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Cooperative Formation Control Method for Unmanned Aerial Vehicle Cluster Based on Less Sensor Data

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The practical cross-regional, rapid, and large-scale deployment of unmanned aerial vehicle (UAV) clusters can effectively be improved by using large UAVs to carry several micro-UAVs for launching operations. In contrast to a UAV taking off from the ground, when multiple micro-UAVs are launched into motion, the UAV body has a nonzero velocity and nonzero attitude, that is, a nonstationary initial state. Combining existing methods for UAV clusters cannot solve the dynamic optimization problem of the group trajectory in a nonstationary initial state. A consensus artificial potential field (APF)-based cooperative method is proposed. This method requires only the position and attitude data of adjacent UAVs, which can reduce sensor data as much as possible. First, a geometric control method and dynamic constraints are used to realize the single-body pose stabilization control in a nonstationary initial state. Second, the consensus control and APF method are combined on the basis of the single-body stabilization control to realize UAV group formation and dynamic collision avoidance with minimum time and position errors. Finally, in the nonstationary initial state, on the basis of the proposed dynamic model and control method, a whole-process simulation of a large UAV carrying 40 micro-UAVs is designed to verify the effectiveness of the proposed method.

1. Introduction

Unmanned aerial vehicles (UAVs), which are equipped with sensors for sensing function, are in great demand in emergency rescue, agricultural plant protection, environmental monitoring, film and television entertainment, and other industries.(1) With the development of network information technology and artificial intelligence, an important development direction of modern UAV technology is to use a large number of low-cost and lightweight micro-UAVs to build UAV clusters with swarm intelligence. UAV clusters, with their high flexibility, wide adaptability, and controllable economy,(2,3) have increasingly extensive application potential and are of great interest domestically and internationally. Developed countries led by the United States have researched the use of multiple micro-UAVs for “drop detection”; that is, large

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manned aerial vehicles and UAVs carrying UAV clusters arrive at the designated search site and wait for the aircraft to arrive to carry out a small-scale fine search, detection, or strike in a specific area, thereby compensating for the short endurance time and small load capacity of micro-UAVs.(4) However, in contrast to a subgrade take-off UAV cluster, a micro-UAV cluster launched in the movement of large aircraft has a nonstationary initial state (mainly referring to the initial velocity and attitude, and the velocity includes both linear and angular velocities). This type of dynamic launch is markedly challenging in terms of the group stabilization control and dynamic collision avoidance path planning of micro-UAV cluster cooperative formation.

Formation control is one of the key technologies of UAV cluster cooperative control.(5) Common formation control methods mainly include the leader–follower,(6) virtual structure, and behavior-based methods. With the development of the cooperative control of group systems, especially the development of consensus theory,(7,8) an increasing number of researchers have realized that consensus theory can be used to solve the formation control problem of group systems. In previous research studies, many results have been obtained regarding consensus control. Ren and Sorensen conducted experiments on a multirobot system to verify the effectiveness of the consensus-based formation control method.(9) Xiao *et al.* proposed a finite-time formation control protocol for a first-order group system and proved that consistent formation can be realized in a finite time.(10) Xie and Wang studied the formation control problem of second-order group systems with a pointless interactive topology and proposed sufficient conditions for constant formation.(11) Hao *et al.* proposed a transmission power allocation algorithm and designed a designated consensus protocol to improve the accuracy of convergence.(12) Liu *et al.* proposed a high-level bilateral consensus control protocol to realize the formation of robots.(13) Savino *et al.* proposed a posture consensus protocol to solve the time-varying formation problem of robot systems.(14) However, in practical applications, the dynamics of some group systems can only be described by high-order models, such as UAV clusters with six degrees of freedom. However, in the above-mentioned research studies, the effects of high-order differential models on the stability of finite-time formation control were not considered, which leads to large errors in the results of entity platform cooperative formation. Moreover, the problem of collision and obstacle avoidance is rarely considered.

In the multi-UAV formation problem, collision avoidance is also very important and is directly related to flight safety. Therefore, increasing attention has been paid to the fusion of collision avoidance and cooperative algorithms.(15) The artificial potential field (APF) approach has become one of the most commonly used collision avoidance methods and is especially suitable for real-time collision avoidance algorithms on multirobot cluster entity platforms.(16) In a conventional APF method, the repulsive and attractive potential fields work together to ensure an accurate equilibrium state.(17) Collision avoidance mainly depends on the repulsive force. The distribution and shape of surrounding UAVs and obstacles are reflected as APF potential energy, and the expected heading and speed of each UAV in a cluster are determined according to the energy of this potential. However, there are two challenges in this method: first, the APF method does not take into consideration the concept of communication topology and weight, and second, most collision avoidance algorithms cannot simultaneously maintain the geometric structure; that is, they have a weak rigid structure.(18) Therefore, this method is not suitable for the application considered in this study, that is, the aerial delivery of a UAV cluster.

The main contributions of this research are as follows:

(1) A control strategy for the application of multirotor UAV cluster throwing is proposed. For the application of multirotor UAV cluster throwing, in this study, we innovatively decompose and integrate the whole process. Firstly, the whole process is decomposed into launch strategy, position and attitude stability control, and formation generation, maintenance, movement, and obstacle avoidance. Secondly, the launch strategy and pose stability control are integrated, and then, the formation generation, maintenance, movement, and obstacle avoidance are integrated. The multirotor UAV cluster throwing control strategy is formed, and the full autonomous control of the whole process is realized.

