A High-Precision Risk Analysis Model of Logistics UAV Network with Multiple Constraining Factors

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Abstract: Logistics unmanned aerial vehicles(UAVs) have brought new opportunities for the expansion of the global express logistics industry, especially to effectively overcome the shortcomings of ground transportation. However, since logistics UAVs are still in their infancy, it is necessary to analyze the collision risk during their operation. Using the theory of collision modeling in conflict zones, this study examines the potential safety hazards of logistics UAVs flying in specific airspace according to their characteristics and limitations. First, to measure the impact of various factors such as reliability and failure rates on the safe operation of logistics UAVs in certain airspace, a collision risk analysis model between logistics UAVs and other drones in a specific airspace is established. Second, by analyzing the factors that affect the safe operation of logistics UAVs, including airspace conditions, human-machine systems, environmental conditions, and management conditions, a collision risk analysis model between logistics UAVs and civil aircraft operating in particular airspace is established. To verify the accuracy of the proposed models, the models in both cases are solved and compared with the safety target criteria established by the International Civil Aviation Organization (ICAO).

Key words: logistics unmanned aerial vehicle(UAV); collision model; collision risk; low-altitude economy; safe operation

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0 Introduction

The advancement of economy and technology has greatly promoted the growth of the express delivery business, leading to the emergence of logistics unmanned aerial vehicles (UAVs). To deploy drone express delivery, e-commerce companies are actively seizing the opportunity. Undoubtedly, logistic UAVs will enable the exponential growth of the modern logistics industry and become a vital infrastructure. However, the distribution of express delivery by UAVs is still in the early experimental stage with limited operation in specific airspace. As a result, logistics UAVs still have to consider some risk factors when transporting and delivering couriers. Therefore, it is crucial to assess and study the risks involved.

To facilitate practical applications, the risk of collisions between drones and man-machines (generally low-altitude aircraft and feeder flights) should be also considered. In recent years, previous researchers have devoted great efforts to the study of UAVs' collision risk. He et al.[1] proposed a method for constructing a UAV flight risk assessment model based on fuzzy cognitive maps, which integrates the knowledge of domain experts to complete the construction of a risk assessment model, and both qualitative and quantitative analysis of UAV

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system risks were obtained. Yan[2] used the gas model and the reliability model to construct collision probability models, and established a severity model for the consequences of the drone crash. Based on these two models, they built a risk assessment model for drone operation.

Under the current air traffic management mode, scholars have conducted a lot of research on the collision risk between aircraft. Liang[3] established a collision risk model based on position error, and obtained the risk value through the Monte Carlo uniform random number average method. A collision risk model based on the segmented Wiener process was established, and the risk values under different initial states of the aircraft were obtained. An event tree model was established to obtain the total risk value of the airspace. Finally, the collision risk value between two aircraft under a given safety distance was obtained. Wang et al.[4] established a mathematical conflict avoidance model for the conflict between the notice and the head flight and the cross flight. According to the human cognitive reliability theory, a pilot response failure model is established. The analysis shows that when aircraft meet head-on at the same altitude in low-altitude airspace, there is a certain risk probability of violating the safety separation, and the aircraft that meet and fly at the same altitude can get out of conflict safely. Although the literature has analyzed the safety risks of drone operation, limited efforts have been devoted to the intersection of safety risks involving UAVs in the logistic context. On this basis, we propose an improved model that incorporates the interactions between UAVs, along with those between UAVs and manned aerial vehicles.

The primary objective of this study is the safety collision risk in the delivery process of logistics UAVs. Specifically, this study investigates the collision risk of safe flight between logistics UAVs and other UAVs. Based on Ref.[5], the collision theoretical model based on the collision region is improved. This study introduces the parameters related to the degree of influence on the safety factors of logistics UAVs. Then, the improved Reich collision theory model is investigated for reducing collision risks between logistics UAVs and civil aircraft, and the degree coefficient of airspace, man-machine circuit, and other related factors are introduced. Finally, the relationship between the minimum distance between the logistics UAVs and other UAVs and the collision risk level in safe flight is obtained through the simulation experiment. In addition, the relationship between the density of logistics UAVs and the level of collision risk in a safe flight is obtained. Then we compare it with the safety target standards stipulated by the International Civil Aviation Organization (ICAO) to determine the safe flight conditions of logistics UAVs.

1 Safety Factor Analysis for Logistics UAVs

1.1 Classification of logistics UAVs

Logistics UAVs can be divided into three levels according to transportation radius and load: Main line, branch line, and end. The load capacities of logistics UAVs developed and tested by various enterprises are different. This study focuses on a heavy logistics UAV with a range of 1 000 km, a cruising speed of 200 km/h, a flight altitude of up to 3 000 m, and a mass of 1—5 t, which can fly autonomously in severe weather conditions.

1.2 Airspace conditions of logistics UAVs

The "Air Traffic Management Measures for Civilian UAV Systems" promulgated in China clearly points out that UAVs can only operate in designated airspace, and relevant units and individuals are responsible for the safety of UAV operations[6]. The airspace between 100 m and 3 000 m above the ground is used as the flying airspace for logistics UAVs. When cruising, logistics UAVs should fly within this airspace, and other aircraft are generally not allowed to fly in this airspace. It also stipulates that air traffic control units should provide corresponding workflows for emergencies such as drone avoidance and accidental collision with aircraft. Fig.1 illustrates the airspace division by Civil Aviation Administration of China (CAAC).

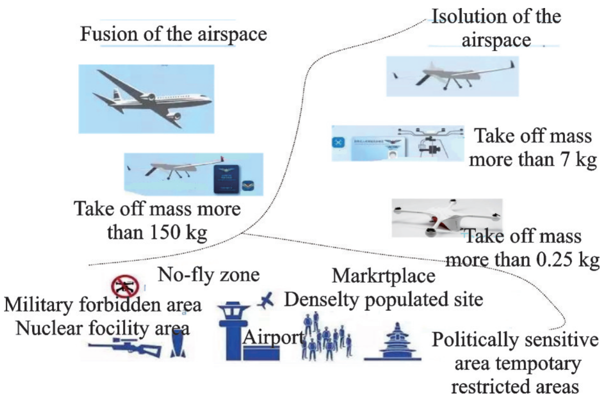

Fig.1 Airspace division by CAAC

1.3 Safety assessment of logistics UAVs

To evaluate the collision risk level in safe flight of logistics UAVs, the level of safety target should be determined. In the field of civil aviation, the relevant evaluation experts of ICAO define the safety target as an acceptable risk level, for example, for the collision risk between aircraft, the stipulated standard is 1.5×10^{-8} (incidents/flight hour). And it is stipulated that one collision is equivalent to two accidents[7]. The logistics UAV in this study follows the same safety standard due to its large size, heavy payloads and fast speed. Table 1 provides a comparative overview of the configurations and performance characteristics of various UAV types for reference.

