A Design Method of UAV Flight Protection Area Based on the Statistical Analysis of Flight Path Deviation

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Abstract. According to the design specification of International Civil Aviation Organization (ICAO) document No. 8168, by referring to the flight record data of UAV and using the statistical and analysis method of flight line deviation limit data, the limit data is obtained, and according to the definition of collision probability model in flight programming specification, the design method of flight protection area for UAV is obtained based on flight path deviation limit data. A simulation experiment was established based on the computational simulation. The calculation results showed that: the design of UAV flight protection area is mainly determined by navigation accuracy, positioning mode, flight link and other factors, and the weight is different. By improving the accuracy and changing the flight link, the scope of UAV flight protection area can be effectively reduced. In the future, the joint operation of manned aircraft and UAV in the hollow and low-altitude airspace provides the basis for airspace planning, which further ensures flight safety and improves operational efficiency.

Keywords: Flight protection area, Flight deviation, Protection area design, Joint operation

1. Introduction
The application of small unmanned aerial vehicles (UAVs) is becoming more and more extensive. The way to carry out tasks has changed from human operators to autonomous navigation and active obstacle avoidance gradually, and the removal of artificiality becomes prominent. In future production, the airspace planning department will further enhance UAV control, such as demarcating its operating area, traversable area, and no-lift-off area, etc. [1]. At this stage of flight path planning for civilian UAVs, there is no regulatory framework in place, with operational companies or individuals exercising self-regulatory control over performance parameters. The design specification for UAV flight protection zone is formulated to provide the minimum safe interval for each aircraft performing tasks in the unit airspace, thus increasing the flight routes in the unit airspace, increasing the number of simultaneous aircraft, increasing the total number of flights, reducing the probability of conflicts, and realizing the purpose of flight safety management.

According to recent research data, many achievements have been made in trajectory reconstruction or obstacle avoidance. Lee and Gen conducted safety flight assessment in low-altitude airspace through the establishment of fusion algorithm, and obtained a large number of operation data and index types
of fixed-wing aircraft, which has a high reference for simulation modeling\cite{2}. ZHANG et al. discussed the take-off and landing interval of aircraft in depth by using cellular automatic mechanism and equipment, and made a preset of the take-off interval of UAV simulation experiment based on the results, which can further enhance the authenticity and effectiveness of the experiment\cite{3}. Brooker P provided an effective method to quickly obtain the extreme value based on the collection of flight time and take-off and landing number and the optimization of the maximum descent method, which was conducive to the analysis of UAV trajectory and the fast acquisition of the extreme value of yaw\cite{4}.

In summary, the existing achievements mainly focus on the actual operation. Using optimization algorithm, establishing evaluation index and realizing simulation presupposition. However, the UAV’s real historical trajectory is not counted, and the key factor of airborne navigation equipment accuracy is not introduced. $BV$ is a buffer value, representing the safety margin added on the basis of the yaw extreme value. This factor will have a great impact on the deviation between the preset flight path and the actual flight path\cite{5}. So there are limitations in practical application.

2. Algorithm analysis and experimental basis

The calculation of the flight path protection zone needs to sort out the real historical track in order to find the yaw data. Under the influence of navigation accuracy, the yaw distance generated will be an important part of the factors to construct the protection zone. There are many methods to obtain extreme values. In order to improve computational efficiency, reliability and accuracy, as well as to meet the requirement of rapidly processing a large number of data sources for information extraction, the bubble-sort algorithm is selected to seek extreme values\cite{6}. The core of the algorithm is: The clutter array is compared adjacent from the beginning of the queue, and the largest or smallest array elements are replaced to the end of the queue according to the size of the replacement position to form a component of the ordered array. The process continues in turn until all elements are compared and formed into an ordered array. According to the comparison and record times, the result output can obtain the number of yaw frequency and the range of yaw distance, which is conducive to the setting of $BV$. Then, the following equation exists.

