Research Article

An Operational Safety Evaluation Method for Manned Transport Aircraft and Large UAV in Mixed Airspace

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To improve the predictive ability in trajectory of large unmanned aerial vehicle (UAV) and the calculation performance in complicated circumstances with mixed airspace, multiple aircraft types, and joint operations, the concept of phased trajectory deviation (PTD) is introduced and a corresponding minimal interval algorithm (PTD-MI) is set up. This algorithm is capable of deriving the minimal interval between various aircraft types according to the crosswind impacts and the UAV characteristics at different flight phases and thus achieves the effective safety evaluation in airspace operation. To demonstrate the rationality and generality of the proposed algorithm, several simulation experiments are conducted. Based on the experimental results, flight procedure protection area is plotted by PTD-MI algorithm and compared with that generated by Ground-Based Augmentation System (GBAS). Results indicate that the proposed algorithm is capable of deriving a more scientific basis for airspace assignment and outperform GBAS in dealing with wide-area space problems. And, compared with GBAS, PTD-MI algorithm shows a more stable calculation performance and is easier to output the results. PTD-MI algorithm is proposed under the flight safety regulation designed by the International Civil Aviation Organization (ICAO) and designed to provide effective technical supports for the safe and normal operations of aircrafts.

1. Introduction

At present, many older manned aircraft, because of the poor performances of the aircraft, the small commercial payload space of the aircraft, and the deficiency of aviation telecommunication equipment [1], have gradually been modified into large unmanned aircraft, which are used in low-altitude cargo transportation and general aviation flights [2, 3].

In the research field of UAV track prediction and operation safety assessment, the current research accumulation is as follows. First of all is the study of risk factors. By sorting out the unsafe incidents, we can conclude the causes of the accidents. Wang and Chen provided a hybrid optimization algorithm with directivity [4], Zhao et al. proposed a case study for diagnosis [5], Zhang used the learning model to supplement experiments and demonstrate the imperfections in the algorithm and case diagnosis [6, 7]. In this way, the graded management method of

accident factors has been established. Second is the study of risk degree. According to the hierarchical management of accident factors, factor screening and weight design have become the focus of safety evaluation model [8]. In the preliminary studies, the evaluation schemes were mostly built around the SHELL model, which basically realized the accident risk assessment [9]. At this stage of the study, Chen proposed a Hawks optimization scheme based on the computer system [10, 11], Li et al. provide a global optimization strategy [12], and Xia et al. provided intelligent systems [13], and the results of their research explain and justify the implementation of the optimization scheme. Shen used a grasshopper optimizer to enhance the adaptability of previous studies [14, 15] so that the various levels of risk assessment parameters obtained a specific design basis. Third is the study of flight path prediction. According to the available data, the method of graded management of accident factors and the scheme of risk assessment have been initially established [16]. Chen

studied early accident diagnosis and provided research ideas for parameter selection and evaluation [17], Hu studied the defects of accident diagnosis and proposed the use of multiplicity selection method to carry out simulation experiments [18], and Zhang et al. established a method to show the application effect of experimental results by using Image Dehazing (ID) technology [19, 20]. The next step of research will mainly focus on the collection of original data of accident factors [21]. According to different research objects and evaluation criteria, flight path prediction research is mainly used for flight path planning [22]. Fourth is the study on the accuracy of evaluation results. Since all industries have accident evaluation programs, but the requirements for accuracy of evaluation results and quantitative methods are different, civil aviation flight safety assessment emphasizes precision and control [23]. In a study conducted in recent years, Zhao proposed the application of image segmentation and processed the evaluation results graphically [24], Zhang et al. proposed the concept of integer programming to make the evaluation results more accurate in the graphic display [25], and Zhao et al. proposed Improved Ant Colony Optimization (Improved ACO) to improve the display degree and scope of evaluation results [26, 27]. These research results make the simulation results and evaluation results more applicable to the real civil flight practice field. At present, a breakthrough has been made in the study of flight safety evaluation; however, in dealing with problems such as high precision, large scope, and complex airspace structure, the existing algorithms have low computational performance [28], or cannot carry out evaluation for specific environment, and lack a calculation method with high adaptability [29]. At the same time, the existing research lacks the countermeasures to the joint operation. Even so, in terms of algorithm and comparative experiment design, the research results are rich. In the future, experiments and argumentation can be carried out under the premise of optimal design, and evaluation basis and rules can be summarized.