Table 1 Indicators for different types of UAVs

UAV type	Mass/kg	Maximum range/km	Cruising speed/ $(\mathrm{km{\cdot}h^{-1}})$	Physical dimension
Light	2	5	55	0.6 m×1 m×0.1 m
Medium	150	2 000	108	5.85 m×12.4 m×1.6 m
Heavy	1 200	3 000	250	10 m×20 m×1.8 m

The key factors considered in aircraft safety analyses are flying conflicts, hazardous approaches, and collisions. For UAVs, there is also the possibility of a crash. The safety evaluation in this research, which examines the danger of collisions of logistics UAVs in conflict zones, or the number of collisions per unit flight hour, is based on previous studies of aircraft safety. The collision risk assessment process of logistics drones needs to analyze the variables that affect the flight risk of logistics drones. Subsequently, calculation and analysis are performed based on a proposed evaluation model.

1.4 Factors affecting the logistics UAVs' safe flight

A large number of factors contribute to the safe flight of logistics UAVs, including GPS positioning error, normal flight ability of logistics UAVs, type and flight mode of airspace, human reliability, environmental conditions, management factors, etc.

The logistics UAVs mainly use the GPS satellite positioning system to provide position information. This system error is the main reason for the position error of the logistics UAVs.

Compared with manned aircraft, when evaluating the collision risk of logistics UAVs, it is very important to ensure its normal flight capability concerning stability and reliability. The stability mainly reflects the probability that the logistics UAV system will fail without being affected by external factors, while the reliability mainly refers to its ability to resist external interference, such as the ability to resist complex electromagnetic environments and the ability to adapt to changes in the external environment.

The operation safety of logistics drones in the specified airspace is the responsibility of relevant units and individuals. Compared with manned aircraft, its flight restrictions are relatively small, and within a specific airspace, logistics UAVs can freely change flight altitude, speed and heading. The flight safety of logistics UAVs in a specific airspace is guaranteed by controlling the distance between two drones without distinguishing between horizontal, vertical, or vertical intervals. Logistics drones are mainly flying autonomously without the command of a controller, but the drone operator must maintain reliable communication with the control unit. At the same time, air traffic control units should formulate reasonable emergency procedures and mechanisms to command logistics drones to avoid the situation when logistics drones fail or other drones or civil aircraft enter their specific airspace.

The flight of logistics UAV is inseparable from the command of the operator. Although its flight control system will become increasingly intelligent, it still needs an operator to ensure its flight safety.

The influence of UAV operators on the flight safety of logistics UAVs is reflected in the analysis of their reliability, that is, human reliability analysis (HRA). It is worth noting that the gradual development of flight technology has incurred the increase in the proportion of incidents driven by human factors, so the reliability analysis of human factors is very important.

Additionally, environmental conditions have a great impact on the weather factors in the flight of logistics drones, including temperature, air pressure, thunderstorms, strong winds, and other weather and climate conditions. These will reduce the flight performance and visibility of logistics drones, which will lead to flight accidents or accident symptoms of logistics drones. Therefore, environmental conditions are an important factor to be considered for the safe flight of logistics drones.

The orderly and standardized flight of logistics drones is the key factor to ensure their safety. The corresponding management factors mainly include management agencies and logistics drone operators. In addition to supervising the flight missions in each airspace, the management agency must also formulate rules and regulations to ensure that the corresponding airspace is used effectively and rationally, and reduce the occurrence of accidents. The "Administrative Measures for Civil UAV Flight Activities (Provisional)" issued by the Civil Aviation Administration of China (CAAC) regulates the access and supervision requirements for UAVs engaged in general aviation operations within the framework of the "Civil Aviation Management Measures". Relevant operators need to bear legal responsibility for the drones they operate. The "Regulations on the Administration of Civilian Drone Pilots" issued by the Civil Aviation Administration's Flight Marking Department regulates the management of civilian drone pilots.

2 Collision Risk Model Between Intra-logistics UAVs and Inter-logistics UAVs

This section focuses on the collision risks among logistic UAVs (intra) and those between logistic UAVs and other ordinary small UAVs (inter) in the specified airspace. The risk of collision between UAVs and ground obstacles along with the collision of bird strike is not considered. In addition, under the specified airspace conditions, the flight of civil aircraft and the deployment of controllers are not considered. Based on Ref.[5], which considers airspace, human factors, normal flight ability of logistic UAV and other limiting factors, the collision model of the conflict area at the intersection of air routes is improved. The conflict area of an UAV is given in the form of a polyhedron. By establishing the relationship between the course angle of two routes in the plane determined and the angle formed by their projection on the horizontal plane, the coordinate system and the conflict area are established. Then the coordinates of the UAV at any time are determined. According to the space expression of the two UAVs in three coordinate directions, the space expression between the two UAVs is determined.

2.1 Description of parameters

Φ_x^i: Fuselage length of UAVi($i=1,2$); unit: m.

Φ_y^i: Wingspan of UAVi($i=1,2$); unit: m.

Φ_z^i: The height of UAVi($i=1,2$); unit: m.

R: Sphere protection zone radius; unit: m.

L: The distance between the centers of two airframes; unit: km.

l_i: The estimated route of UAVi($i=1,2$).

O: The expected intersection of the two routes in airspace.

σ_x^i: Position error in the x-axis direction caused by navigation UAVi($i=1,2$); unit: m.

σ_y^i: Position error in the y-axis direction caused by navigation UAVi($i=1,2$); unit: m.

σ_z^i: Position error in the z-axis direction caused by navigation UAVi($i=1,2$); unit: m.

β: The angle between the expected route of UAV2 and the xOy-plane.

γ: The angle between the expected route of UAV1 and the xOy-plane.

α: The angle between the two UAVs along the expected flight direction.

$L_{\min}$: Minimum safe distance between UAVs; unit: km.

t_F: The time from point H to point F.

t_G: The time from point E to point G.

Δt: The time interval between UAV 1 to H and UAV 2 to E, $\Delta t \in (0, t_F)$.

$V_1(t)$: Expression of UAV1 speed $\left(V_1(t) \geqslant 0\right)$; unit: km / h.

$V_2(t)$: Expression of UAV2 speed $\left(V_2(t) \geqslant 0\right)$; unit: km / h.

d_1: The distance from UAV1 to the expected crossing point of the route; unit: m.

d_2: The distance from UAV2 to the expected crossing point of the route; unit: m.

v_M: The speed of a civil aircraft, that is, the maximum cruising speed or maximum flight speed of the aircraft; unit: km / h.

2.2 Parameterizations of the collision risk model

2.2.1 Parameters of collision risk

The collision model of the cross-route conflict area uses the UAV as a benchmark to establish a protection area[8]. The UAV can freely change its flight attitude in the specified airspace, so the setting of the protected area takes the maximum value of the average fuselage height Φ_z^i, the average fuselage length Φ_x^i and the average wingspan width of the two UAVs Φ_y^i. We choose one of the drones as a reference and set up a spherical protection zone with the drone as the radius. It can be calculated as

$$R = \max \frac{1}{2}\left(\Phi_x^1 + \Phi_x^2, \Phi_y^1 + \Phi_y^2, \Phi_z^1 + \Phi_z^2\right) \tag{1}$$

and when $L \leqslant R$ is satisfied, it is regarded that the logistics UAV collides with the UAV.