\begin{align}
T_{\text{max}} &= \frac{n(n-1)}{2} = P(n^2) \\
L_{\text{max}} &= \frac{3n(n-1)}{2} = P(n^2)
\end{align}

Where, $T$ is the maximum number of comparison, $L$ is the maximum number of records, and $P$ is the average time complexity. The Bubble-Sort first loop needs to make $n-1$ times of visits to the array, and the second loop is to compare $f[0]$ to $f[n-1]$, where $i$ is the number of visits to the first loop, If the $f[j-1] > f[j]$ will be replaced until $f[0]$ and $f[1]$ are compared, at which time the number of comparison and recording reaches the maximum.

After the yaw extreme value is obtained, the extreme value of yaw, navigation accuracy and relevant tolerances are used for reference in the Large Aircraft Visual and Instrument Flight Program Design Code (8168), a normative document of the International Civil Aviation Organization. Targeted establishment of construction factors for UAV flight path protection area design specifications. Then, the formula for $AW$ existing route protection zone is as follows:

\[
\frac{1}{2}AW = 1.5XTT + BV
\]

Where, $AW$ is the width of section protection zone; $XTT$ is yaw tolerance; $BV$ is the buffer value, indicating the safety margin added on the basis of the yaw extreme value. In this way, the width of the protection zone can not only contain the actual maximum deviation in the total flight
time, but also have the safety margin to improve the flight safety. In practical application, yaw tolerance is the maximum yaw of the allowable lateral interval on the preset flight path (nominal track), that is, the extreme yaw value under the current experimental data. Therefore, the extreme value of yaw is sought according to the historical flight path. Considering the design specification of the flight path protection area, taking advantage of the flight environment and UAV performance, and taking the conclusion as the test test basis, the experimental plan is set up to carry out the test test verification.

3. Collection and analysis of historical tracks Protection Zone Design
Based on previous studies and analysis of the design specifications for fixed-wing aircraft flight protection areas, it is found that the establishment of UAV flight protection areas needs to consider the positioning equipment carried, the positioning technology applied, and the positioning accuracy achieved to process the historical trajectory. Select several operating company history data collection of the same type of equipment. The navigation accuracy of the selected equipment was ±5 meters. This parameter was published by the UAV manufacturer according to the GPS real-time positioning system technology. For the consideration of cost control, wide application and experimental effect, equipment with RTK differential technology is not selected. Data collection is targeted at the operation companies that carry out plant protection, garden monitoring and topographic mapping.

3.1. Setting of preset flight routes
By screening the validity of the data, the historical flight data of an operating company was selected for the key research. After analysis, it was found that the coverage of the historical flight path was mainly concentrated in the area with the center of the UAV’s lift-off point and a radius of about 7 km. After sorting out the flight data of the operation company, it was found that a total of 2,423 flights were launched and 2,397 missions were completed during 2015 and 2016, which was the mission with the most valid data of all missions. It was named route 1 as the research object. In order to meet the need of later digitized data, the preset flight path of route 1 was divided into four parts, represented by points A to D, the system's preset flight path data was derived, and the schematic diagram of the preset flight path was input into the computer.

Schematic diagram of flight route is shown in Figure 1. The circle near Point A is the launch point, and the preset flight route is designed from point A to Point D in a clockwise direction.

A total of 2397 valid flight data of route 1 were collected through the UAV flight control system, and the preset flight path and a large amount of historical flight trajectory data were obtained and presented in the form of longitude and latitude coordinates.

![Figure 1. Diagram of flight path of route 1 for the preset.](image)

3.2. Conversion of latitude and longitude coordinates to polar coordinates
Import latitude and longitude coordinates into the conversion tool to convert them to polar coordinates, the transformation interface is shown in Figure 2. In the figure, "starting point" is the latitude and longitude coordinates of the take-off point, and "end point" is the latitude and longitude coordinates of each feedback point on the flight path. After correcting the magnetic difference, the distance and magnetic direction relative to the starting position can be converted. Thus, the polar coordinate data of each feedback position point on the flight path and trajectory relative to the liftoff point are obtained.