In the current practical operation and production process, more and larger UAV and manned aircraft are carrying out joint operation missions [30]. In this mixed airspace, flight safety assessment is a difficult work, and the main difficulties lie in the choice of parameter types and the use of evaluation criteria [31]. At the same time, transform old manned aircraft into large UAV; it has been gradually realized at this stage, and this kind of transformation is more and more [32], and the number of old aircraft is also large [33]. As a result, general aviation missions at low altitudes will increasingly performed using large UAV; if a safety assessment method can be developed which is suitable for the joint operation of large UAV and manned aircraft in mixed airspace [34, 35], these findings can improve the flight safety of general aviation and promote the strategy of further opening up the low-altitude airspace [36].

This paper takes operational safety assessment as the research direction and tries to establish a trajectory prediction model. This model can be used to evaluate the operational safety trend in the low-altitude airspace, and the evaluation scope should cover the local airspace of the

airport, and the evaluation results should meet the ICAO requirements for the accuracy of risk assessment.

2. Problem Description

First of all, because of the preflight planning stage, it is impossible to accurately obtain all kinds of conditions during the actual flight, such as airspace situation, meteorological information, and flight environment [37]. Those differences in the preplanning and implementation leads to the result between the planned trajectory and the actual trajectory which is different [38]. According to the conflict probability value stipulated by ICAO [39], the navigation equipment accuracy of large UAV is used to analyze various influencing factors under the operating environment [40], and the fusion algorithm is established for the overall airspace to calculate and obtain the interval safety value that should be maintained between aircrafts, so as to complete the evaluation of flight conflict [41]. As described above, the current model lacks the analysis and processing of aircraft performance parameters and does not consider the turning radius trajectory deviation or the linear [42]. If the flight procedure design specification of transport aircraft is used for analysis, many unfavorable factors will be brought so that the calculated results cannot be used for correct evaluation [43]. Therefore, the design of PTD-MI algorithm needs to avoid the above adverse factors.

Secondly, the airport has a wide range of local airspace. If ground equipment is used for trajectory observation and prediction [44], the increase of observation distance will lead to the increase of evaluation error [45]. Therefore, the design of PTD-MI algorithm needs to consider the optimization of evaluation error.

Finally, the evaluation results derived from the algorithm can easily show the application effect.

3. Improved Computational Model

According to ICAO regulations, calculate flight envelope on the mission to carry out the plan, and all running implementation stages need to meet standards, including the conflict between aircraft probability which are restricted to 1.5×10^{-8} (accident/flight hours) [46]; the data can be seen as the flight safety guarantee value, and it can be used to represent the current conflict between the probability of aircraft operating. In the design of the improved model, the large UAV is used as the experimental object [47].

3.1. Established Model of Turning Stage. As experimental objects, large UAVs are generally equipped with Global Positioning System, which can autonomously and accurately search for preset airway points, and have the ability to fly along the preset path [48]. All of them have no flight technical tolerance and do not need to set the time margin for the pilot response. In the actual flight process, compared with the transport aircraft, the experimental subjects need to focus on the data such as lift-off point position, turning speed, turning slope, and flight mission altitude, which are the main parameters for the formation of flight trajectory of

large UAV. Assuming rated cruising speed v_1 and turning slope γ_1 , there is a relationship between rated turning radius R_1 and flight parameters under current flight conditions:

$$R_1 = \frac{v_1^2}{g \tan \gamma_1}. \quad (1)$$

Assuming that the real slope is γ_2 and the cruising speed v_2 is arbitrary, the normal distribution relationship is established:

$$F_\gamma(\gamma_2) = \frac{1}{\sqrt{2\pi}\sigma_\gamma} \exp\left(-\frac{(\gamma_1 - \gamma_2)^2}{2\sigma_\gamma^2}\right), \quad (2)$$

$$F_v(v_2) = \frac{1}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{(v_1 - v_2)^2}{2\sigma_v^2}\right).$$

