control protocol in this study. This shows that obstacle mass has a certain influence on obstacle avoidance. The above results demonstrate that the real-time formation tracking control protocol designed in this study has a good control effect in obstacle avoidance and real-time tracking control applications.

VI. CONCLUSION

The main conclusions are as follows.

1) UAVs can quickly and safely avoid obstacles at greater velocities through a repulsive potential field, considering the obstacle mass. UAVs can recover and maintain their expected stable formations faster after avoiding obstacles.

2) The real-time formation tracking control protocol was designed using the improved potential field method, third-order consensus theory, and graph theory. The control protocol has higher tracking control precision.

There may be a communication delay in the actual formation system; therefore, the cooperative formation control of multiple UAVs in a time-delay environment can be regarded as the next research focus.

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