Research on synergic Control Algorithm and Collision Avoidance of unmanned aerial vehicle Formation

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Abstract: The current study mainly researches the problem of leader-follower based formation cooperative maintenance of fixed-wing UAV. First, the fixed-wing UAV formation with the leader-follower structure is used as the research object, and the flight dynamics model is established; the formation synergic control law is designed for the follower and the leader in the formation, especially the follower's control law is improved to realize the state tracking control of the follower by controlling the speed and roll Angle of UAV; as stated by the master-slave formation, the distributed topology is introduced to realize the information interaction between adjacent UAVs, and on this basis, a collision avoidance strategy has been added to prevent drones from colliding with each other in the formation. Finally, the formation control algorithm and collision avoidance strategy are simulated through data simulation, and the results prove that the UAV formation can effectively complete the formation task and avoid collisions within the formation.

1. Introduction
A single Unmanned Aerial Vehicle (UAV) has intrinsic shortcomings such as short endurance, a small radius of activity, and poor anti-jamming ability, so it has poor efficiency and low success rate when performing large and complex tasks[1]. Relatively speaking, multi-UAV formations can resolve the conflicts in time, space, and mission levels that exist in the implementation of large and complex tasks, thereby greatly improving mission efficiency[2]. Synergic control technology, which is the basis for the integrated development of multi-UAV combat system, has received extensive attention and development, and abundant research achievements have emerged in recent years. As one of the basic researches of synergic control, formation control has also achieved considerable progress[3].

As reported by the internal communication method of multiple UAV formations, the formation control is generally divided into centralized and distributed[4]. Centralized control is to select one or more leaders in the formation, and send instructions to each member in the formation through the leader, so as to realize the control of the entire formation. Distributed control achieves control goals through information interaction between adjacent individuals in the formation, which can not only reduce the communication pressure of the formation, but also has strong fault tolerance and adaptability. Therefore, distributed control has gradually become a popular control strategy for formation control.

In comparison with rotary-wing UAVs, fixed-wing UAVs have the characteristics of fast speed, heavy payload, and large combat range, which have greater advantages for the successful implementation of large and complex tasks. The fixed-wing UAV is a typical nonlinear agent with non-integrity constraints, and there are restrictions on the maximum/minimum airspeed and the
maximum heading angular rate, thus its formation control problem is more challenging\cite{5}.

This paper takes the fixed-wing UAV formation using the leader-follower method as the study object and introduces a distributed structure into the formation topology network for improving the topology of formation communication. Different formation controllers are designed according to the different task requirements of the leader and the follower, and the formation controller of the follower is optimized to realize the state tracking control of the follower by controlling the speed and roll Angle of the follower; and dynamically adjust the expected distance parameter in the controller according to the speed of the follower in the addition to the change of the flight path for achieving more accurate and smooth control; The information exchange between adjacent followers was realized by the distributed structure in the topological network, and the control state was determined by comparing the relative distance between followers in real-time. The normal control method and the temporary collision avoidance control method were switched in time to realize the collision avoidance control of UAV formation. Finally, the collision avoidance strategy with the feasibility and effectiveness of the control algorithm are verified by simulation experiments through data simulation for different control scenarios.

2. Formation model

In a fixed-wing UAV formation with a leader-follower structure, the UAV follows a preset trajectory to fly, and the follower obtains the target position according to the lead plane’s position and formation requirements. By tracking the target position, the tracking control of the pilot is achieved to realize the formation flight. The dynamic model and network topology are established separately in accordance with the actual needs of the formation.

2.1 Dynamics model

Taking the rhombus formation constituted of 4 fixed-wing UAVs as the study object, in which the specific UAV model is a fixed-wing UAV model with a flight control system. The altitude control can be carried out in real time as required by the mission through the altitude channel of the flight control system. Therefore, this article only conducts two-dimensional model analysis. In the ground coordinate system, $x_i$ is the projection position of the drone on the $x$ axis, $y_i$ is the projection position of the drone on the $y$ axis, $\theta_i$ is the yaw angle of the drone ($i=1, 2, 3, 4$). The angle between the speed and the positive direction of the $y$ axis is the heading angle, clockwise is positive).