(2) A cooperative formation obstacle avoidance method based on consensus control and the APF method is proposed. The cluster control method based on consensus theory has been a research hotspot in recent years. It can be applied to different network topologies and is easy to expand on a large scale. However, this method cannot effectively solve the problems of collision between UAVs in a cluster and between UAVs and external obstacles. On the basis of a cooperative formation control method based on consensus control, combined with the APF method, this study will lead to the realization of the formation control and obstacle avoidance of UAV clusters.

The structure of this paper is as follows. In Sect. 1, we introduce the research background. In Sect. 2, we establish the mathematical model of UAVs and propose a position and attitude stabilization control method for a single-body UAV in the nonzero initial state. In Sect. 3, we introduce the cooperative formation control method based on consensus control with the APF function added to complete the formation generation, maintenance, movement, and collision avoidance control of micro-UAVs. In Sect. 4, we verify the performance characteristics of the algorithms by simulation. The fifth section concludes our work.

2. Pose Stabilization Control Method for a Multirotor UAV

In general, a conventional stabilization control method is usually based on the stationary initial state of subgrade takeoff so that the attitude angular velocity and acceleration of a UAV are basically zero in the stable flight state. In this study, the initial attitude of a micro-UAV is random, and the velocity is not zero because it corresponds to the nonstationary initial state. Such a conventional stabilization control method is not suitable for the transition from an unstable initial state to a stable state where the acceleration and angular velocity are close to the equilibrium point. A novel control method is presented below.

2.1 Pose and position stabilization control method

As shown in Fig. 1, the origin of the inertial coordinate system $\{e_1, e_2, e_3\}$ is fixed at a point on the ground, where e_1 points to the north, e_2 points to the east, and e_3 points downward. The origin of the body coordinate system $\{b_1, b_2, b_3\}$ is fixed at the center of gravity of the UAV, where b_1 points to the head of the UAV, b_2 points to the right side, and b_3 points downward. The position of the UAV can be described by the three-dimensional vector of the origin of the body

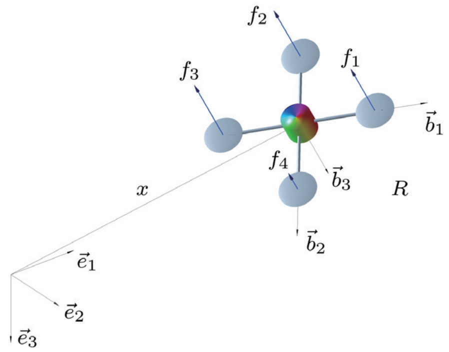


Fig. 1. (Color online) Quadrotor UAV and definitions of the coordinate systems.

coordinate system relative to the origin of the inertial coordinate system, and the attitude can be described by the rotation angles of the body coordinate system relative to the inertial coordinate system.

The dynamic and kinematic equations of a quadrotor UAV can be described as[(19)]

$$\dot{x} = v, \tag{1}$$

$$m\dot{v} = mge_3 - fRe_3, \tag{2}$$

$$\dot{R} = R\widehat{\Omega}, \tag{3}$$

$$J\dot{\Omega} + \Omega \times J\Omega = M, \tag{4}$$

where x is the three-axis position, v is the three-axis velocity, and x and v can be obtained from the sensor data. M is the mass of the UAV, J is the moment of inertia of the UAV, g is the acceleration of gravity, R is the rotation matrix that describes the attitude of the UAV, $\Omega = [\omega_1, \omega_2, \omega_3]$ is the three-axis angular velocity, and $\widehat{\Omega}$ is defined as

$$\widehat{\Omega} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}. \tag{5}$$

The power of the quadrotor UAV is provided by four rotors fixed on the airframe. The pull and torque provided by the rotors are proportional to the square of the rotational speed. By controlling the rotation speed of the four rotors, one can control the pulling force f and the three torques M_1, M_2, and M_3 acting on the body of the four-rotor UAV. The relationship among tension, torque, and the speed Q can be described by the following mixed control equation:[(19)]

$$\begin{bmatrix} f \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & -d & 0 & d \\ d & 0 & -d & 0 \\ -c_{\tau f} & c_{\tau f} & -c_{\tau f} & c_{\tau f} \end{bmatrix} \begin{bmatrix} Q_1^2 k_f \\ Q_2^2 k_f \\ Q_3^2 k_f \\ Q_4^2 k_f \end{bmatrix}. \tag{6}$$

Here, k_f is the pull coefficient, d is the distance between the rotor center and the UAV center, and $c_{\tau f}$ is the coefficient of tension and reverse torque. When d and $c_{\tau f}$ are not zero, the above matrix is invertible. Therefore, when the controller is designed, only the pulling force f and the three torques M_1, M_2, and M_3 are needed.

On the basis of the above dynamic model, the attitude and angular velocity tracking errors are respectively defined as

$$e_R = \frac{1}{2}\left(R_d^T R - R^T R_d\right)^{\#}, \tag{7}$$

$$e_\Omega = \Omega - R^T R_d \Omega_d, \tag{8}$$

where R_d is the desired attitude rotation matrix, Ω_d is the desired angular velocity, and $(\bullet)^{\#}$ is the inverse of $\widehat{(\bullet)}$.