Assuming that the center of the circle is O , the model expression of the turning trajectory is established:

$$\begin{cases} x_2 = x_1 + R_0 \cos \alpha, \\ y_2 = y_1 - R_0 \sin \alpha. \end{cases} \quad (3)$$

Assuming that the center of the allowed maximum turning trajectory is represented by $O_1(x_1, y_1)$ and the center of the real turning trajectory is represented by $O_2(x_2, y_2)$, it is assumed that the trajectory of the real flight overlaps with the preset trajectory, which is generated by the true course angle, represented by α . Because global positioning system is widely used for navigation and positioning in the field of civil aviation transportation, its civil precision is usually about 50 meters [49]. At the same time, equipment error, installation error, and aerodynamic error exist in real environment and experiment. After taking all kinds of errors into consideration, a normal distribution relationship is established. Assuming that the maximum permissible heading angle is α_1 and the true heading angle is α_2 , then

$$F_\alpha(\alpha_2) = \frac{1}{\sqrt{2\pi}\sigma_\alpha} \exp\left(-\frac{(\alpha_1 - \alpha_2)^2}{2\sigma_\alpha^2}\right). \quad (4)$$

According to the relevant provisions of aircraft operation attached to ICAO Annex 6, the σ_α value is 2.58° , without considering the case of $\alpha_1 = \alpha_2$, and the expression of α is established as follows:

$$\alpha = \begin{cases} \pi - \arctan\left(\frac{y_1}{x_1}\right), \\ 2\pi - \arctan\left(\frac{y_1}{x_1}\right). \end{cases} \quad (5)$$

3.2. Established Model of Crosswind Influence. Assuming that the experimental object is affected by the crosswind with wind speed of WS , according to the conservative principle, omnidirectional wind is used to represent the crosswind; then,

$$R_2 = R_1 + \frac{WS}{\mu}, \quad (6)$$

where, under the omnidirectional wind, the true turning radius is R_2 and the angle to complete the turn is μ . Therefore, under the influence of the above turning slope, height, and other factors, the trajectory deviation component S_{rd} can be expressed as follows:

$$S_{rd} = x_L - x_2 + R_1, \quad (7)$$

where x_L is a known quantity. The value of x_L is the value of the actual flight position of the experimental object in the coordinate system O_2 .

3.3. Established Model of Straight Flight. Generally, in the straight flight stage, due to the influence of navigation equipment precision and wind, there are differences between the actual flight path and the preflight planned path. In the total flight time of the experiment, the experimental subjects spent more flight time in the straight way and less flight time in the turning way. If, in the advance path planning stage, the deviation caused by straight flight and turn flight is calculated separately and integrated, then this approach will increase the workload of preflight preparation [50]. According to the conservative principle of ICAO in the way of safety assessment, the deviation value of the straight line segment and the turning segment can be calculated uniformly, to obtain the total amount of deviation satisfying the two modes of flight, thus ensuring the adaptability of the calculation results.

Assumptions exist in space plane position point $A_3(x_3(t, t_\Delta), y_3(t, t_\Delta))$, it means, in the preset trajectory points, to allow maximum deviation, there is a position point $A_4(x_4(t, t_\Delta), y_4(t, t_\Delta))\cos^{-1} \theta$, and it means the current real trajectory point position. Because the experiment task is to

fly straight and then temporarily not consider height variation, d means the distance between the two points above, flight time for t_Δ ; then, we can get the space position of expression:

