Research on collision avoidance of fixed-wing UAV

Conference Paper · July 2019

DOI: 10.1145/3351917.3351933

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ABSTRACT

In this paper, a hybrid collision avoidance approach, outer planning control and inner emergency control, is designed to solve the problem of avoidance of the non-cooperative target and the cooperative Unmanned Aerial Vehicles (UAVs) in the formation. For non-cooperative target, a multi-layer obstacle avoidance model is employed to determine the current situation of the UAV, for which different layer corresponds to different methods. If the UAV is far away from the obstacle, the method of planning control is implemented. A collision cone with a transition domain is introduced to reduce response time and eliminate local minima. If the UAV is closer to the obstacle, an emergency avoidance method is needed to ensure safety. For the cooperative UAVs in the group, we set the avoidance strategy table in advance and select the best response method by optimizing the security value. The feasibility and effectiveness of the proposed strategies are verified by simulations.

KEYWORDS

Fixed-wing UAV, Two-layer collision avoidance model, Single-aircraft obstacle avoidance, Multi-aircraft collision avoidance

1 INTRODUCTION

The research on the collision avoidance of the UAV under the unknown environment has a series of theoretical and practical results. In general, the collision avoidance algorithm is divided into three categories: the avoidance method based on the path planning (PP), reactive obstacle avoidance (ROA) method and the avoidance method based on the optimization control.

The avoidance method based on PP is mainly to obtain a collision-free flight trajectory by online or off-line planning according to the distance between the UAV and obstacles. The representative methods include artificial potential field (APF) method, A* algorithm, random search tree, .etc. The planning method based on APF method is a common obstacle avoidance method because of its low adjustment parameters and efficient operation. Reference [1] uses APF method, by adjusting the integrated navigation equation so that the vehicle can converge to a collision-free path. In reference [2], A collision prevention method for UAV cluster based on improved APF method is designed by Xu Zhu, in which the consistency theory and the idea of weighted combination are used to ensure the safety of the leader UAV, and then the collision avoidance of the whole cluster is carried out. In reference [3], aiming at some problems existing in traditional APF method, obtained feasible domain by referring to geometric topology theory, and pre-planned track points within the feasible domain. In reference [4], model predictive control (MPC) method is used in unknown environment, especially in urban complex environment. In reference [5], the anti-interference performance of the system is greatly improved by combining the APF method with MPC.

ROA method mainly refers to the method to get rid of the current dangerous situation directly through emergency operations in a period of time. This method is a local planning method, which does not need global information, and can be controlled only according to the nearest point with obstacles. By reducing the demand of information, the computational complexity is reduced and the response time is shortened [6]. For dynamic obstacles, when the movement of obstacles in space satisfy specific assumptions, ROA method can still effectively avoid obstacles. In reference [7], the application of ROA method in dynamic scenes is given without strict proving, and this paper puts forward a modified Newton method which can eliminate oscillations. In reference [8], Xu analyzes the key factors affecting the collision prevention decision, and puts forward an autonomous collision control strategy combining course angle, speed and altitude.

MPC method is an optimal control strategy based on model, which includes centralized and distributed methods. The centralized method is good at dealing with the problems of motion coordination and collision avoidance, but it is not easy to expand and is more complex. The distributed method decomposes the problem into multiple sub-problems, which reduces the scale and complexity of the problem, and distributed has gradually replaced the centralized method. In reference [9], a distributed MPC method is adopted, which does not prove the stability of the system, but provides a strategy based on adjacent UAV avoiding collide. In reference [10], based on distributed MPC, applies linear time-varying control method and linear nonlinear model to realize trajectory tracking and ensure good dynamic performance.

The main contribution of this paper is that we introduced a collision cone with a transition domain to reduce response time and eliminate local minima in this paper. Meanwhile, we designed the safety value to evaluate the collision avoidance strategy. By constructing a multi-vehicle response strategy table, the strategy with the highest safety value is selected as the best way to avoid obstacles. Designed and implemented the UAV obstacle avoidance simulation tests under various conditions.