This study assumes that the UAVi ($i=1,2$) changes its altitude and speed during a flight, and only calculates the collision risk when the UAV is in the conflict area, regardless of the situation outside the conflict area. As shown in Fig.2, the Cartesian coordinate system is a schematic diagram of the relative flight of the internal logistics UAV and the inter-logistics UAV.

Here, $\beta = \angle AOB$, $\gamma = \angle OCD$, $\alpha = \angle AOC$,

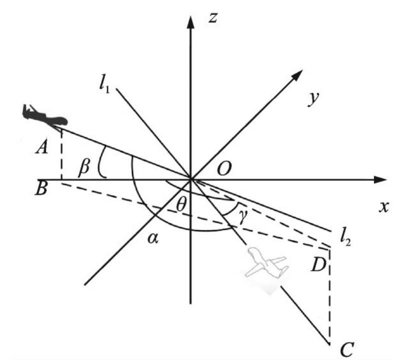

Fig.2 Relative flight diagram of two UAVs

$AB \perp xOy, CD \perp xOy, \theta = \angle BOD$. Then, the following geometric relationship can be obtained

$$\cos\theta = \frac{|OD|^2 + |OB|^2 - |BD|^2}{2 \times |OD| \times |OB|} \tag{2}$$

$$|OB| = |OA|\cos\beta, |AB| = |OA|\sin\beta \tag{3}$$

$$|OD| = |OC|\sin\gamma, |CD| = |OC|\cos\gamma \tag{4}$$

$$\cos\alpha = \frac{|OA|^2 + |OC|^2 - |AC|^2}{2 \times |OA| \times |OC|} \tag{5}$$

$$|AC|^2 = (|AB| + |CD|)^2 + |BD|^2 \tag{6}$$

According to the geometric relations in Eqs.(2—6), it can be concluded that the angular relationship between θ, α, β and γ is

$$\cos\theta = \frac{\cos\alpha + \sin\beta\cos\gamma}{\sin\gamma\cos\beta} \tag{7}$$

The collision area enclosed by the intersection O of the expected route between the logistics UAV and other UAVs is represented by the polyhedron shown in Fig.3.

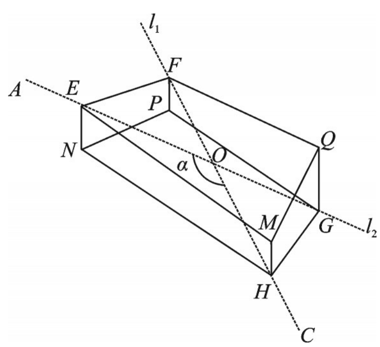

Fig.3 Conflict area at the intersection of two UAVs

From Fig.2 and Eq.(7), the size of the conflict area is determined by the four quantities: $L_{\min}$, α, β and γ. Accordingly, the following rules are defined:

(1) On the expected route l_1, logistics UAV1 flies from point C to point H and then to point F;

(2) On the expected route l_2, logistics UAV2 flies from point A to point E and then to point G;

(3) Logistics UAV1 arrives at point H before UAV2 arrives at point E;

(4) The moment when UAV2 flies to point E is recorded as zero.

The position coordinates of both UAVs at time t after entering the conflict area are expressed as $U_1=\left(x^1, y^1, z^1\right)$ and $U_2=\left(x^2, y^2, z^2\right)$.

When the reverse flight logistics UAV1 rises, the UAV2 descends, and the flight angle is $90^{\circ}<\theta<180^{\circ}$, for any fixed time interval Δt and any fixed time $t\in[0, T]$, $T=\min\{t_F-\Delta t, t_G-t_E\}$, we can get

$$\begin{cases} x^1=\sigma_x^1\times\cos\theta-\sigma_y^1\times\sin\theta+ \\ \quad (d_1-d_3)\times\cos\theta\sin\gamma \\ y^1=\sigma_x^1\times\sin\theta-\sigma_y^1\times\cos\theta+ \\ \quad (d_1-d_3)\times\sin\theta\cos\gamma \\ z^1=\sigma_z^1-(d_1-d_3)\times\cos\gamma \end{cases} \tag{8}$$

$$\begin{cases} x^2=\sigma_x^2+\cos\beta\times(-d_2+d_4) \\ y^2=\sigma_y^2 \\ z^2=\sigma_z^2+\sin\beta\times(d_2-d_4) \end{cases} \tag{9}$$

where

$$d_1=\frac{1}{2}\int_{-\Delta t}^{t_F}V_1(t)\mathrm{d}t,\quad d_2=\frac{1}{2}\int_0^{t_G}V_2(t)\mathrm{d}t \tag{10}$$

$$d_3=\int_0^{t+\Delta t}V_1(t)\mathrm{d}t,\quad d_4=\int_{\Delta t}^{t+\Delta t}V_2(t)\mathrm{d}t \tag{11}$$

For any fixed time interval Δt, the distance between two UAVs in x, y and z directions at time t can be expressed as $|x^{12}|$, $\left|y^{12}\right|$ and $|z^{12}|$, respectively. Then we have

$$\begin{cases} x^{12}=\sigma_x^1\times\cos\theta-\sigma_y^1\times\sin\theta-\sigma_x^2+L_x^{12} \\ y^{12}=\sigma_x^1\times\sin\theta-\sigma_y^1\times\cos\theta-\sigma_y^1+L_y^{12} \\ z^{12}=\sigma_z^1-\sigma_z^2+L_z^{12} \end{cases} \tag{12}$$

where

$$\begin{cases} L_x^{12}=\cos\theta\times\sin\gamma\times(d_1-d_3)+\cos\beta\times(d_2-d_4) \\ L_y^{12}=\cos\gamma\times\sin\theta\times(d_1-d_3) \\ L_z^{12}=\cos\gamma\times(d_1-d_3)-\sin\beta\times(d_2-d_4) \end{cases} \tag{13}$$