On the basis of the attitude and angular velocity tracking errors, a nonlinear attitude controller is designed.

$$M = -k_R e_R - k_\Omega e_\Omega + \Omega \times J\Omega - J\left(\hat{\Omega} R^T R_d \Omega_d - R^T R_d \dot{\Omega}_d\right), \tag{9}$$

where k_R and k_Ω are the control parameters of the attitude and angular velocity, respectively. The hypotheses k_R and k_Ω are any positive numbers, and the rotation dynamics and kinematics Eqs. (3) and (4) of the UAV are considered. Then, under the action of the above controller [Eq. (9)], the domain of attraction of the closed-loop system is

$$\psi\left(R(0), R_d(0)\right) < 2, \tag{10}$$

$$\left\| e_\Omega(0) \right\|^2 < \frac{2}{\lambda_M\left(J\right)} k_R \left(2 - \psi\left(R(0), R_d(0)\right)\right), \tag{11}$$

where $\psi\left(R, R_d\right) = \frac{1}{2} tr\left[I - R_d^T R\right]$.

The above equation shows that for a given desired attitude R_d, as long as the initial attitude R of the UAV satisfies $\psi\left(R, R_d\right) < 2$ and when the angle deviation between the initial attitude and the target attitude is less than 180 degrees, the UAV can track the desired attitude under the action of the controller (9).

To design the position controller, the following position and velocity tracking errors are respectively defined as

$$e_x = x - x_d, \tag{12}$$

$$e_v = v - \dot{x}_d, \tag{13}$$

where x_d is the desired three-axis position, its first time derivative is the desired velocity, and its second time derivative is the desired acceleration. On the basis of the attitude controller (9), the pull force f can be calculated using the following controller:

$$f = \left(k_x e_x + k_v e_v + mge_3 - m\ddot{x}_d\right) \cdot Re_3, \tag{14}$$

where k_x and k_y are the control coefficients of position and speed, respectively.

For trajectory tracking, the desired attitude rotation matrix of the UAV can be calculated according to the above controller.(19)

$$R_d = \left[b_{1_d}, b_{3_d} \times b_{1_d}, b_{3_d}\right], \tag{15}$$

$$b_{3_d} = \frac{-k_x e_x - k_v e_v - mge_3 + m\ddot{x}_d}{\left\|-k_x e_x - k_v e_v - mge_3 + m\ddot{x}_d\right\|}, \tag{16}$$

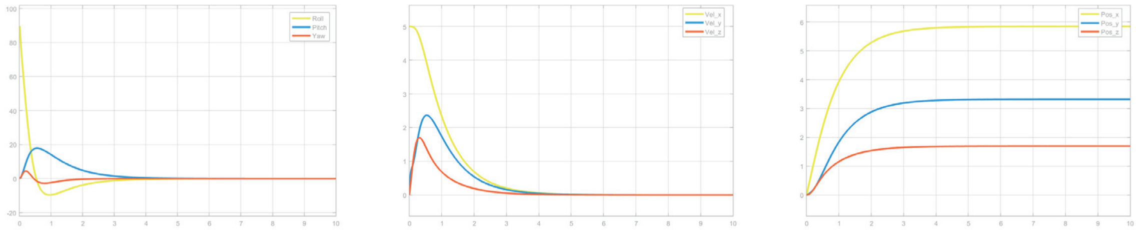
where b_{1_d} is perpendicular to b_{3_d}.

2.2 Simulation verification of control method

The effectiveness of the above controller is verified by simulation. The method proposed in this paper is compared with the proportional integral derivative (PID) control method.

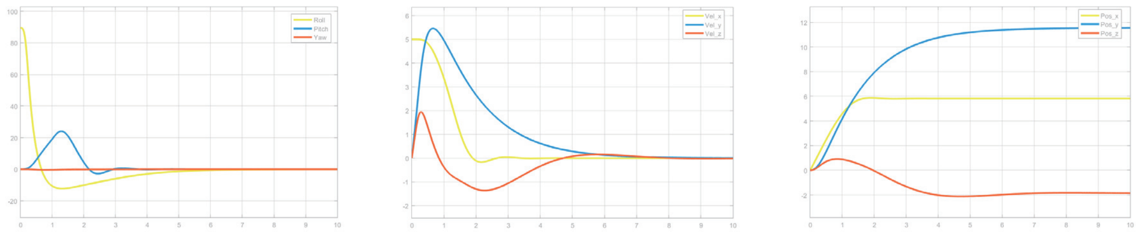
Assume that the initial rolling attitude angle of the UAV after throwing is 90 degrees, the pitch and heading angle are both 0 degrees, the forward speed is 5 m/s, the lateral and vertical speeds are both 0, the control target is to make the UAV achieve a stable hovering state, and the three-axis speed is 0. The simulation results obtained on the basis of the pose stabilization controller proposed in this paper are shown in Fig. 2. The simulation results show that after the UAV is thrown, under the action of the controller, the stable control of attitude is achieved, and the three-axis speed is stabilized to 0, thereby realizing the stable control of position and attitude.

The results of the PID control method are shown in Fig. 3. The simulation results show that the position and attitude stability control of the UAV after throwing can also be realized, but the



(a) (b) (c)

Fig. 2. (Color online) Method proposed in this paper. (a) Attitude. (b) Speed. (c) Position.