![Figure 2. Coordinate data conversion tool interface.](image)

Export polar coordinates converted by the conversion tool to Excel in batch and open them with CAD. Use plot point imaging editor to display the preset flight path of route 1 and a large number of historical flight trajectory curves. Due to the overlap of flight data, sections A to C are selected as examples for the convenience of data analysis. The typical historical trajectory is screened and the total historical trajectory diagram of effective flight data is drawn.

3.3. Determine the apogee position of the historical trajectory

After obtaining the schematic diagram of the total historical track, set the interception interval to profile the preset flight path. Capture the distance between the preset flight path and the historical track in each section. The interception interval can be determined according to the precision requirements of the output data, every 50 meters is used as an interception interval in the experiment. Through profiling, the actual position of a historical track at each interception point is obtained. If the actual position does not overlap with the preset flight path and there is a distance, the distance is the yaw distance between the current flight path under the section and the preset flight path. All historical trajectories are profiled, and the distance between all actual positions and the preset flight path is found under the same section to obtain the maximum value, that is, the maximum yaw distance under a section on one side of the preset flight path. Connect the maximum yaw distance under all sections on both sides of the preset flight path in turn. Recreate the boundary to produce the farthest yaw curve under each profile on either side of the preset flight path. The preset flight path, total historical track and each intercept point are shown in Figure 3. The coordinate axis is in meters.
Figure 3. Diagram of flight paths coverage areas of route 1 from section A to C.

As can be seen from Figure 3, in section A to C of route 1, intercepts every 50 meters along the direction of the preset flight path and recreates the boundary. The gray part of the figure is the coverage area of the total historical track. The black points at the edge of the coverage area are the most distant actual points under each section. Connect all the black points in turn to obtain the yaw curve of each section on both sides of the preset flight path under the current experimental data. The area enclosed by this curve is the coverage area of the total historical track.

3.4. Yaw curves are digitized and sorted

Set the preset flight path as X-axis, and set the yaw curve on both sides as Y-axis to draw respectively and save them in graphic format. We use Origin's Digitize function to digitize the yaw curve after drawing and convert it into data in the form of X and Y coordinate axes.

The steps are as follows: Open the obtained yaw curve boundary diagram in Origin. Select linear coordinates of X and Y coordinate axes as the output result. In the yaw curve, take any two points a and b to represent the distances X1 and X2 relative to the take-off starting point on the preset flight path. Then, by using the distance Y1 and Y2 of these two points on the yaw range curve, any points a (X1, Y1) and b (X2, Y2) on the X and Y axes can be obtained as the reference points of curve digitization. According to further analysis in Figure 3, the extreme value of yaw and the position where the extreme value appears are obtained. The yaw extreme value data along the left side of the track direction and the fragment information of each position point in Origin are shown in Figure 4 and Table 1, where X axis is along the track(in meters), Y axis is yaw distance along the left side of the track(in meters).

As can be seen from Figure 4, the extreme yaw value of section A to C of flight route 1 is 6.13 meters, which appears at the left side 5200 meters along the track direction, that is, near the turning point of section B.

3.5. Bubble-Sort to find extreme values

The yaw curve of the whole sections of flight route 1 was analyzed digitally. Take Y value and use Bubble-Sort to edit computer code and Sort to find extreme value. The corresponding X-axis value is found through the extreme value of Y-axis, so as to obtain the exact position where the extreme value appears on the track. The flow chart is shown in Figure 5.

According to the computer, the extreme Y-axis values of the yaw curve on both sides at each stage of flight route 1 are obtained. As shown in Table 2, the negative value of Y is the left side along the track direction. The performance research of civil aircraft is based on conservative data, and 6.13m is finally selected as the maximum unilateral yaw of the actual flight trajectory under the experimental data.
Figure 4. The range of the extreme deviation of the image in Origin.