The nominal distances in x, y and z directions are L_x^{12}, L_y^{12} and L_z^{12}. In the conflict area, for any fixed time interval $\Delta t\in(0, t_M-t_F)$, when time t is determined, the flight distance (nominal distance) of the two UAVs in accordance with the expected flight route is the nominal flight distance of the two UAVs

$$L_b^{12}=\sqrt{(L_x^{12})^2+(L_y^{12})^2+(L_z^{12})^2} \tag{14}$$

The actual flight distance between the two UAVs is

$$L_s^{12}=\sqrt{(x^{12})^2+(y^{12})^2+(z^{12})^2} \tag{15}$$

Logistics UAVs and other UAVs should maintain a certain flight distance to meet the level of safety objectives when they are at a certain distance from the intersection of the expected route. If the flight distance between the two UAVs is greater than the minimum safety interval standard, they can still fly along the planned routes

$$|L_s^{12}|\geqslant L_{\min} \tag{16}$$

Then, for any fixed time interval $\Delta t\in(0, t_M-t_F)$ and $t\in[0, T]$, the collision probability of two UAVs in the conflict area in a specific airspace can be expressed as

$$P_b^{12}=P_s^{12}\left(|L_s^{12}|\leqslant R\right) \tag{17}$$

The logistics UAV uses GPS for navigation and positioning such that its positioning error $\sigma_\mu^i(i=1,2)$ obeys a Gaussian random distribution[9] with standard deviation $\sigma_{i\mu}$ and the mean value of 0. The density function of σ_μ^i in the $\mu\left(\mu=x,y,z\right)$ direction is

$$f_\mu^i(\sigma)=\frac{1}{\sqrt{2\pi\sigma_{i\mu}}}\exp\left(-\frac{\sigma^2}{2\sigma_{i\mu}}\right) \tag{18}$$

Then, for a fixed interval Δt, at any $t\in[0, T]$, Eq.(19) can be used to calculate the likelihood of two UAVs colliding in the designated airspace[7].

$$P_b^{12}=\int_{-R}^{R}f(L-L_b^{12})\mathrm{d}L=$$
$$\int_{-R}^{R}\left[\frac{1}{\sqrt{2\pi\sigma^{12}}}\exp\left(-\frac{(L-L_b^{12})^2}{2(\sigma^{12})^2}\right)\right]\mathrm{d}L \tag{19}$$

where $\sigma=L-L_b^{12}$ and σ^{12} can be represented as

$$\begin{cases} (\sigma^{12})^2=(\sigma_x^{12})^2+(\sigma_y^{12})^2+(\sigma_z^{12})^2 \\ (\sigma_x^{12})^2=(\sigma_x^1)^2+(\sigma_x^2\times\cos\theta)^2+(-\sigma_y^2\times\sin\theta)^2 \\ (\sigma_y^{12})^2=(\sigma_y^1)^2+(\sigma_x^2\times\sin\theta)^2+(-\sigma_y^2\times\cos\theta)^2 \\ (\sigma_z^{12})^2=(\sigma_z^1)^2+(-\sigma_z^2)^2 \end{cases} \tag{20}$$

Therefore, for a fixed time interval T, the collision probability of the logistics UAV and other UAVs within time t can be expressed as

$$\mathrm{CP}^{12}=\frac{\int_0^T P_b^{12}(t)\mathrm{d}t}{T} \tag{21}$$

Assuming that Δt obeys Poisson distribution, then the density distribution function $f^{12}(\Delta t)$ of Δt is calculated as

$$f^{12}(\Delta t)=\begin{cases}\dfrac{1}{\bar{t}-\Delta t_{\min}}\mathrm{e}^{\frac{t_F-\Delta t_{\min}}{\bar{t}-\Delta t_{\min}}} & \Delta t_{\min}\leqslant\Delta t\leqslant t_F\\ 0 & \text{Others}\end{cases} \tag{22}$$

At any time $t\in[0,T]$, the collision risk of the two UAVs on the route l_1 and l_2 is represented by

$$\mathrm{CP}^r=\int_{\Delta t_{\min}}^{t_f} f^{12}(\Delta t)\mathrm{CP}^{12}\mathrm{d}\Delta t \tag{23}$$

where CP^r represents the collision risk between the two UAVs.

2.2.2 Reliability and failure rates

GPS is the primary positioning method employed by UAVs. The pseudo distance of the satellite, also known as the user equivalent distance error, is typically applied to calculate the user equivalent distance error in order to evaluate the impact of satellite positioning error on accuracy. Theoretically, it is generally stipulated that satellite user equivalent distance errors are independent of each other, and all are approximately subject to a normal distribution with a mean value of 0, and the variance is determined by the variance of each error component together[10]. In this study, GPS positioning with selective availability (SA) is selected, the total error of the system user equivalent distance is 33.3[10]. Therefore, $\sigma_x^i=\sigma_y^i=\sigma_z^i=\sqrt{4\times 33.3^2}=66.6\,(i=1,2)$.

Since different types of UAVs show different reliabilities, with the proportion of different types of UAVs in the specified airspace, the probability of ensuring the normal flight ability of UAVs in the specified airspace is given as

$$\omega_1=\sum_{j=1}^{n}W_j p_j \tag{24}$$

where W_j represents the reliability of the UAV of type j and p_j the proportion of the UAV of type j in the airspace.

The calculation formula of the serious failure rate ω_2 of UAV in unit time is given as

$$\omega_2=\sum_{j=1}^{n}U_j p_j \tag{25}$$

where U_j represents the probability of serious failure in the unit time of UAV of type j.

2.2.3 Human factors reliability

A total of 104 accidents/incidents in 44 models are summarized by FAA[11]. The cause of the accidents includes human factors, UAV system failure, environment and other three categories. The number and proportion of each category are shown in Table 2. It can be seen from Table 2 that the proportion of accidents/incidents caused by human factors is only 9.62%. The proportion of accidents/incidents caused by UAV system failures accounted for 86.54%. So it can be concluded that the proportion of accidents caused by unmanned operators accounted for 9.62% of the total accidents.

That is, the reliability of a safe UAV flights is $\omega_3=1-9.62\%=90.38\%$.

Table 2 FAA civil UAV system accidents / incidents classification statistics

Index	Human factors	UAV system failure	Environment and others	Total
Number	10	90	4	104
Proportion/%	9.62	86.54	3.85	100

2.3 Collision risk model

According to ICAO, one collision is equal to two mishaps. Therefore, the level of collision risk (CR) in safe flight between logistics UAVs and other UAVs may be expressed using the following equation through the derivation and analysis of the above three components

$$\mathrm{CR}=2\times(1-\omega_1)\times(1-\omega_2)\times(1-\omega_3)\times \mathrm{NP}\times\mathrm{CP}^r \tag{26}$$

where ω_3 represents the human reliability, and NP the average logarithm of UAVs in the conflict area under the specific airspace.

3 Collision Risk Model Between Logistics UAVs and Civil Aircraft

In general, the logistics UAVs operate within the specified airspace without encountering with civil aircraft. However, in some emergent conditions, the civil aircraft may pass through the airspace, or the civil aircraft may improperly enter the airspace. Thus, the collision risk of logistics UAV should be considered in the collision risk model. According to Ref.[8], the Reich collision theory model is improved according to the collision risk between logistics UAVs and civil aircraft, combining with airspace, man-machine environment management, and other limiting factors. Moreover, the collision template of civil aircraft relative to logistics UAVs is established, and the velocity relationship between civil aircraft and logistics UAV is built. Finally, the relationship between the volumes of the collision template swept through the airspace is determined.

3.1 Description of parameters

v_E: the speed of UAVs; unit: km/h.

$l_{ix}, l_{iy}, l_{iz} (i=1,2)$: Airframe's length, wingspan's width, and fuselage's height; unit: m.

l_x, l_y, l_z: The length, width and height of collision template P; unit: m.