(a) (b) (c)

Fig. 3. (Color online) PID control method. (a) Attitude. (b) Speed. (c) Position.

stabilization time is longer, the attitude fluctuates in the process, the lateral speed is higher, and the displacement of the UAV after stabilization is larger.

3. Multi-UAV Cooperative Formation and Collision Avoidance Method

After the micro-UAV is launched, it can gradually stabilize from any initial state to a hover state under the action of the attitude stabilization controller and then start formation flight, including formation generation, maintenance, movement, and collision avoidance. In formation flight, assuming that the UAV is not flying with a large attitude, only the horizontal motion model of the UAV is considered; that is, the UAV can be regarded as a particle, and only its position and velocity state are considered. Thus, the dynamic model of the UAV can be described by a linear time-invariant (LTI) model. In the following, we introduce the cooperative formation control method based on consensus control and add the APF function to complete the formation generation, maintenance, movement, and collision avoidance control of micro-UAVs.

3.1 Consensus control method

If all agents reach a consensus on some variables of interest, it is considered that the cluster system has reached a consensus, and the variables are called coordination variables. To reach a consensus, the agents in the cluster system usually interact locally. For each agent, the distributed controller is constructed by using the sensor data of adjacent agents to achieve local interaction, which can reduce the sensor data as much as possible.

Consider the following high-order LTI trunked system:

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bu_i(t), \\ y_i(t) = Cx_i(t), \end{cases} \tag{17}$$

where i = 1, 2, ..., N, $A \in R^{n\times n}$, $B \in R^{n\times m}$, and $C \in R^{q\times n}$ are constant matrices and $x_i(t) \in R^n$, $y_i(t) \in R^q$, and $u_i(t) \in R^m$ are the state, output, and control inputs of the system, respectively.

Definition 1: Consider a high-order LTI cluster system (17). If for any $i, j \in \{1, 2, \ldots, N\}$,

$$\lim_{t\to\infty}\left(x_i(t) - x_j(t)\right) = 0; \tag{18}$$

then, the cluster system (17) is called a state consensus. If for any $i, j \in \{1, 2, \ldots, N\}$,

$$\lim_{t\to\infty}\left(y_i(t) - y_j(t)\right) = 0; \tag{19}$$

then, the cluster system (17) is called an output consensus. For the state consensus problem, Xiao and Wang proposed the following distributed control rate: [20]

$$u_i(t) = K_1 x_i(t) + K_2 \sum_{j\in N_i} w_{ij}\left(x_j(t) - x_i(t)\right), \tag{20}$$

where K_1 and K_2 are constant gain matrices of appropriate dimensions, w_{ij} is the influence coefficient of the j-th agent on the i-th agent, and the necessary and sufficient conditions for the control rate (20) to make the high-order cluster system (17) reach the state consensus are given.

For the output consensus problem, Ma and Zhang proposed the following distributed static output feedback control rate and provided the necessary and sufficient conditions for a high-order cluster system (17) to reach the output consensus.[21]

$$u_i(t) = K \sum_{j\in N_i} w_{ij}\left(y_j(t) - y_i(t)\right) \tag{21}$$

Definition 2: Consider the state equation of the cluster system (17). If the following condition holds for any bounded initial state, then cluster system (17) realizes formation tracking control.

$$\lim_{t\to\infty}\left(x_i(t) - r_i - c(t)\right) = 0 \tag{22}$$

It should be pointed out that in definition 2, if $r_i \equiv 0$, definition 2 becomes similar to definition 1, where $c(t)$ is defined as a consensus function. Therefore, the consensus-based formation tracking control method can be regarded as an extension of consensus control; alternatively, consensus control is a special case of formation tracking control.

3.2 Consensus APF method for cooperative formation and collision avoidance

On the basis of consensus control theory, by considering the cluster system with n UAVs and referring to the system (17), we can describe the dynamic model of the cluster system as

$$\dot{x}_i\left(t\right) = Ax_i\left(t\right) + Bu_i\left(t\right), \tag{23}$$

where $i = 1, 2, ..., N$ is the i-th UAV in the cluster, $x_i = [p_x\, p_y\, p_z\, v_x\, v_y\, v_z]$ is the system state vector, including the three-axis position and three-axis velocity, u_i is the control quantity (its physical meaning is the three-axis acceleration that needs to act on the aircraft), and A and B are constant matrices defined as

$$A = \begin{bmatrix} 0_{3\times3} & 1_{3\times3} \\ 0_{3\times3} & 0_{3\times3} \end{bmatrix}, B = \begin{bmatrix} 0_{3\times3} \\ 1_{3\times3} \end{bmatrix}. \tag{24}$$

On the basis of Eq. (20), the controller can be designed to realize the state consensus of the UAV cluster system (23), that is, the position and speed consensus of each UAV in the UAV cluster. However, in the formation problem, the UAVs are required to maintain a constant distance rather than the same position. Therefore, it is necessary to find new consensus variables through a certain state transformation to achieve formation control.

The time-varying formation state description function $h_i(t)_{3\times1}$, which describes the state of the ith UAV in formation at time T, is defined as

$$h_i\left(t\right) = r_i + c\left(t\right), \tag{25}$$

where r_i is the formation state description function and $c(t)$ is the virtual formation center state. In this way, the relative state of UAVs in the cluster can be determined by r_i. The movement of the whole cluster can be described by $c(t)$.

