Research on UAV flight safety interval under wind influence

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Abstract. With the progress of aerospace technology, unmanned aerial vehicles (UAV) are gradually showing incomparable advantages over manned aircraft. However, the safety interval of formation flying has always puzzled us. In order to solve this problem, this paper mainly studies the collision risks of three UAVs in flight considering the two factors of wind and positioning error. It provides a reference for the research on the flight safety interval of UAV formation.

1. Introduction

At present, unmanned aerial vehicles (UAV) have attracted extensive attention in both civil and military fields due to their small size, low cost, high survival rate, simple structure, flexible use, strong adaptability and no risk to life. The formation flying of UAVs refers to a certain formation arrangement or task allocation organization mode for multiple UAVs to meet the task requirements. During the formation flying process, each UAV must maintain a specified distance and height. However, how to control the safety interval inside the UAV formation is an urgent problem to be solved at present.

Domestic research on UAV formation flight is still in its infancy. Ref.[1] suggests that for larger UAVs that can accommodate the load of airborne radars and generate the required electrical energy, equipped with airborne radars is a good choice to resolve conflicts. Ref.[2] proposes a mathematical framework of UAV perception & avoidance system, which is defined and analyzed by differential game and survivability theory. Ref.[3] also mentions the concept of perception and collision avoidance system, which is divided into two categories: cooperative and non-cooperative. Ref.[4] quantifies the collision probability between two UAVs when flying in formation. Ref.[5] makes a general analysis and discussion on the safety interval of aircrafts flying in low-altitude airspace.

Some scholars abroad have suggested that UAVs cannot avoid conflicts according to the principle of “seeing and avoiding”[6]. Ref.[7] transforms the conflict resolution problem into a nonlinear optimization problem. Jenie proposed a conflict detection and resolution method for unmanned aerial vehicles[8]. Based on the uncertainty of the future UAV position[9], Xiang J proposed a method to evaluate the collision probability between the space point and the UAV airbag at the mid-term horizon[10]. After that, Jenie used Monte Carlo simulation to evaluate the safety of UAVs in different airspace densities[11].

There are still many difficult problems to be solved in the research of formation flying of UAVs. This paper starts with the influence of wind on UAV flight, calculates the collision probability
between UAVs by changing the size and direction of the wind, thus determining the UAV flight safety interval in this case.

2. Modeling of UAV formation flight

2.1. Dynamic model

In this paper, Euler-Newton method[12] is used for specific analysis. If the speed of the UAV along the positive direction of the three coordinate axes of the ground coordinate system is \( u, v, w \), then:

\[
\dot{x} = u \\
\dot{y} = v \\
\dot{z} = w \\
\]

\[
u = m^{-1} (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) \sum_{i=1}^{4} T_i \\
\]

\[
\dot{v} = m^{-1} (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi) \sum_{i=1}^{4} T_i \\
\]

\[
\dot{w} = -gm^{-1} (\cos \phi \cos \theta) \sum_{i=1}^{4} T_i \\
\]

The state variables in this model are: \( x, y, z, u, v, w \). The control variables are: \( \phi, \psi, \theta, T \) (\( \psi \) is the yaw angle; \( \theta \) is pitch angle; \( \phi \) is the roll angle). And random interferences include: wind, navigation errors, and reaction delay.

2.2. Risk assessment model

The formation of unmanned aerial vehicles will be affected by various weather conditions when flying, of which wind is the most important. Sometimes the sudden change of wind speed will change the interval between UAVs in the formation, especially the UAVs on the windward side will be greatly affected. At this time, ground personnel cannot control the position of UAVs in time. Therefore, leaving a certain margin of safety can better ensure the flying safety of the formation.

Because of the irregular configuration of the UAV, the method in Reich collision model is adopted to abstract the UAV into a cuboid, and the length, width and height of the cuboid are \( l_x, l_y, l_z \), so the collision critical values in all directions are respectively:

\[
d_i = (l_i + l_{i+1})/2, \quad i = x, y, z \\
\]

This paper mainly studies the influence of wind speed and navigation positioning error on formation, and takes the formation of three unmanned aerial vehicles arranged in a horizontal row as the research formation. The formation formation is shown in the figure 1.