2 MODELING AND PROBLEMS

2.1 Dynamic Model

In this paper, it is assumed that the UAV is always flying at the same altitude. The problem of collision avoidance of the UAV in two-dimensional plane is mainly considered. The dynamic model

$$\begin{cases} \dot{x} = v\cos\theta, x(0) = x_0 \\ \dot{y} = v\sin\theta, y(0) = y_0 \end{cases} \tag{1}$$

is employed. Where, (x, y) and v represent the position and the speed of the UAV, and θ indicates the heading angle. (x_0, y_0) is the position of the UAV in the initial. In general, the flight speed of the UAV is assumed to be a constant value, which is unit.

Further, the simulation step size is l. Discretizing equation (1) can get:

$$\begin{cases} x(k+1) = x(k) + l\cos\theta(k+1) \\ y(k+1) = y(k) + l\cos\theta(k+1) \end{cases} \tag{2}$$

2.2 Complex Environment Analysis

Definition 1 : Hinder. Various unknowable external factors that pose a threat to the safe flight of a single UAV are composed of various static and dynamic objects which can’t go through.

Definition 2 : Obstacle. The spherical region with the center of hinder $P_b(x_b, y_b, z_b)$ for the center of the sphere, and the furthest distance from the center of the sphere R_b for the radius is defined as an obstacle.

Definition 3 : Collision Conflict. The detection radius of UAV radar is R_s . At any time T , when the distance between the obstacle and the UAV is satisfied $d = \|P - P_b\|_2 < R_s + R_b$, it is believed that there will be a collision conflict.

Definition 4 : Collide. At a certain time during flight, when the position relationship between UAV and obstacle satisfies: $\|P - P_b\|_2 \le R + R_b$, it is considered that the collision occurred.

In order to compare the performance of different algorithms, this paper defines the following concepts.

Definition 5 : Safety Value. The mean distance between UAV and all obstacles in airspace, or the mean distance between UAVs in airspace is considered to be safety value.

$$d_{safe} = \begin{cases} mean(\|P - P_{b1}\|_2, \|P - P_{b2}\|_2 \cdots, \|P - P_{bn}\|_2) & Single\ UAV \\ mean(\|P_1 - P_2\|_2, \|P_1 - P_3\|_2, \|P_2 - P_3\|_2) & Multiple\ UAV \end{cases} \tag{3}$$

2.3 Two-layer Collision Avoidance Model

As shown in Figure 1, the outer layer has the radius R_o . When an obstacle appears in Ω_o , using planning control strategy to avoid obstacles. The inner layer has the radius R_i . When an obstacle appears in Ω_i , the distance between the UAV and the obstacle is relatively short, the time for the UAV to react is short, and the mobility requirement of the UAV is high, using the emergency obstacle avoidance strategy to avoid obstacles.

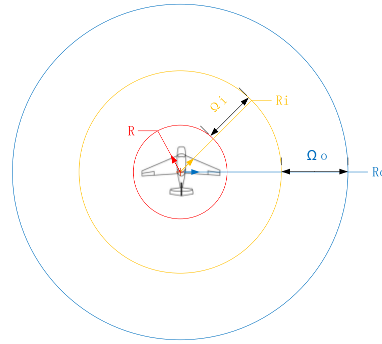


Figure 1: Two-layer obstacle avoidance model

At any time T, measure the distance between the UAV and obstacle $d = \|P - P_b\|_2$, when $d = \|P - P_b\|_2 < R_o + R_b$, the outer layer uses the APF method based on the improved collision cone to avoid obstacles; when $d = \|P - P_b\|_2 < R_i + R_b$, the inner layer can avoid obstacle from three aspects: the heading angle, the speed and the altitude, and can also select the integrated control strategy of various scheme combinations according to different situations.

3 MAIN WORK

3.1 Outer Planning Control Strategy

The basic principle of the APF method is to construct a virtual potential field, to establish a repulsive force field of the obstacle and a gravitational field of the destination, so that the UAV can avoid the collision while flying to the destination under the combined force of the obstacle’s repulsion force and the destination’s attraction force.