$$\begin{cases} x_3(t, t_\Delta) = \varepsilon_{3x} + \left(-d_3 + \int_0^{t+t_\Delta} v_3(t)dt\right) \cdot \cos \phi, \\ y_3(t, t_\Delta) = \varepsilon_{3y}, \end{cases} \begin{cases} x_4(t, t_\Delta) = \varepsilon_{4x} \cdot \cos \phi - \varepsilon_{4y} \cdot \sin \phi + \cos \beta \cos \phi \left(-d_4 + \int_{t_\Delta}^{t+t_\Delta} v_4(t)dt\right), \\ y_4(t, t_\Delta) = \varepsilon_{4x} \cdot \sin \phi + \varepsilon_{4y} \cdot \cos \phi + \cos \beta \sin \phi \left(-d_4 + \int_{t_\Delta}^{t+t_\Delta} v_4(t)dt\right), \end{cases} \quad (8)$$

where i is the number of the experimental subject, β is the position point with the maximum allowable deviation, ϕ is the real position point, there is an included angle between points β and ϕ and any point O on the preplanned trajectory in the flight direction, and ε is the coordinate system position tolerance. In the current case, the trigonometric relationship

consisting of a line of points O , flight direction, and trajectory deviation values is established.

Suppose the time interval is t_Δ ; then, $|x_{34}(t, t_\Delta)|$ and $|y_{34}(t, t_\Delta)|$, respectively, represent the position relationship of β and ϕ with respect to the position point O , and the relationship is as follows:

$$\begin{cases} x_{34}(t, t_\Delta) = \varepsilon_{3x} - (\varepsilon_{4x} \cos \phi - \varepsilon_{4y} \sin \phi) + S_{34x}(t, t_\Delta), \\ y_{34}(t, t_\Delta) = \varepsilon_{3y} - (\varepsilon_{4y} \sin \phi + \varepsilon_{4x} \cos \phi) + S_{34y}(t, t_\Delta), \end{cases} \begin{cases} S_{34x}(t, t_\Delta) = \cos \phi \left(-d_3 + \int_0^{t+t_\Delta} v_3(t)dt\right) - \cos \phi \cos \beta \left(-d_4 + \int_{t_\Delta}^{t+t_\Delta} v_2(t)dt\right), \\ S_{34y}(t, t_\Delta) = -\cos \beta \sin \phi \left(-d_4 + \int_{t_\Delta}^{t+t_\Delta} v_4(t)dt\right), \end{cases} \quad (9)$$

where position point O is the initial point, the experimental subject and point O exist at points $S_{34x}(t, t_\Delta)$ and $S_{34y}(t, t_\Delta)$, and points $S_{34x}(t, t_\Delta)$ and $S_{34y}(t, t_\Delta)$ are symmetric with the preplanned trajectory, the three establish trigonometric relations. Then, when t_Δ is a specific value that can be measured and obtained, the distance between two points can be obtained:

$$S_{34}(t, t_\Delta) = \sqrt{S_{34x}^2(t, t_\Delta) + S_{34y}^2(t, t_\Delta)}. \quad (10)$$

According to the above expression, the distance between the real flight trajectory position point and point O should be greater than the minimum safety distance, so the distance between the two points should be wider than 0, which is a positive number. If that is true, that means the mission can continue, in which the subject is at an appropriate range, and it satisfies the probability of safety collision and is not easy to have collision and conflict. If the conclusion is equal to 0 or less than 0, it means that the experimental subject is in the restricted range, or already in the dangerous area. According to the conservative principle, the expression of the minimum critical deviation component in the straight flight stage is obtained, and the relationship is as follows:

$$|S_{34}(t, t_\Delta)| = S_{L\min}. \quad (11)$$

After derivation, the total deviation M in the turning flight stage and the straight flight stage is obtained, and the expression is as follows:

$$S_{r,d} + S_{L\min} = M. \quad (12)$$

3.4. Established Model of Safe Operation. The initial design of the model is as follows:

$$\begin{cases} w_1 = w_{mx} + w_{nx}, \\ w_2 = w_{my} + w_{ny}, \\ w_3 = w_{mz} + w_{nz}, \end{cases} \quad (13)$$

where w_{mx} , w_{my} , w_{mz} and w_{nx} , w_{ny} , w_{nz} are the dimensions of transport aircraft and experimental objects and the parameters are length, wingspan, and height in order. If the transport aircraft and the experimental subject regard each other as points, when their respective initial models are in contact, it can be considered that the operation conflict has been generated and the safety is affected (see Figure 1).