λ: The angle between the direction of the civil aircraft and the x-axis.

ϑ: The angle between the speed direction of the logistics UAVs and the xOy-plane.

∂: The angle between the projection component of the velocity direction of the civil aircraft and the logistics UAV on the xOy-plane.

$v_R(v_{Rv})$: Average value of relative velocity between the two aircraft in time t.

t: Time for civil aircraft to fly over the specified airspace.

n_P: Number of civil aircraft.

ρ: Density of logistics UAVs.

c_i: Collision risk between class i aircraft and logistics UAVs.

V_0: The volume of the collision template.

3.2 Parameterizations of the collision risk model

3.2.1 Model under the impact of airspace conditions

The collision model of the cross-route conflict area uses the UAV as a benchmark to establish a protection area[8]. The UAV can freely change its flight attitude in the specified airspace, so the setting of the protected area takes the maximum value of the average fuselage height.

This section takes the starting point of civil aircraft entering the specified airspace as the origin. The horizontal component of the direction indicated by the track is the positive direction of the x-axis. The wingspan direction is the positive direction of the y-axis. The positive direction of the z-axis is perpendicular to the xOy-plane. The establishment of a spatial rectangular coordinate system is shown in Fig.4.

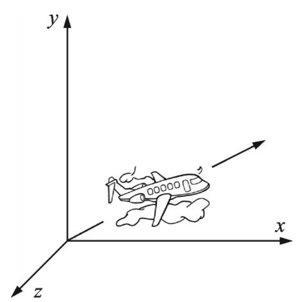

Fig.4 Space rectangular coordinate system of civil aircraft flight

The collision template is initially built up, in accordance with the collision model theory, as depicted in Fig.5.

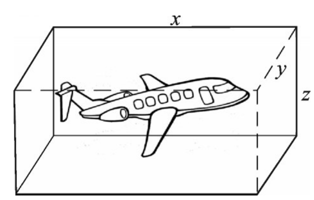

Fig.5 Civil aircraft collision template

The length, width and height of the UAV are indicated as l_{1x}, l_{1y}, l_{1z}, respectively, while those of the civil aircraft are expressed as l_{2x}, l_{2y}, l_{2z}, respectively. The civil aircraft entering a specific airspace is taken as the benchmark to establish the collision template P. The length, width and height of the collision template P are the average fuselage length, the average wingspan width, and the average airframe height of the two aircraft, denoted as l_x, l_y, l_z, respectively. Then, Eq.(27) can be obtained

$$\begin{cases} l_x = \dfrac{1}{2}(l_{2x} + l_{1x}) \\ l_y = \dfrac{1}{2}(l_{2y} + l_{1y}) \\ l_z = \dfrac{1}{2}(l_{2z} + l_{1z}) \end{cases} \tag{27}$$

When multiple civil aircraft emerge in the designed airspace at the same time, the collision situation between civil aircraft is not considered. Because of the different types and speeds of civil aircraft, the collision risk between each type of aircraft and logistics UAVs is calculated separately.

When there are j types of civil aircraft, we have

$$c = \sum_{i=1}^{j} c_i \tag{28}$$

where c_i represents the level of collision risk in safe flight of type i aircraft with the logistics UAV in the designed airspace. The speed of the civil aircraft is the maximum cruising speed or maximum flight speed of the aircraft. Therefore, the types of civil aircraft are different, and their speeds are different.

It is assumed that the number of collisions between logistics UAVs and civil aircraft is $N = V\rho$, and one collision is equivalent to two accidents. When considering only airspace factors, the collision risk of UAV per unit time is c. The calculation formula of c is as

$$c = 2 \cdot K \cdot \frac{N}{t} \tag{29}$$

where K indicates the number of civil aircraft, ρ the density of the logistics UAVs, and V the volume swept by the collision template.

After the collision template is established, the logistics UAV is regarded as a particle point E, and the collision can be regarded as the mutual contact between the collision template P and particle point E. Assume that when a civil aircraft enters a prescribed airspace, the logistics UAV instantly becomes a mass point in the airspace (Fig. 6). If the mass point E is in the space swept by the collision template P in time t, it represents a collision between the two aircraft.

The relative speed of a civil aircraft and a logistics UAV is represented by

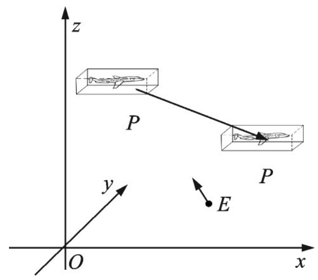

Fig.6 Relative relationship between logistics UAV and civil aircraft collision template

$$v_{Rv} = (v_M^2 + v_E^2 - 2v_M v_E \cos\lambda \cos\vartheta \cos\partial - 2v_M v_E \sin\lambda \sin\vartheta)^{1/2} \tag{30}$$

where $v_{Rv}^2 = v_{xOy}^2 + v_z^2$.

The relative velocity in the xOy-plane and the relative velocity in the z-axis direction are defined as

$$v_{xoy} = (v_M^2 \cos^2\lambda + v_E^2 \cos^2\vartheta - 2v_M v_E \cos\lambda \cos\vartheta \cos\partial)^{1/2} \tag{31}$$

$$v_z = v_M \sin\lambda - v_E \sin\vartheta \tag{32}$$

The average value of the relative speed of the civil aircraft and the logistics UAV during time period t is calculated as

$$v_R(v_{Rv}) = \frac{d_{Rv}}{t} \tag{33}$$

In this study, the velocity and direction of the UAV in the specified airspace are uniformly distributed, so ϑ and ∂ are also uniformly distributed, where $v_E \in [v_{E_{\min}}, v_{E_{\max}}]$, $\vartheta \in \left[0, \frac{\pi}{2}\right]$, $\partial \in [0, \pi]$. The movement distance of civil aircraft relative to logistics UAVs during time period t is given by

$$d_{Rv} = \int_0^t v_{Rv} \mathrm{d}t \left(\frac{1}{v_{E_{\max}} - v_{E_{\min}}} \int_{v_{E_{\min}}}^{v_{E_{\max}}} \mathrm{d}v_E \right) \left(\frac{1}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \mathrm{d}\vartheta \right) \cdot \left(\frac{1}{\pi} \int_0^{\pi} \mathrm{d}\vartheta \right) \tag{34}$$

And

$$v_R(v_{Rv}) = \frac{\int_0^t \int_{v_{E_{\min}}}^{v_{E_{\max}}} \int_0^{\frac{\pi}{2}} \int_0^{\pi} v_r \, \mathrm{d}\vartheta \mathrm{d}\vartheta \mathrm{d}v_E \mathrm{d}t}{t\pi^2 (v_{E_{\max}} - v_{E_{\min}})} \tag{35}$$