According to the analysis in Sect. 3.1, the function h can be used to complete the coordinate transformation of the position state of the cluster system (23).

$$\hat{x}_i\left(t\right) = x_i\left(t\right) - h_i\left(t\right) \tag{26}$$

On this basis, by referring to Eq. (20), we obtain the formation controller of a distributed cluster system based on consensus theory as follows:

$$u_{1i}(t)=K_1x_i(t)+K_2\left(x_i(t)-h_i(t)\right)+K_3\omega_{ij}\sum_{j\in N_i}\left(x_j(t)-x_i(t)-h_j(t)+h_i(t)\right), \tag{27}$$

where N_i is the neighboring UAV of the i-th UAV, that is, the i-th UAV can obtain the N_i state of each UAV in the set, and the value of N_i is related to the formation of the UAV cluster, link communication capability, and grouping strategy. ω_{ij} is the connection strength between two UAVs. K_1, K_2, and K_3 are controller parameters, which are used to ensure that the time-varying formation state description function $h_i(t)$ is reachable. However, at this research stage, the selection of controller parameters mainly depends on experience. In future research, adaptive methods will be studied. Bringing the above equation into the cluster system (23),

$$\dot{x}(t)=\left(I_N\otimes\left(A+BK_1+BK_2\right)-L\otimes BK_3\right)x(t)+\left(L\otimes BK_3-I_N\otimes BK_2\right)h(t), \tag{28}$$

where $x^T = [x_1\ x_2\ ...\ x_N]^T$, I_N is the N-dimensional identity matrix, $\otimes$ is the Kronecker product, and L is the Laplacian matrix, where $L = D - W$. Here, D is the degree of communication topology and $W=[\omega_{ij}]\in R^{N\times N}$.

It can be seen from the closed-loop system (28) that by selecting the appropriate controller parameters K_1, K_2, and K_3, the stability of the closed-loop system can be ensured; that is, formation tracking can be realized. Here, K_1 and K_2 are not necessary in enhancing the stability of the system by adjusting K_1 and K_2, which can increase the effect of the system (23) on the formation adaptability $h_i(t)$ to meet the needs of more formation.

The above controller $u_{1i}(t)$ can realize the UAV's gradual convergence to the time-varying formation state description function in the cluster, but it cannot guarantee that the UAVs in the cluster do not collide or strike external obstacles in this process. To solve this problem, the APF method is used to design the collision avoidance controller. Thus, we select

$$\phi(d)=-(e^{k_{APF}*d}-e^{k_{APF}}), \tag{29}$$

where k_{APF} is used to adjust the shape of the force function curve. Therefore, the mathematical structure of the controller is described as

$$u_{2i}(t)=K_4\sum_{j\in N_i}\phi\left(x_j(t)-x_i(t)\right)\frac{x_j(t)-x_i(t)}{\left\|x_j(t)-x_i(t)\right\|}+K_5\sum_{j\in O_i}\phi\left(o_j(t)-x_i(t)\right)\frac{o_j(t)-x_i(t)}{\left\|o_j(t)-x_i(t)\right\|}, \tag{30}$$

where O_i is the set of external obstacles and K_4 and K_5 are the coefficients of action strength to control the response characteristics of UAVs at different distances from other UAVs or obstacles. Therefore, the consensus-based APF controller for the cooperative formation and collision avoidance of multirotor UAVs can be obtained by

$$u_i(t)=u_{1i}(t)+u_{2i}(t). \tag{31}$$

4. Simulation Verification

To verify the effectiveness of the method proposed in this paper, a whole-process simulation of a large UAV carrying 40 micro-multirotor UAVs is designed, and the processes of sequential launching, posture stabilization, and formation assembly, tracking, and collision avoidance are simulated.

4.1 Simulation process design

It is assumed that 40 micro-UAVs are carried by a large UAV to the airspace near the target location, where they are launched one by one. The simulation process is divided into the following five stages: in the first stage, the micro-UAVs are launched one by one from the large UAV; in the second stage, each micro-UAV completes the pose stabilization control; in the third stage, the UAV cluster completes the formation assembly; in the fourth stage, the UAV cluster goes to the target point to complete the collision avoidance function; and in the fifth stage, the UAV cluster completes the collision avoidance function. The cluster reaches the target point and hovers stably. In detail, the simulation process is as follows.

In the first stage, through a simulation calculation, the large UAV maintains a uniform linear motion; its north velocity is 5 m/s, and its east and vertical velocities are both 0. From the 0th second of the simulation, a micro-UAV is launched every 1 s. The initial attitude of the launched UAV is random, and the initial velocity is consistent with that of the large UAV. After each micro-UAV is launched, it enters the second stage.

In the second stage, after the micro-UAV is launched, the position and attitude stabilization controller starts, and its control goal is to achieve stable hovering of the UAV with any initial attitude and initial speed. After each UAV hovers stably, it enters the third stage.

In the third stage, the formation is defined as a circle with a radius of 40 m. The formation center coordinates are 100 m to the north, 0 m to the east, and 10 m in the vertical direction. In this stage, the formation controller of each UAV is used as the outer loop controller. According to the communication network topology of the UAV cluster, it receives the state of the neighbor nodes, completes the cooperative formation control, and outputs the desired acceleration control command. The position and attitude stabilization controller is used as the inner loop controller, receives the acceleration command given by the formation controller, and calculates the required acceleration of the UAV pull force and triaxial moment. After the 40 UAVs have completed the formation assembly, they enter the fourth stage.