![Fig.1 UAV Formation Model](image)

Without considering the wind disturbance, the yaw angle of the UAV is the heading angle. The coordinated aircraft dynamics (CFV) model mentioned in the literature\cite{6} is used for describing the plane motion of a fixed-wing UAV. The CFV model is described by ordinary differential equations with moderate complexity, which can reflect the nonlinear characteristics of the flight process, as shown in equation (1).
In the formula, \((x_i, y_i)\) is the state quantity of the UAV, which represents the position of the UAV; \((\dot{x}_i, \dot{y}_i)\) is the eastward and northward velocity of the UAV in the ground coordinate system; \(v_i\) is the UAV's Navigation speed; \(\theta_i\) is the heading angle of the UAV; \(\dot{\theta}_i\) is the heading angular rate of the UAV; \(\phi_i\) is the roll angle of the UAV; \(a_i\) is the lateral acceleration of the drone \((i = 1, 2, 3, 4)\); \(g\) is the acceleration of gravity.

\[
\begin{align*}
\dot{x}_i &= v_i \cdot \cos \theta_i \\
\dot{y}_i &= v_i \cdot \sin \theta_i \\
\dot{\theta}_i &= \frac{g \tan \phi_i}{v_i} \\
a_i &= g \tan \phi_i
\end{align*}
\]

(1)

2.2 Formation network topology
During the flight of the UAV formation, the communication link in the communication network topology is used to realize information interaction, thereby realizing the flight mission. In the course of the flight, the leader sends longitude, latitude, altitude, speed, heading, and other information to the follower, but does not get information from the follower. The leader only needs to maintain its own flight on the expected route; On the one hand, the follower obtains the position and attitude information of the leader and determines its desired position through the relative distance between the leader and the follower, and on the other hand, obtains the position information of the neighboring wingman to avoid the collision. This paper uses a combination of directed and undirected topology. The advantage of this topology is that followers can fulfill information interaction through the undirected topology between followers, which overcomes the indirect acquisition of follower’s position information through the leader pass iteration error, and avoid unnecessary error correction processes, the specific structure is shown in Figure 2.

![Fig.2 UAV Formation Topology Structure](image)

3. Formation control law design
The No.1 UAV in the rhombus formation was selected as the captain and the other UAVs as followers, and the control law was designed for the leader and follower respectively.

3.1 The design of the leader control law
The leader flies on the expected route at a constant speed and transmits information to the follower in the formation in real-time, so the leader only needs to ensure that it can track the expected route smoothly.

The leader control law is designed according to the need. The basic principle of the leader control law is to find a target point on the target route that is far away from the UAV and use the target point to lead the UAV to fly. The particular method is to make a circular arc tangent to the UAV speed vector.
on one side of the target route, and the intersection of the arc and the target course is the target point, which is shown in Figure 3[7]. Assume that the distance between the target waypoint and the leader is $L_1$, the arc radius is $R$, and the azimuth angle between the pilot and the target waypoint is $\varphi$.

![Leader Tracking Model](image)

Fig.3 Leader Tracking Model

According to the geometric relationship:

$$R = \frac{L_1}{2 \sin \varphi} \quad (2)$$

Substituting formula (2) into the centripetal acceleration formula can be obtained[7]:

$$a = \frac{v_1^2}{R} = \frac{2v_1^2 \sin \varphi}{L_1} \quad (3)$$

According to Equation (3), the angle between the speed of the leader $v_1$ and the vector $L_1$ should be calculated for lateral acceleration as follows:

$$\varphi = \arccos \left( \frac{\vec{v}_1 \cdot \vec{L}_1}{|\vec{v}_1| \cdot |\vec{L}_1|} \right) \quad (4)$$

The vector can be represented by the state quantity $(\hat{x}_1, \hat{y}_1)$; the expected route of the leader and the pilot coordinates $(x_1, y_1)$ are known, the coordinates of the target point $P$ can be determined through the tracking model, and then the vector $\vec{L}_1$ can be obtained.

3.2 Follower control law

For the follower, the relationship between the target position and the actual position is described by determining the horizontal relative distance and the vertical relative distance according to the local Cartesian coordinate system of the lead plane. The local Cartesian coordinate system is established with the heading direction of the long engine as the forward X-axis and the right X-axis (from the top view) as the forward Y-axis. The relationship between the local Cartesian coordinate system and the global inertial coordinate system is shown in Figure 4.
The conversion relationship between the two coordinates is shown in formula (5) \(i=2, 3, 4\).

\[
\begin{align*}
X_i &= (x_i - x) \sin \theta_i + (y_i - y) \cos \theta_i \\
Y_i &= (x_i - x) \cos \theta_i - (y_i - y) \sin \theta_i 
\end{align*}
\]  

From formula (5), the real-time relative distance between the follower and the leader is \(l_{xi} = |X_i|\), \(l_{yi} = |Y_i|\) \(i=2, 3, 4\).