The volume of the space swept by the collision template during time period t is formulated by

$$V = l_y l_z v_R(v_{Rv}) \cdot t + V_0 \tag{36}$$

3.2.2 Human factor reliability

When a civil aircraft enters the specified airspace, it is necessary for the pilot of the civil aircraft, the controller, the logistics UAV, and its operators to work together for ensuring the safety of both in the airspace. Therefore, it is necessary to consider the reliability μ_1 of the civil aircraft crew to avoid collision, the reliability μ_2 of controllers to adjust flight conflicts, the reliability μ_3 of logistics UAVs to ensure normal flight capability, and the reliability μ_4 of the logistics UAVs' pilots to ensure safe flight. The reliability of the human-machine system in successfully avoiding collisions, that is, the human factor reliability μ can be given by

$$\mu = 1-(1-\mu_1)(1-\mu_2)(1-\mu_3)(1-\mu_4) \tag{37}$$

that is

$$\mu = 1-(1-\mu_1)(1-\mu_2)[1-\omega_1(1-\omega_2)](1-\omega_3) \tag{38}$$

For the reliability analysis of the collision avoidance of civil aircraft crews, Ref.[12] conducted a statistical analysis of the accidents and incidents of China's civil aviation between 2006 and 2015. In the past decade, there have been 2 196 flight incidents and 56 accidents, including one transportation accident, 15 transportation aviation ground accidents, 16 transportation aviation accidents (50.86 million take-off and landing completed, and the accident rate of one million during that period was 0.31), and 40 general aviation accidents. This study inquires the accident data from China Aviation Safety Information Network, and finds that the probability of accidents caused by aircraft crew is 0.452 6. Then, the reliability that the aircraft crew can avoid collision can be calculated by

$$\mu_1 = 1-\left(\frac{56}{56+2\,196}\times 0.452\,6\right)=0.989 \tag{39}$$

For the reliability analysis of flight conflicts induced by controllers, this study compares Ref.[13] and Ref.[14]. In Ref.[13], the geometric average method, the sampling method, the Delphi method, and the Bayesian network (BN) method are used to quantify the reliability of controllers in mediating flight conflicts. The results obtained are closer to the actual situation than the results obtained by using the CREAM method and the HEART method to analyze the reliability of controllers in mediating flight conflicts in Ref.[14]. Therefore, the result of Ref.[13] is 0.849, which is the basis of the analysis and calculation in this paper.

3.2.3 Environmental impact coefficient

The influence of environmental conditions, especially weather conditions, on flight is very important. The specific airspace selected in this paper belongs to low-altitude airspace, so the influence of weather conditions in this airspace on the flight of civil aircraft and logistics drones is considered. In the low-altitude airspace, when the altitude is low, the low-level wind shear has a great influence on both. Whether it is headwind shear or tailwind shear, it will increase the difficulty of both operations and the degree of collision risk in safe flight. At the same time, the downburst will also cause great damage to it, and even cause aircraft accidents.

Therefore, the deterioration of environmental conditions will greatly reduce the flight conditions and flight performance of the two aircraft leading to an increase in the probability of flight accidents. However, due to the changeable weather conditions, the impact of different weather conditions on the two is different, so it is difficult to get a specific estimate. This section specifies the degree of influence of environmental conditions on the flight of the two aircraft, that is, the influence coefficient is η_1. When there is no severe weather phenomenon in specific airspace, $\eta_1=1$. When there is severe weather phenomenon, $\eta_1>1$.

3.2.4 Management impact coefficient

In the field of UAVs, regulations on the management of UAVs are still in the preliminary stage. China stipulates the real name registration management of civil UAVs. In 2018, CAAC issued the "Measures for the Management of Civilian Unmanned Aircraft Flight (Interim)" to regulate the commercial flight of unmanned aircraft, strengthen market supervision, and promote the safe, orderly, and healthy development of the unmanned aircraft industry. Foreign countries have also introduced corresponding policies for the management of UAVs. In 2017, the FAA of the United States announced that UAVs are prohibited from flying over national and landmark buildings. In 2018, President Trump signed the Defense Authorization Act, which requires that UAV operators must register drones with the FAA. In 2018, France stipulated that all UAVs manufacturers must register each civilian drone that mass more than 800 g, and it must be equipped with acousto-optic signal devices in order to be clearly identified during flight or when an operational failure occurs alarm. These regulations have a positive effect on the regularization, legalization, and reduction of UAV flight accidents.

The supervision of aircraft is the basis of ensuring flight safety. China has issued many relevant regulations such as Basic Rules for Flight, Civil Aviation Law, Regulations for the Operation of Light and Small UAVs, Measures for the Management of Air Traffic in Civilian Unmanned Aircraft Systems, etc. After the incident of UAV interference in Chengdu Shuangliu International Airport in 2017, China's Civil Aviation Administration announced that, since June 1 of that year, UAVs with the mass of more than 250 g must be registered in relevant departments.

The impact of management conditions on the collision risk of logistics UAV is as difficult to estimate as the environmental conditions. This section specifies the influence degree of management conditions on the flight of two aircraft, that is, the influence degree coefficient is η_2. When management factors play a positive role in collision risks, it is specified that $0<\eta_2<1$. When management factors have a negative effect on reducing collision risks, it is specified that $\eta_2>1$.

3.3 Collision risk model

The collision model comprehensively considers the influencing factors such as the man-machine loop and airspace conditions, and combines the characteristics of the logistics UAV to analyze. Therefore, the level of collision risk in safe flight between logistics UAVs and civil aircraft in the designated airspace is defined as

$$\mathrm{CR}=c\cdot(1-\mu)\cdot\eta_1\cdot\eta_2 \tag{40}$$

4 Simulation and Results

4.1 Parameter setting

In this section, a simulation experiment is conducted. To obtain the level of collision risk in safe flight of the logistics UAVs under certain conditions, the level of collision risk in safe flight between the logistics UAV and other UAVs, and between the logistics UAV and civil aircraft in the specified airspace are solved and analyzed.

The calculation of collision risk in this section only considers the influence of airspace factors. Normal environmental conditions along with nominal training, organizational, and regulatory measures is assumed in this context. Therefore, $\eta_1=\eta_2=1$ is adopted in this simulation.

For the risk study between the logistics UAV and other UAVs, JD logistics UAVs and other UAVs are used as examples for analysis. The logistics UAV adopts "JINGHONG" UAV and other UAV uses China's "Pterodactyl" UAV. Relevant parameters are shown in Table 3.

Table 3 Parameters for the level of collision risk in safe flight

Φ_x^1	Φ_y^1	Φ_z^1	Φ_x^2	Φ_y^2	Φ_z^2
7.01	10.12	2.635	9.05	14	2.775
$v_2(t)$	$V_2(t)$	ω_1	ω_2	ω_3	R
$300t+220$	$-200t+180$	0.9	8.5×10^{-4}	0.903 8	3.99

The program based on MATLAB 2016a is used to analyze and solve the four cases of relative flight between two UAVs. Without loss of generality, UAVs climb and descent together in the same direction, and it is assumed that $\gamma=30°$, $\beta=20°$ and $\alpha=62°$. One UAV climbs and one UAV descents in the same direction, and it is assumed that $\gamma=-30°$, $\beta=20°$ and $\alpha=70°$. In reverse, they climb and descent together, and it is assumed that $\gamma=-30°$, $\beta=-20°$ and $\alpha=130°$. And in reverse, one climbs and one descents, and it is assumed that $\gamma=-30°$, $\beta=20°$ and $\alpha=130°$. While the four cases feature high climb/descend angles to represent high collision risks, more experiments with varying angles sampling from empirical distributions can be conducted for further supplement risk likelihoods.