![Figure 1. UAV formation.](image)

UAV’s positioning error \( \delta \) follows normal distribution[13], \( \delta \sim N(\mu, \sigma^2) \). The distance between the two agents can be expressed as: \( d_0 = d + (\delta_i + \delta_j) \), then there is:

\[
d_{12} \sim N(\mu_1 + \mu_2 + x_0, \sigma_x^2 + \sigma_y^2) \\
\]
Assuming that the probability density function of the distance between the two machines is \( f_d(x) \), the probability distribution function of collision is \( P(x) = \int_{x_1}^{x_2} f(t) dt \). Where \( x_1 = 0 \), \( x_2 \) is the minimum safe distance between the two agents [14].

Several assumptions and settings are made:

• The force exerted on an aircraft decreases by 1/4 for each passing aircraft.
• The moment when the wind starts to act on the UAV is 1 second later along the wind direction.
• The response delay of each UAV is 3 s, that is, each UAV will move for 3 s under the action of wind force within one change.

Take No.1 as the origin and the horizontal right direction as the positive direction to establish the axis, then:

\[
F_s = WS = \frac{Y}{2g} v^2 S
\]

\[
a = \frac{Y}{2mg} v^2 S
\]

Each variable is defined as follows: \( Y \) is the gravity per unit volume of air, \( g \) is the gravity acceleration, \( W \) is the wind pressure per unit area, \( S \) is the force area of unmanned aerial vehicle subjected to wind, \( F_s \) is the wind force along axis \( x \), \( m \) is the mass of unmanned aerial vehicle, and \( v \) is the wind speed.

If the initial distance between the two UAVs is \( d_i \), then:

\[
d'_{ij} = \begin{cases} 
  d_y - \frac{1}{2} at^2 + (\delta_i + \delta_j), t \in [0,1) \\
  d_y + \frac{3}{4} a(t-1)^2 - \frac{1}{2} at^2 + (\delta_i + \delta_j), t \in (1,3]
\end{cases}
\]

Since formation flying is unsafe as long as there is collision between two UAVs, the probability of collision between UAVs \( i \) and \( j \) is defined as \( P_{ij} \), and the probability of safe flying of the whole formation is:

\[
P_{safe} = (1-P_{12})(1-P_{23})
\]

3. Experimental analysis

When UAV formation flies at low altitude, the wind direction and wind speed are always changing. The influence of wind in different directions and different sizes on UAV formation is different. For formation flying side by side, as long as the projection of wind speed in the lateral direction is not zero, it will affect the formation. In this paper, two typical wind directions are selected to study, one is the left side wind, and the other is the left rear wind that forms an angle of 45° with the track. The collision risk is simulated by Matlab 2016a. Each parameter is set to: \( m = 5 \) kg, \( S = 0.1 \) m², \( \gamma = 12 \) N/m², \( g = 9.8 \) m/s², \( l_x = l_y = 1.35 \) m, \( l_z = 0.6 \) m, \( x_1 = 0 \), \( x_2 = 1.5 \).

When the initial distance \( d_0 \) is 4-7 m, the collision probability of UAVs 1 and 2 (\( P_{12} \)), 2 and 3 (\( P_{23} \)) and the probability of safe flight of the whole formation (\( P_{safe} \)) are calculated respectively under the influence of two kinds of wind as the wind speed increases from 0 to 9 m/s.

When the wind is on the left, the probability change trend at different initial distances is shown in figure 2:
Obviously, when the initial distance and wind direction are fixed, $P_{12}$ and $P_{23}$ shows an upward trend with the increase of wind speed, while the probability of safe flight of the whole formation shows a downward trend, and $P_{12}$ rises faster than $P_{23}$.

A comprehensive comparison of figure 2(a)-(d) shows that when the wind direction is constant, the larger the initial interval, the smaller the slope of the curve, that is to say, the smaller the impact of the wind on flight safety. As can be seen from figure 2(d), when the initial distance is more than 7 m, the left wind from 0 to 9 m/s has little effect on the formation safety.