The gravitational field in the environment in which the UAV is located can be expressed as follows:

$$U_{att}(q) = \tfrac{1}{2}\xi_{att}\|X - X_g\|_2 \tag{4}$$

By calculating the negative gradient of the gravitational field, the gravitational on the UAV can be obtained:

$$F_{att}(q) = -\nabla U_{att}(q) = \xi_{att}\,|X - X_g| \tag{5}$$

The repulsive force field in the environment in which the UAV is located can be expressed as follows:

$$U_{rep}(q) = \begin{cases} \tfrac{1}{2}\xi_{rep}\left(\tfrac{1}{\rho(q,q_o)} - \tfrac{1}{\rho_o}\right)^2 & 0 \le \rho(q,q_o) \le \rho_o \\ 0 & \rho(q,q_o) > \rho_o \end{cases} \tag{6}$$

Likewise, by calculating the negative gradient of the repulsive force field, the repulsive force on the UAV can be obtained:

$$\begin{aligned} F_{rep}(q) &= -\nabla U_{rep}(q) \\ &= \begin{cases} \xi_{rep}\left(\tfrac{1}{\rho(q,q_o)} - \tfrac{1}{\rho_o}\right)\tfrac{1}{\rho^2(q,q_o)}\nabla\rho(q,q_o) & 0 \le \rho(q,q_o) \le \rho_o \\ 0 & \rho(q,q_o) > \rho_o \end{cases} \end{aligned} \tag{7}$$

The combined field in the environment of UAV is the combined field of gravitational field and repulsive force field:

$$
\begin{aligned}
U(q) &= U_{\text{att}}(q)+U_{\text{rep}}(q) \\
&= \begin{cases} \frac{1}{2}\xi_{rep}\left(\frac{1}{\rho(q,q_o)}-\frac{1}{\rho_o}\right)^2+\frac{1}{2}\xi_{att}\,\| X-X_g \|_2 & 0\le \rho(q,q_o)\le \rho_o \\ \frac{1}{2}\xi_{att}\,\| X-X_g \|_2 & \rho(q,q_o)>\rho_o \end{cases}
\end{aligned} \tag{8}
$$

By summing up the gravitational and repulsive forces on the UAV, the resultant force on the UAV can be obtained, that is:

$$
F_{\text{rep}}(q)=\begin{cases} \xi_{rep}\left(\frac{1}{\rho(q,q_o)}-\frac{1}{\rho_o}\right)\frac{1}{\rho^2(q,q_o)}\nabla\rho(q,q_o) & \\ +\xi_{att}\,| X-X_g | & 0\le \rho(q,q_o)\le \rho_o \\ \xi_{att}\,| X-X_g | & \rho(q,q_o)>\rho_o \end{cases} \tag{9}
$$

In this formula, ξ_{att} is the gravitational gain coefficient; $\| X-X_g \|_2$ is the distance between UAV and target point; ξ_{rep} is the repulsive force gain ; $\rho(q,q_o)$ is the distance between UAV and obstacle; ρ_{o} is the range in which the repulsive force of the obstacle have influence.

The idea of collision cone is put forward in reference [11]. Hence, we combined with the idea of the transition domain to improve it, the APF method based on improved collision cone is designed.

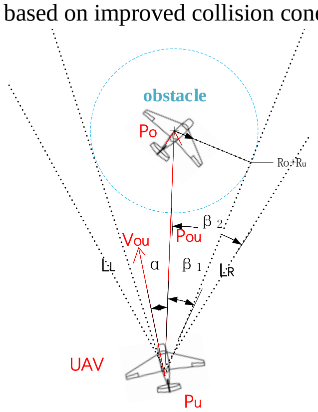


Figure 2: Improved collision cone schematic diagram

As shown in Figure 2, P_{u} , P_{o} is the location of the UAV and obstacle, P_{ou} is the relative position vector of the UAV and obstacle, R_{u} , R_{o} is the radius of the UAV and obstacles, $R_{\text{o}}+R_{\text{u}}$ is the radius in which UAV hit obstacle, the collision area is the sphere which center is P_{o} and radius is $R_{\text{o}}+R_{\text{u}}$. V_{ou} represents the velocity vector of UAV relative to obstacle, L_L, L_R is the left tangent and the right tangent for crossing the UAV to the collision area, and it is easy to see from the diagram that L_L, L_R is symmetrical relative to P_{ou} .

Make the angle between relative position vector P_{ou} and the tangent L_R to be β_1 , then $\beta_1=\arcsin\dfrac{\text{R}_{\text{o}}+R_u}{\| P_{ou} \|}$. α is the angle between relative velocity vector V_{ou} and relative position vector P_{ou} , and it is positive when it is on the left of P_{ou} , otherwise, it is negative. When a collision conflict occurs and $|\alpha|\le|\beta_1|$, the influence of the obstacle should be considered while drawing the next step with the artificial potential field method.