Concerning the risk analysis between the logistics UAV and civil aircraft, JD logistics UAVs is used to analyze with heavy aircraft, medium aircraft, and light aircraft. That is, to adopt the JD "JINGHONG" large logistics UAV and heavy aircraft (A330-300), medium-sized aircraft (A321), and light aircraft (Yun-12) as examples for analysis. Other relevant parameters are shown in Tables 4—6.

Table 4 Parameters for risks in safe flight of the "JINGHONG" logistics UAV and heavy aircraft

l_{1x}	l_{1y}	l_{1z}	l_{2x}	l_{2y}	l_{2z}
7.01	10.12	2.635	39.5	34.31	12.55
l_x	l_y	l_z	v_M	$v_{E_{min}}$	$v_{E_{max}}$
23.255	22.165	7.593	258	40	200

Table 5 Parameters for risks in safe flight of the "JINGHONG" logistics UAV and medium aircraft

l_{1x}	l_{1y}	l_{1z}	l_{2x}	l_{2y}	l_{2z}
7.01	10.12	2.635	63.7	60.3	16.9
l_x	l_y	l_z	v_M	$v_{E_{min}}$	$v_{E_{max}}$
35.355	35.21	9.768	259	40	200

Table 6 Parameters for risks in safe flight of the "JINGHONG" logistics UAV and light aircrafts

l_{1x}	l_{1y}	l_{1z}	l_{2x}	l_{2y}	l_{2z}
7.01	10.12	2.635	14.86	17.235	5.57
l_x	l_y	l_z	v_M	$v_{E_{min}}$	$v_{E_{max}}$
10.935	13.678	4.103	250	40	200

Therefore, seven experiments are conducted in this study to explore the two cases: Climb/descend together, and one climb one descend. According to the above analysis, four experiments are carried out in the first case and three in the second case.

4.2 Results and analysis

4.2.1 Intra-logistics UAV and inter-logistics UAVs

Given different values of L_{min}, the relationship between the distance, that is, between the logistics UAV and other drones, and the level of collision risk in safe flight can be obtained. The results are shown in Figs.7—10.

From Fig.7, it can be found that when $L_{min}>$ 1.12 km, the level of CR in safe flight between the logistics UAV and other UAVs is less than 1.5×10^{-8} (accidents/hour). It can meet the safety target criteria selected in this paper.

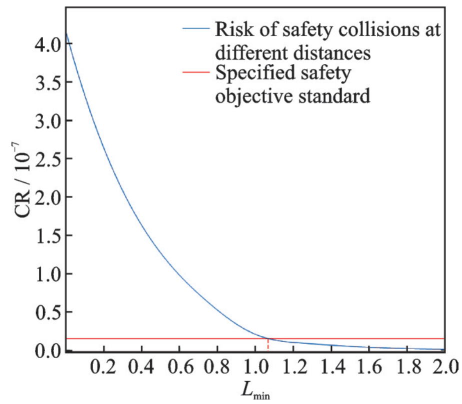

Fig.7 CR level under varying distances between a logistic UAV and another UAV in the same direction and the same descend/climb intention

It can be concluded from Fig.8 that when $L_{min}>1.21$ km, the level of CR in safe flight between the logistics UAV and other UAVs is less than 1.5×10^{-8} (accidents/hour). It can meet the safety target criteria selected in this paper.

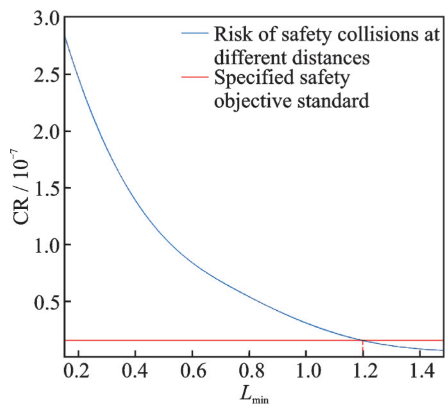

Fig.8 CR level under varying distances between a logistic UAV and another UAV in the same directions and different descend/climb intentions

It can be concluded from Fig.9 that when $L_{min}>1.09$ km, the level of CR in safe flight between the logistics UAV and other UAVs is less than 1.5×10^{-8} (accidents/hour). It can meet the safety target criteria selected in this paper.

Fig.10 shows that when $L_{min}>1.05$ km, the level of CR in safe flight between the logistics UAV and other UAVs is less than 1.5×10^{-8} (accidents/

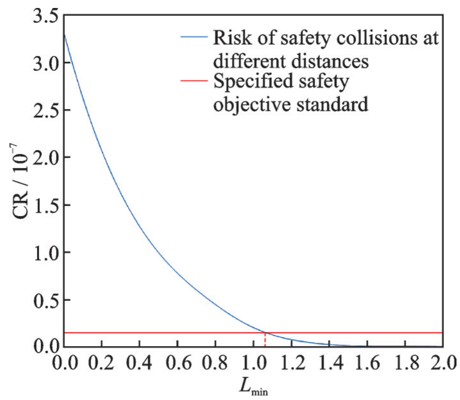

Fig.9 CR level under distances between a logistic UAV and another UAV in reverse directions and the same descend/climb intention

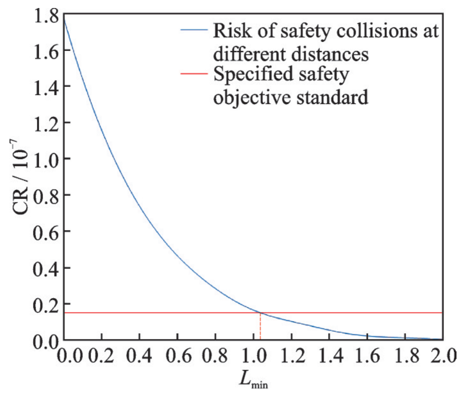

Fig.10 CR level under varying distances between a logistic UAV and another UAV in reverse directions and different descend/climb intentions

hour). It can meet the safety target criteria selected in this paper.

From the above four flight conditions, the following findings can be obtained:

(1) When the flight distance L_{min} between the logistics UAV and other UAVs is more than 1.05 km, CR is more than 1.5×10^{-8} (accidents / hour). As a result, the level of CR in safe flight is higher.

(2) When the flight distance L_{min} between the logistics UAV and other UAVs is more than 1.05 km but less than 1.21 km, depending on the flight conditions of the two, CR is more than 1.5×10^{-8} (accidents / hour) or less than 1.5×10^{-8} (accidents / hour). As a result, the level of CR in safe flight is average.