Table 1. Coordinate axis data of the range for the primary extreme deviation.

| Flight route 1 | serial number | X axis | Y axis |
|---------------|---------------|--------|--------|
| Near turning point B | 1 | 5050 | 1.862113 |
| | 2 | 5100 | 3.221624 |
| | 3 | 5150 | 4.211253 |
| | 4 | 5200 | 6.130261 |
| | 5 | 5250 | 4.021357 |
| | 6 | 5300 | 4.030551 |
| | 7 | 5350 | 4.223186 |
| | 8 | 5400 | 4.423177 |
| | 9 | 5450 | 3.670408 |
| | 10 | 5500 | 4.125842 |
| …… | …… | …… | …… |

Figure 5. Flowchart of the Bubble-Sort.

4. Protection Area Design

The 8168 sets several different values for $BV$ for reference in different flight stages and types, but there are no assignment settings for the UAV. $BV$ will be adjusted annually by ICAO experts. Based on the analysis of historical flight paths that have been implemented around the world, the trend is to reduce the $BV$ value year by year, to reduce the safety margin in the design specification, to improve flight efficiency on the premise of ensuring flight safety.
According to the statistics of several $BV$ values in the regulation and the analysis of $T$, $L$ and $P$ values output by computer data, it is found that in the airspace within the radius of 55.56KM (38NM) of the liftoff point, $BV$ is always between 0.5 and 1 times, and value of the UAV section protection area is set as 1 times of $XTT$\cite{11}.

According to the interpretation of 8168 regulation, more yaw influencing factors can be obtained by substituting the experimental data for calculation. The formula of route protection zone changes as follows:

\begin{equation}
XTT = \sqrt{NSE^2 + FTE^2 + PDE^2}
\end{equation}

\begin{equation}
AW = 2\left(1.5\sqrt{NSE^2 + FTE^2 + PDE^2} + BV\right)
\end{equation}

Where, $NSE$ is the navigation system error, $FTE$ is the flight technology error, and $PDE$ is the defining the track error.

Based on the current experimental data, the navigation accuracy error provided by the manufacturer is 5 meters, autonomous flying UAV do not have flight technology tolerance, then the maximum yaw value generated by the actual flight trajectory should be generated by the remaining influencing factors. The yaw extreme value obtained above and the above experimental data are used for calculation. The preliminary design specification is as follows:

It is calculated that the half width of the UAV flight path protection area is 15.325 meters, which is about 16 meters, $AW$ is 32 meters, $NSE$ is 5 meters, $PDE$ is 3.72 meters, and the values of $XTT$ and $BV$ are both 6.13m.

5. Test Flight Verification
Establish test flight verification based on preliminary design specifications. The circular mountain area with a radius of 5 kilometers is selected for terrain monitoring. A total of 9 verification aircraft of the same type were used in the task, 3 in a group and 3 in total. Each group takes off at the same time and flies a different route, The take-off interval of the same route verification aircraft is tentatively fixed as 10 times of the lateral interval, that is, the flying distance at the average flight speed of about 60 seconds, so the take-off interval of different groups of verification aircraft is 60 seconds. According to the preliminary design specification, the width of track protection zone is preset, and the lateral spacing of two verification aircraft is set as 32 meters. Considering the safety margin, no additional transition areas outside the boundaries of each protection zone of the verification aircraft are added. The flight speed is set according to the average speed. It is estimated that the average time of stagnation of single aircraft is about 45-60 minutes, which meets the requirements of battery and continuous flight regulations.

The verification results show that the analysis of the flight track data sent back by the flight control does not appear that the lateral distance between two aircraft is less than 16 meters. The preset scheme of experimental verification and actual operation results are shown in Table 3, and the flight trajectory imaging of the aircraft is shown in Figure 6. At the same time, due to the application of the interval setting of the preliminary design specification, the same group of aircraft can be launched simultaneously. There are multiple aircraft performing tasks simultaneously in the unit airspace. The total flight time from the first group to the last group is 2.4 hours, which is much lower than the current flight mission without the use of protected areas. It takes 6 hours for the single aircraft to take off and land successively, and the flight efficiency is greatly improved.