When the UAV first entered the collision cone area, like in Figure 3, we make the collision cone bigger at this time, let β_1 increase to β_2 , that is, to increase $\Delta\beta=\beta_2-\beta_1$. In planning the next step of the UAV, it is considered that as long as the UAV enters the collision cone for the first time, until $|\alpha|>|\beta_2|$ the UAV can come out of the collision cone area.

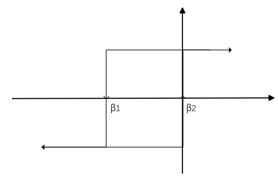


Figure 3: Schematic diagram of transition domain

That is, the angle β used to judge if UAV enters the collision cone area is difference from the angle β used to judge if UAV comes out of the collision cone region. When the UAV comes out of the collision cone area, restore the area to its original size β_1 .

To sum up, the specific method of improving the collision cone is to make the collision cone area of an obstacle initially be β_1 , when the UAV has collision conflict for the first time and enters the collision cone, the collision cone area is expanded to β_2 and is recovered to the initial size until it comes out of the collision cone. And by calculating the size of the security value, the optimal transition region can be found by experiments.

3.2 Inner Emergency Control Strategy

3.2.1 Heading Angle Control Strategy.

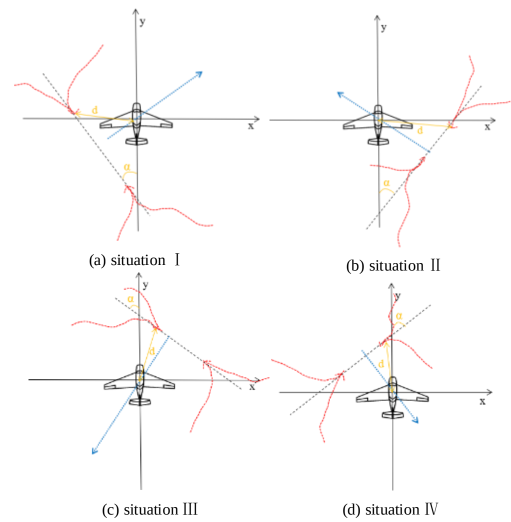


Figure 4: Direction angle distribution of UAV and obstacles

When the collision conflict occurs, according to the relative position of the obstacle and the UAV, the position of the obstacle trajectory relative to the UAV is predicted. Then let the UAV fly in the opposite direction.

In Figure 4, the UAV is in this direction along the y axis, when the obstacle flies in the direction indicated by the red arrow, and the speed is in the direction of the black dotted line. At this time, the distance between the center of mass of UAV and the center of mass of obstacle is d, and the angle between the y axis and dotted line in the velocity direction is α, and the angle is positive when it is on the left side of y axis and is negative when it is on the right side of y axis. At this time, the obstacle avoidance strategy of UAV is as follows: flying in the direction of the blue dotted line。

Therefore, the change of UAV heading angle at a certain time is related to the distance d between UAV and obstacle, and the direction α of obstacle relative to UAV. That is, satisfying:

$$\Delta\phi = \mathrm{F}_{\phi}(\mathrm{d}, \alpha) \tag{10}$$

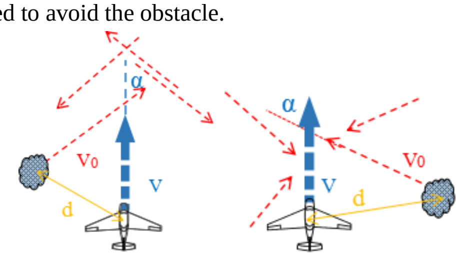
Through the analysis of the relative position relationship, the following mathematical relations are obtained:

$$\phi = \begin{cases} \alpha - \dfrac{\pi}{2}\cdot \mathrm{sgn}(\alpha) & d \le R_0 + R_i \cap b < 0 \\ \alpha + \dfrac{\pi}{4}\cdot \mathrm{sgn}(\alpha) & d \le R_0 + R_i \cap b \ge 0 \\ 0 & otherwise \end{cases} \tag{11}$$

In this formula, b is positive when the obstacle relative to the UAV is located in the first and second quadrants of the coordinate system with the UAV as the origin and the speed direction of the UAV as the x axis; while b is negative when the obstacle relative to the UAV is located in the third and fourth quadrants of the coordinate system.