In the fourth stage, under the action of the cooperative formation controller, the UAV cluster moves to the formation center coordinates of 150 m to the north, 150 m to the east, and 70 m in the vertical direction. At the same time, it is assumed that there is a spherical obstacle with a radius of 15 m at 120 m to the north, 120 m to the east, and 30 m in the vertical direction. When the UAV cluster reaches the above position M, it moves 100 m to the north, 100 m to the east, and 100 m in the vertical direction. When the UAVs reach the target position, they enter the fifth stage.

In the fifth stage, the 40 UAVs maintain the desired formation and hover stably, and the simulation ends.

The communication topology used in this simulation is shown in Fig. 4. The i-th UAV can only obtain the status information of the $(i - 1)$-th UAV, and the connection strength between the UAVs is assumed to be 1.

4.2 Simulation results

The whole-process simulation position trajectories of the 40 micro-quadrotor UAVs launched by the large UAV are shown in Fig. 5 (the vertical coordinates are reversed for ease of understanding). The red circles represent the launching positions of the micro-UAVs from the large UAV, which can be obtained from the sensor data. The blue asterisks are the final hovering positions of the UAVs, and the pink ball is the obstacle. The simulation results show that the 40 micro-quadrotor UAVs are launched at equal intervals. After launching, on the basis of completing the position and attitude stability control, the formation assembly, the overall movement of the formation, and the formation collision avoidance are completed successively. Finally, the UAVs reach the designated target position, and the simulation verification of the whole task process is completed.

The following is the analysis of the simulation in the second to fourth stages. In the second stage, the pose stabilization control method is mainly simulated and verified. Taking the 1st,

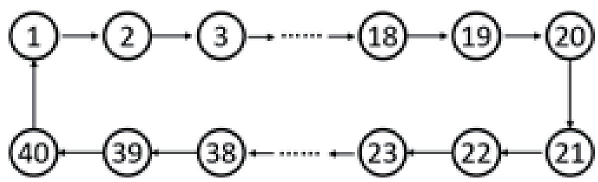


Fig. 4. UAV cluster communication topology.

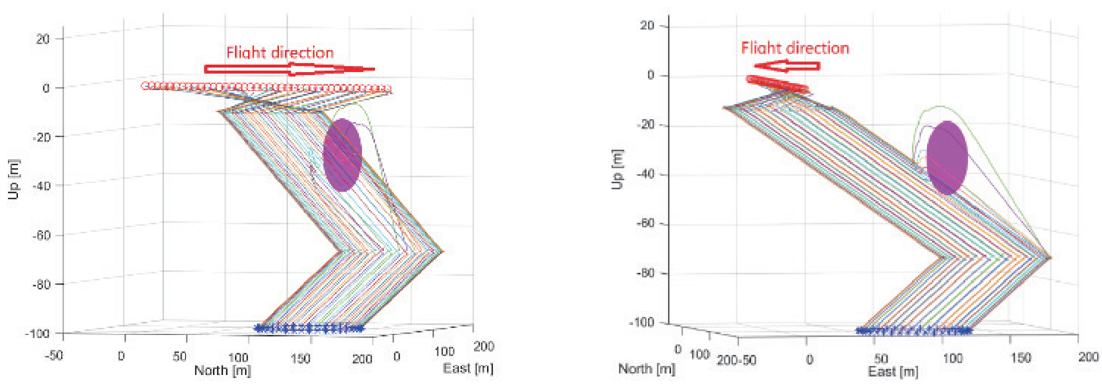


Fig. 5. (Color online) Simulation position trajectories of the 40 micro-quadrotor UAVs in the whole process of cluster launching.

15th, 27th, and 40th UAVs as examples, the simulation results in the second stage are shown in Fig. 6. The simulation results show that the initial attitudes of the 1st, 15th, 27th, and 40th UAVs are roll angles of 90, 100, and 100 degrees, and a pitch angle of 90 degrees, respectively. For these initial attitudes, the attitude stabilization controller realizes the attitude stabilization control of the above UAVs.

In the third stage, the position trajectory simulation results of the 40 micro-quadrotor UAVs are shown in Fig. 7. According to the simulation results, the 40 micro-quadrotor UAVs form and maintain the designated formation at the designated position under the action of the formation controller. In this process, the maximum position deviation of the formation is shown in Fig. 8. According to the simulation results, the deviation finally converges to 0; that is, the UAVs in the formation finally reach the designated position of the formation while maintaining their formation.