The improved model is established by comprehensively considering all the safe operation parameters, and the relationship is as follows:

FIGURE 1: The initial model and model contact.

$$G = \frac{A}{M} \left(w_1 + \frac{U_s w_2}{V_s} \right) P \left(1 + \frac{W_s w_2}{V_s w_3} \right) \eta + \frac{B}{M} \left(w_3 + \frac{U_o w_2}{V_o} \right) P \left(1 + \frac{W_o w_2}{V_o w_3} \right) \eta, \quad (14)$$

where G is the value of conflict probability obtained through calculation by importing the security operation parameters into the improved model, η is the operating sorties of transport aircraft per hour, A represents for the number of experimental subjects (UAV), which is consistent with the flight direction and flight trend of transport aircraft in the current airspace, and B also represents for the number of experimental subjects (UAV), which is remains opposite with the transport aircraft in flight direction and trend within the current airspace. Assuming that when the conflict occurs if the flight trend of the experimental subject and the transport aircraft is consistent, then U_s, V_s , and W_s are used to represent the velocity data parallel to the flight direction, perpendicular to the flight direction, and above the flight direction. Similarly, U_o, V_o , and W_o are data under the trend of remaining relative flight. P is the probability that the transport aircraft and the experimental subject (UAV) fly over each other.

In order to make the experimental conclusion adaptable to civil aviation manned transport aircraft, the parameter composition and constant setting in the model should meet the requirements of ICAO on flight standards and safe operation, etc [51]. Computational and research objects mainly include experimental objects (UAV), other aircraft similar in type to experimental objects, and civil aviation manned transport aircraft. Assume that φ_1 is the quality of flight mission execution, φ_2 is the pilot operation technology, and φ_3 is the probability of operating failure per 100,000 hours, and statistics of real operation data in recent ten years is shown in Table 1 [52, 53]. Because the research objects are civil aviation manned transport aircraft and experimental objects (UAV), civil aviation transport flight has a strict set of retention barriers, as required by the law and regulations, and it is permissible for a civilian transport aircraft with a fault to fly missions; according to the conservative principle,

the operation failure probability of transport aircraft can refer to the ICAO regulation, namely, the maximum number of failures per 100,000 hours allowed.

According to the preset data and real data in the table, the expression of φ_1 is obtained as follows:

$$\varphi_1 = \sum_{i=1}^n E_i T_i, \quad (15)$$

where E_i is the applicability of flight status and T_i is the number of aircraft in the experimental airspace. In addition, according to formula (15), E_i is used to represent the failure data per 100,000 hours and T_i is used to represent the failure interval data. So, the expression of φ_2 can be obtained.

Pilot's flying skills are mainly reflected in the civil aviation manned transport aircraft, and UAV is not affected by this factor and can directly use the former accident ratio 9.62%; then, $\varphi_3 = 1 - 0.0962 = 0.9$.

To sum up, according to the provisions of ICAO, one conflict in safe operation will be recorded as two accidents, and the evaluation model of safe operation conflict will be established. The expression RE is as follows:

$$RE = 2(1 - \varphi_1) \cdot \varphi_2 \cdot (1 - \varphi_3) \cdot G. \quad (16)$$

If the calculated result of RE is set as the probability value of safe operation conflict, which is constant and meets the requirements of ICAO for safe operation, the improved model is used for analysis and calculation. Assuming that the relative motion states of the transport aircraft and the experimental subject are unchanged, the structure of the airspace remains unchanged, the operating conditions remain unchanged, then $(A + B)$ can be regarded as the sum of the number of aircraft in the current airspace so that the airspace density data can be obtained. This calculation result is a quantified airspace management conclusion and meets the flight standard of safe operation conflict probability.