3.2.2 Speed Control Strategy.

When the collision conflict occurs, according to the relative position relationship between the predicted trajectory of the obstacle and the UAV, the speed change of the UAV can be controlled to avoid the obstacle.



(a) situation I (b) Situation II

Figure 5: Relative velocity of UAV to obstacle

In Figure 5, the speed of the UAV is V , the speed of the obstacle is V_0, the distance between the UAV and the mass of the obstacle is d , the angle between the straight line where the obstacle speed is located and the velocity direction of the UAV is α , and the angle is positive on the left of V and is negative on the right. Then according to the direction and size of the speed of the UAV and the obstacle at this time, the future position of the UAV and the obstacle is predicted respectively.

If the obstacle passes through the intersection of the predicted trajectory of the UAV and the obstacle, the UAV avoids the obstacle by decelerating, and if the UAV passes through the intersection first, the UAV avoids the obstacle by accelerating. That is, the speed change of UAV is related to the distance d between UAV and obstacle, the direction α of UAV, the speed v of UAV, and the speed V_0 of obstacle.

That is, satisfying：

$$\Delta \mathrm{v} = \mathrm{F}_{\mathrm{v}}(\mathrm{d}, \alpha, v, v_0) \tag{12}$$

It can be deduced to that:

$$v = \begin{cases} V_{\min} & d \le R_0 + R_i \cap v \le v_0 \cos\alpha \\ V_{\max} & d \le R_0 + R_i \cap v > v_0 \cos\alpha \\ V & otherwise \end{cases} \tag{13}$$

3.2.3 Integrated Control Strategy.

Due to the limitation of the dynamic characteristics of UAV itself, it is necessary to meet certain constraints when controlling the heading angle, speed and altitude. There is a maximum turning rate in the flight process of UAV, so in the heading angle control strategy, the output of the heading angle should satisfy: $\dot{\psi} \le \dot{\psi}_{\max}$, $\varphi \le \varphi_{\max}$. Moreover, the flight speed of the actual UAV system cannot be zero or infinite, so the speed in the Speed control strategy should satisfy: $\mathrm{v}_{\min} \le v \le \mathrm{v}_{\max}$.

Because of the complexity of the situation, it may not be possible to avoid obstacles by considering these factors alone, so these strategies are synthesized and integrated control strategies are designed. We can change heading angle, speed, altitude at the same time or several of them at the same time. According to the distance between the UAV and the obstacle, the current speed and direction of the UAV and the relative height of the UAV, we design a barrier avoidance strategy table. Giving each strategy a cost value, then selecting the least expensive case of all as the corresponding obstacle avoidance strategy.

4 Simulation Experiment

4.1 Simulation Flow

The schedule of two-layer collision avoidance strategy is shown in Figure 6. First, enter the starting and ending point of the UAV, as well as the location and number of UAV and obstacles, and then determine whether the UAV has reached the ending point. If the UAV reaches the ending point, then stop it, else judge the distance between the UAV and the obstacle. If the distance is bigger than d_2 , the UAV tracks trajectory. If the distance is bigger than d_1 and smaller than d_2 , UAV adopts outer planning control (calculate gravity and repulsive force, and then calculate the magnitude and direction of the resultant force) . If the distance is smaller than d_1 , UAV adopts inner emergency control (control speed, heading angle) .Through the control, the speed and heading angle of the UAV are obtained, and the next position of the UAV is calculated, then judge again and circulate continuously.