As can be seen from Figure 6, in the trajectory data imaging of the flight control return, circles are the lift-off points of each group of verifiers. The three aircraft of the first group take off on the flight route of the west side, similarly, the second group and the third group fly on the flight route of the east side and the south side. The width of both sides of the nominal track, is preset to 32 meters, which is equal to the sum of the respective lateral intervals between two aircraft[11]. After further study, digital analysis using trajectory imaging curve found that, large short-time crosswinds may be
encountered at turning 16 and 18 of the western flight route. The west task aircraft of the first group has a relatively large position deviation in a very short time at the turn, the minimum lateral interval is 25.87 m, but still within 16 meters of the reserve. Had no effect on the results. At the same time, this detail also indicates that further research on the factors affecting the width of the reserve will be the focus in the future[12]. The actual trajectory data is imported into GOOGLE Map imaging, and the lateral minimum interval time at turning 16 and 18 of the west flight path is shown in Figure 7.

Table 2. The extremum of Y axis for the route 1 flight paths of deviation curve at each phase.

| Task No. | Node scope | + Y value (in meters) | - Y value (in meters) |
|----------|------------|-----------------------|-----------------------|
| Flight route 1 | A to B | 6.101483 | 6.030636 |
| | B to C | 5.988912 | 6.130261 |
| | C to D | 6.081013 | 5.972148 |
| | D to A | 6.072354 | 5.992353 |

Figure 6. Chart of the flight test.

Figure 7. Lateral minimum distance at the west side of the flight routes.

6. Summary
The ICAO regulation 8168 is interpreted as: It can effectively guarantee the safety of flight missions and aircraft. The remaining airspace of the current flight mission protection zone is not included, so additional flight missions can be reallocated to make rational use of the airspace to reduce air flight conflicts and meet the requirement that the collision probability is no more than 10^-7. Subsequent studies should focus on the influencing factors of the UAV flight path protection zone along the track direction. Based on the results of further experiments, the design specifications of UAV flight path protection zone under a variety of navigation accuracy should be refined. The supervision of airspace structure will be strengthened in the future faced with various ways and restrictions of airspace use, the diversity of flight route planning in unit airspace is particularly important. Based on experimental data and computer imaging, this paper sets up the flight path protection zone and determines the flight area and yaw range required by the current flight mission by relying on the flight control return track data, combining the navigation accuracy and preset flight path. Through the test flight verification, the preliminary specification for UAV flight path protection zone design is proposed for the first time,
which has reference value for enhancing the safe and efficient flight route planning and design in the unit airspace.

**Table 3.** The result of the presupposition and Practice plan.

| The default package | Actual operating results |
|---------------------|--------------------------|
| Number of aircraft  | 9 plane                  |
| Preset flight path  | 3 lines                  |
| Protection zone half width | 16.00 m            |
| Horizontal interval | 32.00 m                  |
| Total west flight path length | 35.00 km            |
| Total length of east flight route | 20.00 km    |
| Total length of south flight path | 17.00 km    |
| Rated flight speed  | 1 to 10 m/s              |
| Average latency per flight | 45 to 60 minutes |
| Number of aircraft to complete the mission | 9 plane |
| Complete flight path | 3 lines                  |
| Protection zone half width | 16.00 米             |
| Actual horizontal interval/occurrence position | 25.87 m/west route, turning 16, 18 |
| Average length of flight path on the west side | 36.27 km |
| Average length of flight path on the east side | 20.86 km |
| Average length of flight path on the south side | 17.41 km |
| Actual average flight speed | 7.5 m/s |
| Average latency per flight | 54 minutes |

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