4. Design of Simulation Experiment

An airport in the south of China was selected for the simulation experiment, and the flight performance data of the research object were referred to Airbus 320 and AT200, as shown in Table 2 [54, 55]. Because the AT200 and the same class of UAV, which are large fixed-wing UAV, must take off from civilian airports, so, in flight, take-off climb and approach phase is more prone to conflict. The parameters were added into the improved calculation model, the influence of flight trajectory deviation is considered, and the conflict probability value of safe operation is considered, so the minimum interval value between the research objects can be calculated to obtain the turning flight stage and the straight flight stage. The above calculation results can be used as the capacity conclusion of the flight airspace, which is a quantitative result.

Considering the airport information, consider the route and route point information and then start the design of the simulation experiment. Normally, July and August are the busiest months for transport aircraft; select the hourly flight flow in the low-altitude airspace within the research airspace,

TABLE 1: The maintenance actions and costs corresponding to different maintenance levels.

Type	Number of serious failures per 100,000 flight hours	MTBF (hour)	Applicability of flight status (%)	Task completion schedule (%)
Airbus 320 (no statistical NEO)	0.20	48.5	12	85
Boeing 737NG (800)	0.20	49.2	12	85
AT-200	12	29.5	96	86
Y-5 (UAV)	9	23.4	87	78
Predator	34	44.1	73	79
Pioneer	248	19.2	77	83
Hunter	15	10.9	96	81

TABLE 2: Parameters of simulation experiment.

Type	Data	Type	Data
V (km/h)	650	w_{mx} (m)	37.57
Γ	45	w_{my} (m)	34.10
σ_v	15	w_{mz} (m)	11.76
σ_α	2	w_{nz} (m)	11.84
P	0.5	w_{ny} (m)	12.80
H	—	w_{nz} (m)	4.04
V_S or V_O	5.23	U_s	3
W_S or W_O	0.58	U_o	497
W_S (km/h)	30	Altitude (m)	3200

using this data as the value of η . According to the influence of the cutting angle and heading angle on the experimental design, three different angle relationships are established.

Design 1. When the two planes are flying in the same direction and the transport aircraft is in the departure and climbing stage, in this case, transport aircraft would travel from low-altitude airspace to medium altitude airspace, or higher altitude, so set the maximum $\beta = 15^\circ$ and $\varphi = 20^\circ$, and this is according to ICAO operating standard.

Design 2. When the two planes are flying face to face and the transport aircraft is in the arrived stage, in this case, the transport aircraft has a high speed, and set $\beta = 5^\circ$ and $\varphi = 20^\circ$.

Design 3. When the two planes are flying face to face and both planes are flying horizontally, in this case, the flight status of transport aircraft is relatively stable, and the possibility of sudden changes in operating conditions is low, and set $\beta = 0^\circ$ and $\varphi = 15^\circ$.

The above three conditions were established to simulate the situation where the transport aircraft and the UAV had a high probability of conflict, increase the redundancy of experimental results, and adhere to the conservative principle.

According to the design of the experiment, parameters are added into the model, and the conclusion can be obtained through equations (12) and (16):

$$(i) \text{ The first case, } M_{(1)} > 3.116\text{km}, \\ (A + B)_1 = 1.203 \times 10^{-3} \text{ (frame/km}^3\text{)}$$

$$(ii) \text{ The second case, } M_{(2)} > 4.214\text{km}, \\ (A + B)_2 = 0.895 \times 10^{-3} \text{ (frame/km}^3\text{)}$$

$$(iii) \text{ The third case, } M_{(3)} > 3.762\text{km}, \\ (A + B)_3 = 1.054 \times 10^{-3} \text{ (frame/km}^3\text{)}$$

The experimental results can be made into a graph to show the relationship between the conflict probability of safe operation and the interval between the aircraft, and the relation of density is obtained, as shown in Figures 2 and 3.