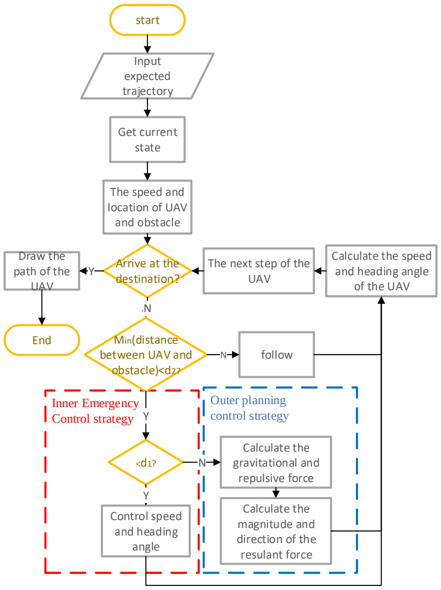
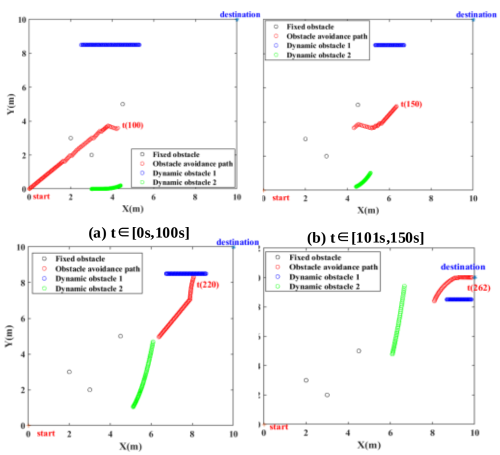


Figure 6: Schedule of two-layer collision avoidance strategy

4.2 Single UAV Obstacle Avoidance Strategy



(a) t∈[0s,100s]

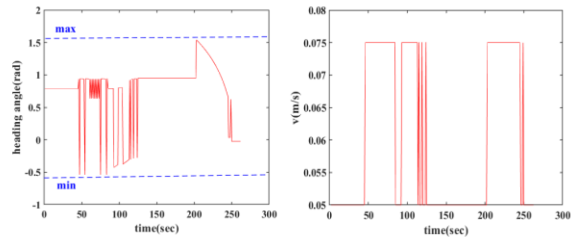
(b) t∈[101s,150s]

(c) t∈[151s,220s]

(d) t∈[221s,264s]

Figure 7: The trajectory of UAV and obstacle of Single UAV using two-layer collision avoidance strategy

The UAV flies from $(0,0)$ to $(10,10)$,and there are static and dynamic obstacles in the route. Set the outer radius to 5 and the inner radius to 1.5. The step size of the UAV is 0.05, the gravitational gain coefficient $k=5$ and the repulsive force gain coefficient $m=10$. In the flight process, the APF method based on the improved collision cone is used in the outer layer, and the integrated obstacle avoidance strategy is used in the inner layer to avoid the collision. The trajectory of the UAV and obstacle is shown in Figure 7. The heading angle and the speed using two-layer collision avoidance strategy are presented in Figure 8.



(a) The change of heading angle with time

(b) The change of speed with time

Figure 8: The heading angle and the speed using two-layer collision avoidance strategy

In order to quantitatively analyze the advantages of the two-layer obstacle avoidance strategy designed in this paper, the data are given in Figure 9.

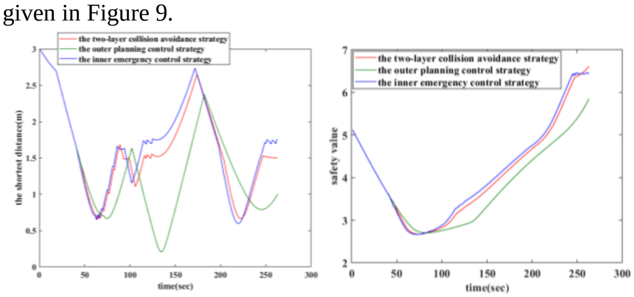


Figure 9: variation of the shortest distance between UAV and obstacles and the safety value with different strategy over time

Only using the outer layer planning control strategy, the average safety value is 1.3445, and only using the inner emergency control strategy, the average safety value is 1.6816, while using the two-layer obstacle avoidance strategy, the average safety value is 1.6192. It can also be seen from the above two figures that only using the inner layer emergency control strategy or the two-layer obstacle avoidance strategy, the shortest distance between the UAV and the obstacle and the safety value of the UAV are basically the same, and the shortest distance between the UAV and the obstacle and the safety value are far higher than that of only using the outer layer planning control strategy. However, only using the inner layer emergency control strategy, the average controlled quantity of heading angle $\overline{u^2}=1.0936$ and the average controlled quantity of speed $\overline{v^2}=0.0039$. Using the two-layer obstacle avoidance strategy, the average controlled quantity of heading angle $\overline{u^2}=0.7951$ and the average controlled quantity of speed $\overline{v^2}=0.0038$. Therefore, the transformation of heading angle and speed are more gentle, and the jitter is smaller, using the two-layer obstacle avoidance strategy. In conclusion, the performance of obstacle avoidance with two-layer obstacle avoidance strategy is optimal.