Conforming to the coordinates of the leader and the needs of the formation mission, the expected relative distance \(L_{xi}, L_{yi}\) between the leader and the follower can be obtained. The error \(\Delta X_i, \Delta Y_i\) between the real-time relative distance and the expected relative distance of the follower is shown in equation (6).

\[
\begin{align*}
\Delta X_i &= l_{xi} - L_{xi} \\
\Delta Y_i &= l_{yi} - L_{yi}
\end{align*}
\]  

When the expected position of the follower is inconsistent with the actual position, by controlling the flight speed and lateral acceleration of the follower, the UAV moves to the target point with a smooth trajectory. The speed of the given follower is

\[
v_i = v_i - k_i \Delta X_i
\]  

where \(k_i\) the scale factor is. Generally constant.

The follower’s tracking control of the leader is essentially tracking the desired position. The difference between the wingman’s control modes is that the wingman’s dynamic desired position is tracked, while the lead aircraft is tracking and controlling a fixed route, so the lateral acceleration of the wingman is taken as for the formula (8).

\[
a_i = \frac{2v_i^2 \sin (\alpha_i + \beta_i)}{L_i}
\]  

In the formula, \(\alpha_i = \theta_i - \theta, \beta_i = \arcsin \left(\frac{\Delta Y_i}{L_i}\right)\), \(\alpha_i + \beta_i \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]\).

\(L_i\) Value is the key parameter to control the follower tracking control and the distance parameter to determine the expected position of the wingman. In the actual tracking control process, the value of \(L_i\) is closely related to the flight path information of the predicted wingman, and its influencing factors mainly include the characteristics of the UAV itself, the expected flight path and the flight speed of the follower. In this paper, the size of fixed wing UAV selected at different speeds is determined according to the fixed wing UAV model and the actual task requirements, as shown in formula (9).

\[
L_i = L_{i0} + K_2 (v_i - v_0)
\]
In the formula, $K_2$ is a proportional coefficient, and appropriate $K_2$, $v_0$, $L_0$ are selected based on the needs of the flight mission and the flight path, so as to acquire the current value of $I_t$, and further getting the lateral acceleration and roll angle commands of the follower.

3.3 Collision avoidance strategy

In order to avoid collision between UAVs in formation during flight, collision avoidance strategy is added to the control method of follower. The follower can know the location of the other followers through the topology structure, and simplify the area where the other wingmen are as a whole into a circular threat area with the follower as the center$^{[8]}$, and avoid collision by avoiding flying over the circular threat area where the other follower are located.

Since the ideal relative distance between the leader and the follower is a fixed value, the ideal position of the follower can be calculated from the position of the leader. The follower’s dynamic ideal position constitutes the ideal route when it intersects the threat area, the follower enters the collision avoidance control; when the ideal position does not intersect the threat area, it exits the collision avoidance control. The ideal position and the collision avoidance threat area are determined according to the positions of the leader and the follower in the formation. Since the position of the drone in the formation changes dynamically, the specific parameters of collision avoidance control are also changing in real time. This is the difference and difficulty between the fixed obstacle avoidance and the scheduled course tracking control.

The basic idea of the collision avoidance strategy is as follows: in the process of tracking the leader, the follower constantly obtains the position information of other followers through the topological network and constantly compares it with its own position. When the conditions of collision avoidance are met, the wingman switches the temporary control method of collision avoidance and controls the follower to bypass the covered area so as to achieve collision avoidance. When the conditions for ending collision avoidance are met, the follower switches the control method to the conventional control method. The basic process of collision avoidance is shown in Figure 5:

![Fig.5 Process of Follower’s Collision Avoidance](image-url)
When the desired position of the follower begins to connect with the circular threat area where the other followers are located, the temporary collision avoidance control method is adopted to control the follower, and the collision avoidance flight is shown in Figure 6. After avoiding the collision, the follower takes the conventional approach to track and control the leader.