5. Description of Application and Innovation

According to three groups of experiments, when the experimental subjects are in the stage of arrival and departure flight, they will have a large space change and speed change for climbing. For this reason, the amount that can be used to adjust the heading angle is reduced, resulting in insufficient space for the flight path to be used for adjustment or avoidance in preflight preparation, and there will a high probability of collision, and it is very likely to happen to intrude into another airspace. At the same time, it also shows that, in this operating state, the density of joint operating aircraft needs to keep low, which conforms to the objective facts. It can be concluded that, in the low-altitude airspace, the adjustment variation of heading angle can provide data support for calculating the probability of collision.

Similar evaluation models mostly exist in the collaborative evaluation between ground operating equipment and aircraft, and the main reason is that both civil aviation and general aviation aircraft perform missions in low-altitude airspace using conventional or visual flight procedures, depending on the location of ground equipment, ground visual references, and route point setting points and lack of accurate positioning ability and monitoring equipment. As a result, the data of the evaluation model contains the positioning tolerance value, so the practical guiding significance is not sufficient, and does not apply to the evaluation of the mixed airspace for large UAV and manned aircraft [56].

In order to reflect the advantages of PTD-MI algorithm in dealing with wide-area space problems, according to the design of simulation experiment, the data in Table 2 were added into the evaluation model of GBAS, and the calculation results are shown in Table 3.

Among them, the experimental results under the GBAS model are divided into two situations: the results within 15 kilometers and the results outside 15 kilometers. Because

FIGURE 2: Curve of the position interval.

FIGURE 3: Curve of the density result.

the distance between ground equipment and aircraft increases, the positioning error of ground equipment also increases. According to the results of the third case of experiments, the flight procedure protection area is drawn, as shown in Figures 4 and 5.

As shown in the picture, there are three colors: white, gray, and black, and they represent the operating areas based on the above two evaluation conclusions. The operation area is divided into three layers: the first layer is the area where flight

missions can be carried out, the second layer is the buffer area where the possibility of conflict needs to be carefully handled, and the third layer is the area where UAV is prohibited to fly. Taking the approach stage and low-altitude airspace as examples, the altitude of low-altitude airspace shall be calculated as below 6000 meters (inclusive), and the spatial planning quantity of simulation experiment results is shown in Table 4. In Figures 6 and 7, the parameters of simulation experiment are set as follows: the elevation of the airport is 1150 meters, and the average mountain height within the range of the approach stage is 1372.26 meters.

The application effect of the experimental results shows that due to the use of the PTD-MI model, the volume of the first layer airspace increases by 10.04%, 9.54%, and 8.09%, which indicates that the flight area of the large UAV is expanded, and the application effect is excellent.

The reasons for the above results can be summarized as three points. First, the GBAS evaluation model evaluates the working data of ground equipment [57]. This equipment uses 30 MHz–300 MHz electromagnetic wave for data transmission to realize navigation and positioning functions [58]. Therefore, there will be an attenuation of efficiency when information is transmitted in a large area, which leads to the fact that the M value is not a constant quantity. Its positioning tolerance value will increase with the expansion of the evaluation airspace [59], so it is not suitable for the research of position interval in the overall airspace. This method is suitable for evaluation in a small space such as near the runway. Second, the ground equipment cannot be built at the midpoint of the runway entrance, so the deviation of heading angle will inevitably occur [60], and when the flight value is smaller, the accuracy of the data is higher, so the error is very obvious due to the existence of deviation. Thirdly, relevant parameters

TABLE 3: Comparison of experimental results based on the two algorithms.

Experimental design sequence number	Types of experimental results	Model of GBAS (within 15 kilometers; outside 15 kilometers)	PTD-MI
The first case	The total deviation M , km	>2.588 ; >3.844	>3.116
	Total number of aircraft $(A + B)$, frame/km ³	1.281×10^{-3} ; 0.982×10^{-3}	1.203×10^{-3}
The second case	The total deviation M , km	>3.602 ; >5.013	>4.214
	Total number of aircraft $(A + B)$, frame/km ³	0.962×10^{-3} ; 0.615×10^{-3}	0.895×10^{-3}
The third case	The total deviation M , km	>3.116 ; >4.607	>3.762
	Total number of aircraft $(A + B)$, frame/km ³	1.138×10^{-3} ; 0.807×10^{-3}	1.054×10^{-3}

FIGURE 4: The result of approach phase based on the GBAS model.