(3) When the flight distance L_{min} between the logistics UAV and other UAVs is more than 1.21 km, CR is less than 1.5×10^{-8} (accidents / hour). As a result, the level of CR in safe flight is low.

4.2.2 Logistics UAVs and civil aircraft

By conducting experiments for analyzing the conflict between logistics UAVs and civil aircraft, the results are shown in Figs.11—13.

From the simulation results in Fig.11, when the density of logistics UAVs in a specific airspace is no more than 0.208 (airframes/km^3), the level of CR in safe flight between logistics UAVs and heavy aircraft under various influencing factors is less than 1.5×10^{-8} (accidents/hour).

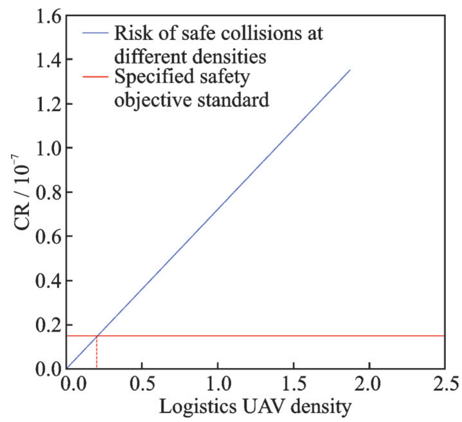

Fig.11 The first relationship between the density of logistics UAVs and the level of CR

From the simulation results in Fig.12, when the density of logistics UAVs in a specific airspace is no more than 0.425 (airframes/ km^3), the level of CR in safe flight between logistics UAVs and heavy aircraft under various influencing factors is less than 1.5×10^{-8} (accidents/hour). As direct comparison between the risks of these two aircraft is challenging, additional oversight of manned aircraft is expected to lower the operating risk.

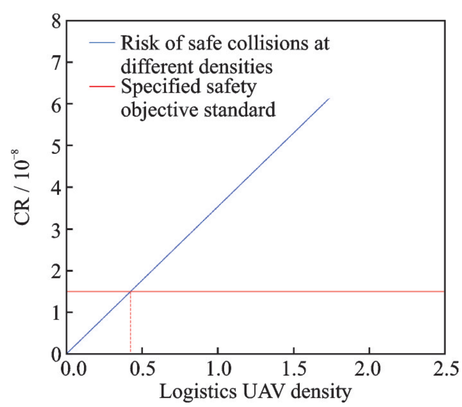

Fig.12 The second relationship between the density of logistics UAVs and the level of CR

Fig.13 illustrates that when the density of logistics UAVs in a specific airspace is more than 1 but no more than 1.271 (airframes/ km^3), the level of CR in safe flight between logistics UAVs and heavy aircrafts under various influencing factors is less than 1.5×10^{-8} (accidents / hour), which can meet the safety target criteria selected in this paper.

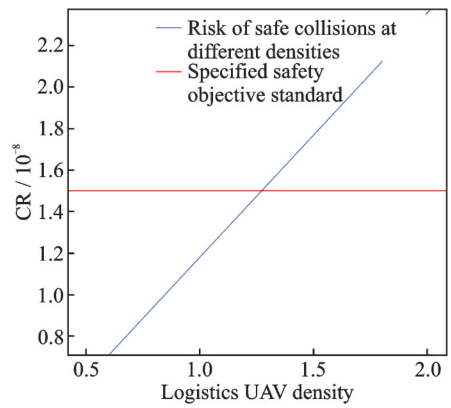

Fig.13 The third relationship between the density of logistics UAVs and the level of CR

5 Conclusions

This study investigates the collision risk level between logistics UAVs and other UAVs, and the collision risk between logistics UAVs and civil aircraft, considering the characteristics and constraints of logistics UAVs as well as various external constraints. The collision model at the intersection and the Reich collision theory model are improved. The two kinds of security risks are analyzed and solved based on simulation experiments. Finally, the relationship curves between the minimum distance, that is, between the logistics UAV and other UAVs, and the level of collision risk in safe flight under different flight conditions are obtained, as well as the relationship between the density of logistics UAV and the collision risk level of safe flight. The results are compared with the selected safety target standards, and the level of collision risk in safe flight in two cases are obtained.

Based on the comparison of the collision risk curve of safety and the standard of safety target between the logistics UAV and other UAVs, it is found that, when the flight distance between the logistics UAV and other UAVs is more than 1.21 km, CR is less than 1.5×10^{-8} (accidents/ hour), the level of CR in safe flight is low. It can be concluded that, based on the relationship between the density of logistics UAVs and the level of collision risk in safe flight, the larger the type of civil aircrafts the smaller the density of logistics UAVs will be. When the civil aircraft is a heavy or medium aircraft and the density of logistics UAVs in the airspace is less than 1, CR is less than 1.5×10^{-8} (accidents / hour). As a result, CRs cannot be explicitly determined, and relevant departments should strengthen the supervision of civil aircraft. When the civil aircraft is a light aircraft and the density of logistics UAVs is more than 1 but no more than 1.271 (airframes/ km^3), the level of CR in safe flight between the two is lower.

In light of the findings from this study, future research directions in the realm of collision avoidance and risk management for logistics UAVs can be explored further to enhance their operational safety and efficiency within shared airspace. Given that the ICAO collision standards are primarily designed for manned vehicles, there is a pressing need to develop tailored guidelines and protocols for unmanned UAVs. Moreover, the presented collision models can be refined by incorporating additional variables like weather conditions, sensor limitations, and operator response times to guide the design of more effective countermeasures.

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Author contributions Mr. **YAN Yonggang** complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Mr. **LI Xinfei** conducted the analysis and model components for the safety analysis of logistic UAVs. Dr. **SHEN Zhiyuan** designed the study, conducted the analysis, contributed to data collection from China Aviation Safety Information Network. Prof. **WEI Wenbin** contributed to the discussion and background of the study and revised the manuscript. All authors commented on the manuscript draft and approved the submission.

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考虑多约束因素的物流无人机网络高精度风险分析模型

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摘要:物流无人机为全球快递物流业的扩张带来了新的机遇,有效克服了地面运输方式的不足。当前物流无人机仍处于起步阶段,因此有必要分析其运行过程中的碰撞风险。本文采用冲突区碰撞建模理论,根据物流无人机的特点和局限性,研究了其在特定空域飞行内的安全隐患。首先,为了衡量可靠性和故障率等多种因素对物流无人机在特定空域安全运行的影响,建立了物流无人机与其他无人机在特定空域的碰撞风险分析模型。然后,通过分析影响物流无人机安全运行的因素,包括空域条件、人机系统、环境条件和管理条件,建立了在特定空域运行的物流无人机与民用飞机碰撞风险分析模型。为了验证所提出模型的准确性,本研究对这两种情况下的模型进行了求解,并与国际民航组织制定的安全性标准进行了比较。

关键词:物流无人机;冲突模型;冲突风险;低空经济;安全运行