![Fig.6 Schematic of Follower’s Collision Avoidance](image)

$R_{ij}$ is the distance between the follower and the calculation formula is as follows:

$$R_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

$r_j$ is the radius of the threat area of the other follower and the calculation formula for the angle $\gamma_i$ and $\eta_i$ is as follows ($j = 2, 3, 4$):

$$\begin{align*}
\gamma_i &= \arccos\left(\frac{L_i^2 + R_{ij}^2 - r_j^2}{2R_{ij}L_i}\right) \\
\eta_i &= \arctan\left(\frac{Y_j - Y_i}{X_j - X_i}\right)
\end{align*}$$

At this time, the follower speed $v_i$ takes a fixed value $v_0$, and the lateral acceleration $a_i$ is shown in the following formula:

$$a_i = \frac{2v_0^2\sin(\eta_i \pm \gamma_i)}{L_i} \tag{10}$$

In the formula, the sign of the $Y$-axis velocity component of UAV $j$ and the $Y$-axis velocity component of UAV $i$’s lateral acceleration should be taken in the opposite direction.

4. Simulation verification

Due to the limitation of the kinematics of the fixed-wing UAV, the roll angle must be limited, namely $-\phi_{\text{max}} \leq \phi_i \leq \phi_{\text{max}}$, $\phi_{\text{max}} = 30^\circ$.

First, carry out a feasibility experiment on the establishment of the formation, and take the initial positions of the UAVs (UAV 1–UAV4) in the formation as $j$ and $k$ respectively, the formation at the initial position is the ideal formation, $L_i = L_j = 90$, $v_0 = 50$. Assuming that the UAVs in the formation all start to move at an initial speed of 50m/s, the lead plane is allowed to track a square trajectory with a side length of 1000 meters (as shown by H0 in Figure 7). The flight trajectories of the drones in the formation are shown in Figure 7.
As can be seen from Figure 7 that the UAV formation can achieve good formation maintenance in straight flight. During the coordinated turn, the relative distance between the formation individuals produced a certain error, and the formation deteriorated, but after the straight flight is restored quickly eliminated errors and restored the ideal formation.

Then verify the effectiveness and feasibility of the collision avoidance strategy. Take $v_1 = v_0 = 30m/s$, the threat area radius $r_2 = r_3 = r_4 = 20m$, the initial coordinates of $UAV_1$–$UAV_4$ are $(220, 260)$, $(180, 60)$, $(80, 20)$, $(30, 20)$, and the initial heading angle is $\theta_1 = 45^\circ$, $\theta_2 = 60^\circ$, $\theta_3 = \theta_4 = 30^\circ$. At this time, the simulated situation is that the position error of UAV2 in the formation is relatively large. In the tracking control process, if the collision avoidance control is not implemented, the collision will occur with UAV3, as shown in Figure 8 and Figure 9.
Fig. 9 Roll Angle Instruction

Time 1, 2, and 3 in Figure 8 are the positions of the drones at the start and end of collision avoidance control, the end of collision avoidance control, and the end of the flight. At the start and end of collision avoidance control, make a circle with the UAV2 position as the center of the circle, and at the same time, it shows the flight path of UAV3 without collision avoidance control and the flight trajectory of collision avoidance control, which proves the necessity of collision avoidance control. It can be seen from Figure 8 and Figure 9 that UAV3 avoids the threat area centered on UAV2 through collision avoidance control, and achieves the purpose of collision avoidance control, thus proving that formation can be effectively prevented by adding collision avoidance strategies to the formation control algorithm. The flight collision risk and the roll angle meet the limit requirements during the control process, proves the feasibility of the method.

5. Conclusion

1) The formation control law proposed for the leader and the follower can basically complete the task of tracking the scheduled route and tracking the dynamic target. The formation can achieve good formation in straight flight, and the formation will be slightly worse in the coordinated turn. But the formation error can be quickly eliminated after the straight-line flight is restored, and the purpose of the formation coordinated control is basically realized.

2) The introduction of a distributed structure in the formation communication network reduces the communication pressure in the formation, improves the accuracy of positioning adjacent drones in the formation, and solves the problem that the UAVs in the formation easily collide with each other by adding collision avoidance strategies, To achieve real-time avoidance of threats to neighboring aircraft during formation flying, and enhance the practicability and feasibility of formation control algorithms.

3) The selection of specific parameters in the control algorithm is very important, and further precision is needed. The accuracy and reliability of the formation control algorithm need to be further improved.

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