FIGURE 5: The result of approach phase based on PTD-MI.

TABLE 4: Spatial planning quantity based on simulation experiment results.

Layer number	Simulation experiment of the first case (km ³)		Simulation experiment of the second case (km ³)		Simulation experiment of the third case (km ³)	
	GBAS	PTD-MI	GBAS	PTD-MI	GBAS	PTD-MI
The first layer	8464.73	9409.55	8016.88	8863.63	8542.81	9288.82
The second layer	1092.78	910.38	1302.83	1059.76	1169.32	988.95
The third layer	2387.95	2387.95	2387.95	2387.95	2387.95	2387.95

FIGURE 6: The results of mixed airspace based on the GBAS model.

FIGURE 7: The result of mixed airspace based on PTD-MI.

based on satellite positioning are not included in the ground equipment evaluation model, which will greatly increase the inaccuracy of the calculation conclusions in the application of space problems. Based on the above three reasons, it can be found that the experimental design takes data accuracy, safety margin and mixed airspace operation into full consideration [61]. The conclusion obtained by the PTD-MI algorithm calculation makes the M value in a more reasonable range and improves the scientific nature of the density value.

There are two innovations about the PTD-MI algorithm. First, the model fully considers the flight characteristics of the turning stage and the straight stage and adds the flight attitude data into the evaluation model to obtain the results. This is the first time to study such a problem. Second, take the flight conflict safety value recommended by ICAO as the basis of experimental design [62], the first discussion of flight planning in the mixed airspace, including conflict assessment between large UAV and manned aircraft, and these

conclusions are applicable to preflight planning of flight missions in the overall airspace.

6. Summary and Conclusions

In this paper, the concept of PTD is introduced, and a corresponding PTD-MI algorithm is set up. According to the actual operation and production situation, the simulation experiment is designed and the experimental results are shown, and the experimental results reflect the application effect of operation safety evaluation. In addition, the experimental results of the GBAS model are compared and analyzed, and the conclusions are as follows:

- (1) The PTD-MI algorithm is consistent with the requirements of rationality and generality in the actual operation, which is conducive to maintaining the accuracy of the experimental results. The algorithm maintains the characteristics of large UAV at all flight stages and under the influence of crosswind, and it provides an optimal basis to deal with airspace planning problems and widens the application range of PTD-MI algorithm.
- (2) In the simulation experiments, the PTD-MI algorithm shows excellent and effective computing performance. In the prediction of the flight path within the local airspace of the airport, the acceptable calculation results can be provided. By comparing and analyzing the results of PTD-MI algorithm and GBAS algorithm, the superiority of PTD-MI algorithm in dealing wide-area space problems is shown.
- (3) Due to the reference of ICAO flight standard parameters, the calculation results derived from PTD-MI algorithm are applicable to the operation safety evaluation of civil aviation.

For future works, we recommend applications of the proposed method to other UAV systems [63–67], adaptive control techniques [68–72], applications of optimization methods such as differential evolution, particle swarm, whale optimizer, differential search, and other optimizers for optimizing parts of the process [73–78], distributed optimization [79], and other optimization forms such as robust, memetic, many objective, multiobjective, and fuzzy optimization [80–87].

Data Availability

The data used to support the findings of the study are available within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

X. M. and X.Z. conceptualized the study; X. M. developed methodology; X. Z. helped with software; H. W. and S. D. validated the study, X. M. carried out formal analysis; X. L. investigated the study; X. M. collected resources; X. M. carried out data curation; X. M. wrote the original draft; X. Z. reviewed and edited the article; X. M. visualized the study; H. W. and S. D. supervised the study; X. M. administrated the project; X. M. helped with funding acquisition. All authors have read and agreed to the published version of the manuscript.

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