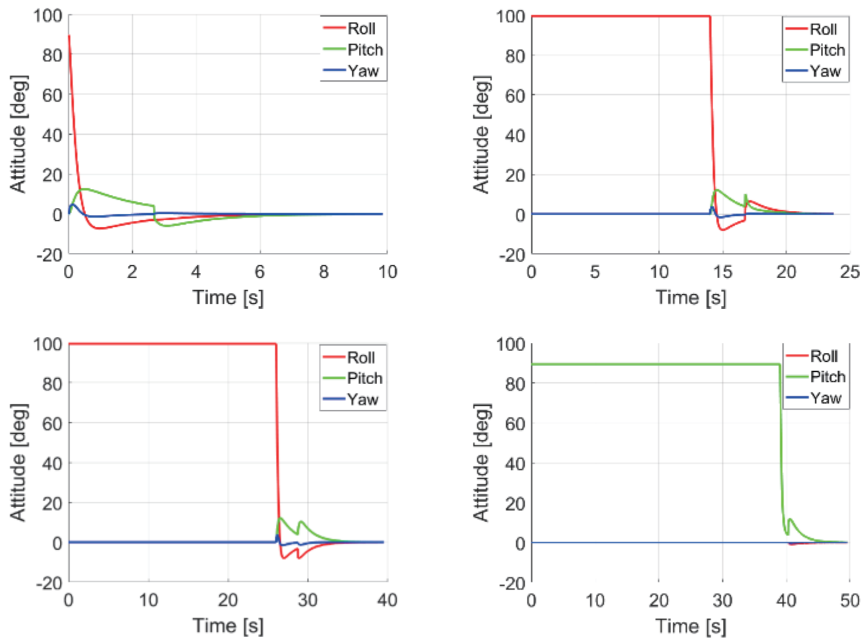


Fig. 6. (Color online) Attitude stability control effect after launch at arbitrary initial attitudes.

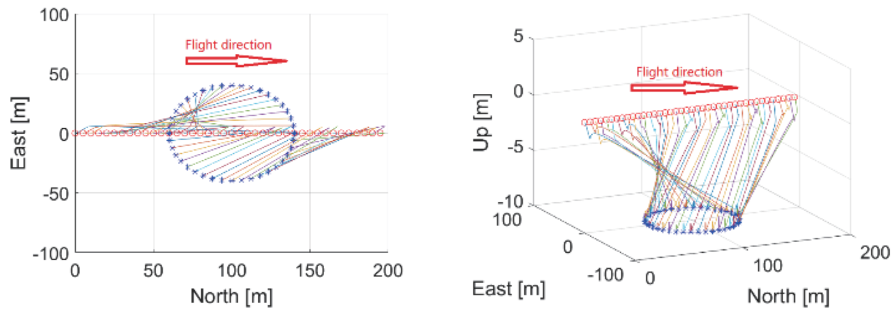


Fig. 7. (Color online) Formation control of 40 micro-quadrotor UAVs.

In the fourth stage, the position trajectory simulation results of the 40 micro-quadrotor UAVs are shown in Fig. 9. The simulation results show that the 40 micro-UAVs complete the whole formation movement with collision avoidance under the action of the formation controller. Taking the 8th–17th UAVs as examples, their collision avoidance trajectories are shown in Fig. 8. From the simulation results, it can be seen that the cluster UAVs achieve autonomous collision avoidance while ensuring the formation to the maximum extent, thus ensuring the safety of the UAV formation.

Finally, the position trajectories of the UAV formation at different times are displayed according to the simulation results. In Fig. 10, the position trajectories at the 30th, 50th, 70th, 90th, 110th, 130th, 150th, and 170th seconds are displayed. From Fig. 8, we can observe the dynamics of the whole-process simulation of multirotor UAV cluster launch, formation assembly, formation tracking, formation collision avoidance, and others. Thus, the effectiveness and feasibility of the proposed method in multirotor group launch operation formation control are verified.

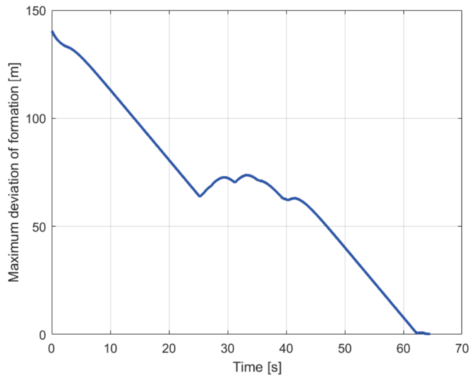


Fig. 8. (Color online) Maximum position deviation of the formation.

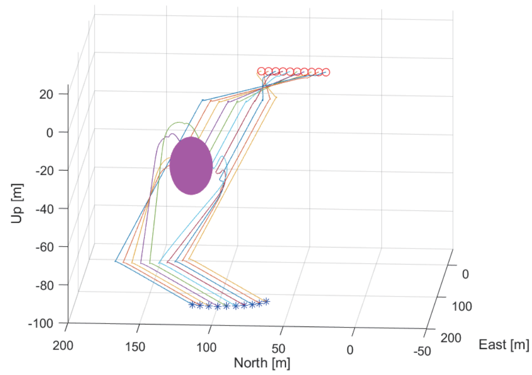


Fig. 9. (Color online) Collision avoidance trajectory.