4.3 Multi-UAV Collision Prevention Strategy

Three UAVs fly from $(0,0),(3,0),(0,2)$ to $(10,10),(8,10),(10,7)$. We assume that three UAVs know each other's location. Set the influence radius of the other two UAVs in addition to themselves for 5, and their step for 0.05, 0.04, 0.035. Set gravitational gain coefficient $k=5$, repulsive gain coefficient $m=10$. In the flight process, the artificial potential field method based on improved collision cone is used to prevent collision. When the distance between the UAV and the obstacle is larger than P_{o2} and less than P_{o1} , using the artificial potential field method based on the improved collision cone. When the distance between the UAV and the obstacle is less than P_{o2} , using the inner emergency control strategy. The trajectory of three UAVs in space in different time periods is shown in Figure 10, and the heading angle and the speed of three UAVs are shown in Figure 11.

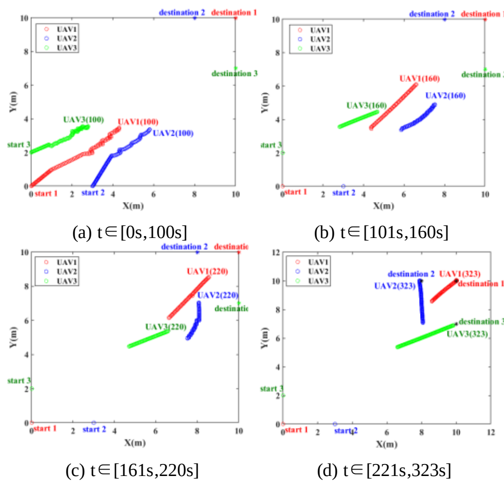


Figure 10: using two-layer collision avoidance strategy to avoid collision for multi-UAV

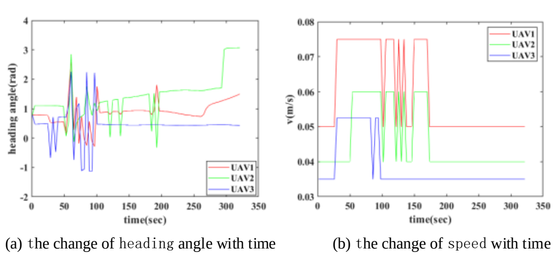


Figure 11: The heading angle and the speed of three UAVs

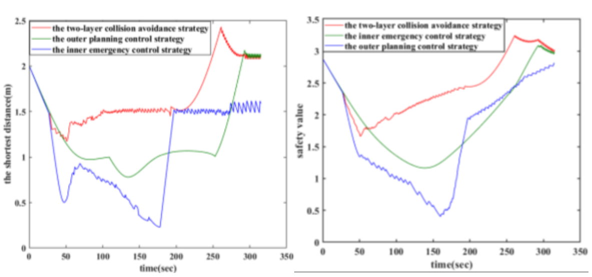


Figure 12: variation of the shortest distance between UAVs and the safety value with different strategy over time

Furthermore, we compare the minimum spacing and safety value within the formation when using three different strategies.in Figure 12. Only using the outer layer planning control strategy, the average safety value is 1.2207; and only using the inner emergency control strategy, the average safety value is 1.2442; while the two-layer obstacle avoidance strategy is used, the average safety value is 1.6727. As can be seen from the above two pictures, the distance between UAVs and the safety value are larger than that only using the outer layer planning control strategy or using the inner emergency control strategy. Therefore, the performance of multi-UAV collision prevention with two-layer obstacle avoidance strategy is optimal.

5 Conclusion

In this paper, the outer layer planning control strategy and the inner emergency control strategy based on the improved collision cone artificial potential field method are synthesized, and a two-layer collision avoidance strategy is designed. Meanwhile, through MATLAB simulation verification of single UAV avoiding bumping into obstacles and multi-UAV avoiding collision, it is verified that the performance of the two-layer collision avoidance strategy is better than that of a single control strategy.

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