When the wind direction is from the left rear and the wind speed and track form an included angle of 45°, the probability change trend at different initial distances is shown in figure 3:

As shown in the figure, the same conclusion obtained from experience is that when the wind direction is left rear, the influence of wind on flight safety is obviously lower than that of left wind, i.e. the larger the angle between the wind direction and the lateral direction of formation, the smaller the influence, and the safer the flight.

4. Conclusion

After selecting a specific formation, this paper studies the change rule of the probability of UAV formation flying safely with the initial interval under the premise of only considering the influence of wind and positioning error. The research finds that:
As the wind speed increases, the collision probability between two adjacent aircrafts increases, and the formation flying safety probability decreases. 

For horizontal formation, under the condition of certain wind speed and initial interval, assuming the angle between wind speed direction and lateral direction is \( \theta \in \left[ \frac{\pi}{2}, \frac{\pi}{2} \right] \), the larger \( \theta \), the higher the probability of formation flying safely.

Under the environment of low-altitude flight, using the 10L type of four-rotor UAV, when the internal interval of the formation is 7 m, the safety probability of the formation flight has basically met the requirements and can ensure the normal communication between the main engines and wingmen in the formation.

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References

[1] Cai Z H, Yang L M, Wang Y X, et al. Analysis for whole airspace flight key factors of unmanned aerial vehicles[J]. Journal of Beijing University of Aeronautics and Astronautics, 2011, 37(2): 175-179.

[2] CUI J H, WEI R X, ZHANG X Q. Dynamic decision-making method for safety region of sense and avoid system for unmanned aerial vehicle [J]. Control and Decision, 2014, 18(12): 219-2200.

[3] ZUO Qing-hai, PAN Wei-jun, ZHUO Xing-yu, TAN Jing-wei. Research on Sense and Avoiding Method of Unmanned Aircraft System[J]. Equipment manufacturing technology, 2016, 35(11): 65-69.

[4] ZHANG Y B. The UAV formations research based on probability calculations and state predicted[D]. Dalian University of Technology, 2013, 3: 18.

[5] CENG G Z. Safety Interval analysis of aircraft flying in low altitude airspace [J]. Technology Innovation and Application, 2015, 6(3): 18.

[6] Udovic A, Jong H D, Vielhauer J. Validation of Unmanned Aircraft Systems' Integration into the Airspace (VUSIL I and II)[J]. Sae International Journal of Aerospace, 2011, 4(2): 1216-1227.

[7] Yang J, Yin D, Niu Y, et al. Unmanned aerial vehicles conflict detection and resolution in city airspace[C]. IEEE, 2015.

[8] Jenie Y I, Kampen E J V, Ellerbroek J, et al. Taxonomy of Conflict Detection and Resolution Approaches for Unmanned Aerial Vehicle in an Integrated Airspace[C]. IEEE Transactions on Intelligent Transportation Systems, 2017, 18(3): 558-567.

[9] Qu Y, Zhang Y. Cooperative localization against GPS signal loss in multiple UAVs flight[J]. Journal of Systems Engineering and Electronics, 2011, 22(1): 103-112.

[10] Xiang J, Yang L, Luo Z. Flight safety measurements of UAVs in congested airspace[J]. CJA, 2016, 29(5): 1355-1366.

[11] Jenie Y I, Kampen E J V, Ellerbroek J, et al. Safety Assessment of Unmanned Aerial Vehicle Operations in an Integrated Airspace[C]. USA: AIAA Infotech & Aerospace, 2016.

[12] LIU C L. Research on modeling and control for quadrotor UAV[D]. Hubei University of Technology, 2016.

[13] QU Y L. Research on Collision Risk Modeling of Air Traffic[D]. Nanjing University of Aeronautics and Astronautics, 2011.

[14] ZHANG Z N, LIANG Y W. Bayesian network-based study on collision risk in free flight [J]. China Safety Science Journal, 2014, 24(9): 40-45.