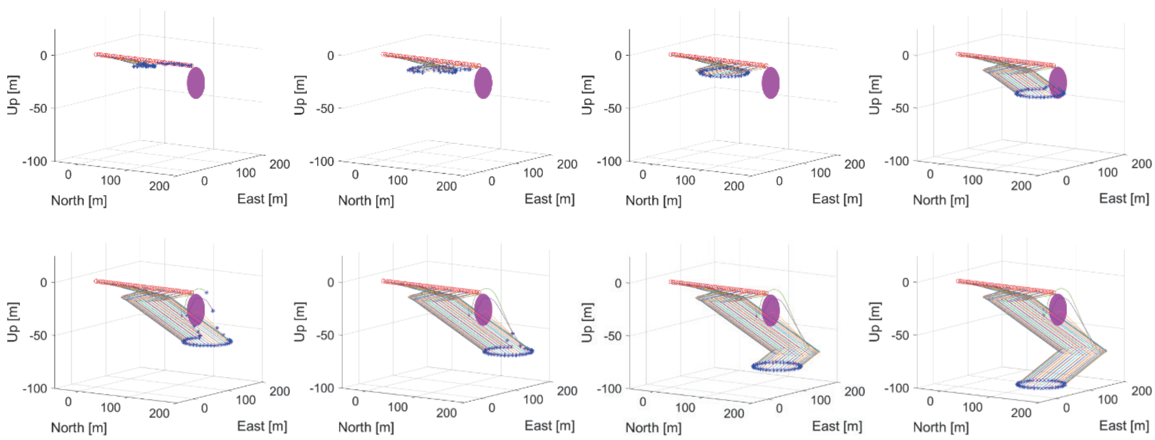


Fig. 10. (Color online) Position trajectories of the UAV formation at different times.

5. Conclusion

To improve the rapidity and robustness of the existing cluster control methods in the application of UAV cluster launching, in this study, we comprehensively analyzed the position and attitude stabilization control of micro-UAVs in a nonstationary initial state and the formation cooperative control and collision avoidance under the condition of local communication. As a result, we developed a cluster cooperative control for launching a UAV cluster. The formation method is based on the consensus APF method, which only needs to obtain the position and attitude information of adjacent UAVs, so it can reduce the sensor data as much as possible. On the basis of the proposed control architecture and theoretical method, in this paper, we presented the complete whole-process simulation of 40 micro-UAVs launched by a large UAV and verified the effectiveness and feasibility of the proposed method.

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References

1 Z. Ding and Y. Li: Sens. Mater. **33** (2021) 3255. https://doi.org/10.18494/SAM.2021.3384
2 W. Gu, K. P. Valavanis, M. J. Rutherford, and A. Rizzo: J. Intell. Rob. Syst. **100** (2020) 1469. https://doi.org/10.1007/s10846-020-01227-8
3 Y. Kartal, K. Subbarao, N. R. Gans, A. Dogan, and F. Lewis: IET Control Theory Appl. **14** (2020) 1628. https://doi.org/10.1049/iet-cta.2019.1151
4 M. Wright, P. W. Krasa, and H. H. Hwang: Aerospace Conf. (IEEE, 2011) 1–14. https://doi.org/10.1109/AERO.2011.5747492
5 A. Tahir, J. M. Böling, M.-H. Haghbayan, and J. Plosila: IEEE Access **8** (2022) 95667. https://doi.org/10.1109/ACCESS.2020.2988773.
6 A. Tahir, J. Böling, M.-H. Haghbayan, and J. Plosila: 2020 Int. Symp. ELMAR (IEEE, 2020) 79–82. https://doi.org/10.1109/ELMAR49956.2020.9219027
7 N. Wang, J. Dai, and J. Ying: 2021 40th Chinese Control Conf. (IEEE, 2021) 99–104. https://doi.org/10.23919/CCC52363.2021.9550138
8 Y. Huang, J. Tang, and S. Y. Lao: Symmetry **11** (2019) 1. https://doi.org/10.3390/sym11091162
9 W. Ren and N. Sorensen: Rob. Auton. Syst. **56** (2008) 324. https://doi.org/10.1016/j.robot.2007.08.005
10 F. Xiao, L. Wang, J. Chen, and Y. P. Gao: Automatica **45** (2009) 2605. https://doi.org/10.1016/j.automatica.2009.07.012
11 G. M. Xie and L. Wang: Int. J. Syst. Sci. **40** (2009) 1019. https://doi.org/10.1080/00207720902974603
12 L. Hao, X. H. Qi, and Z. H. Yang: IET. Commun. **14** (2020) 1730. https://doi.org/10.1049/iet-com.2019.0699
13 D. J. Liu, C. G. Zong, D. T. Wang, W. B. Zhao, Y. H. Wang, and W. Lu: Meas. Control **53** (2020) 983. https://doi.org/10.1177/0020294020905075
14 H. J. Savino, L. C. A. Pimenta, J. A. Shah, B. V. Adorno, G. A. S. Pereira, and P. R. Souza: J. Franklin Inst. **357** (2020) 142. https://doi.org/10.1016/j.jfranklin.2019.09.045
15 F. Liao, R. Teo, J. L. Wang, X. Dong, F. Lin, and K. Peng: IEEE Trans. Control Syst. Technol. **25** (2017) 270. https://doi.org/10.1109/TCST.2016.2547952
16 N. E. Smith, R. G. Cobb, S. J. Pierce, and V. M. Raska: J. Guid. Control Dyn. **38** (2015) 1156. https://doi.org/10.2514/1.G000459
17 L. H. Zhu, X. H. Cheng, and F. G. Yuan: Measurement **77** (2016) 40. https://doi.org/10.1016/j.measurement.2015.09.006

18 O. Khatib: Int. J. Rob. Res. **5** (1986) 90. https://doi.org/10.1177/027836498600500106
19 T. Lee, M. Leok, and N. H. McClamroch: ArXiv.org (2010). https://doi.org/10.48550/arXiv.1003.2005
20 F. Xiao and L. Wang: IET Control Theory Appl. **1** (2007) 830. https://doi.org/10.1049/iet-cta:20060014
21 C. Q. Ma and J. F. Zhang: IEEE Trans. Autom. Control. **55** (2010) 1263. https://doi.org/10.1109/TAC.2010.2042764

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