Identification of Key Conflict Nodes Based on Complex Network Theory

Li Jiawei\(^*\), Wen Xiangxi\(^1\), Zhang Libiao\(^1\) and Liu Fei\(^1\)

\(^1\)Air Control and Navigation College, Air Force Engineering University Xi’an, China

\(^*\)Email: Jiaweilee036@gmail.com

Abstract. The current methods of detecting flight conflicts are difficult to grasp the overall conflict situation in the air, which is not conducive to the controllers to make accurate judgment on different conflict situations. In this paper, a method to identify key nodes of flight conflict based on complex network theory is proposed. Firstly, a conflict situation network model was built based on the ACAS protection area model. Then node degree centrality, closeness centrality and PageRank were used to evaluate the comprehensive importance of all nodes in the conflict situation network by AHP method. And we can find out the key conflict locations and conflict aircrafts based on the evaluation results of the index. The simulation results show that the model can effectively identify the key conflict aircrafts and positions in the airspace. And It can help controllers fully grasp the air security situation by classifying the air conflict situation levels.

1. Introduction

At present, with the rapid development of China's aviation industry, air traffic flow is increasing. Air collision defense is becoming more urgent. How to effectively mediate the air conflict between aircraft and reduce the probability of flight conflict has become an urgent problem to be solved.

In recent years, domestic and foreign scholars have conducted a large number of studies on this problem: HAN Dong et al [1]. used SVM classification learning to solve the problem of conflict detection and relief in air traffic control. Krozel et al[2] used the optimal control theory to propose a method for conflict detection and relief of two aircraft in free flight. LIU Xin et al.[3] used vector method to construct the information conflict detection method based on ads-b technology for the detection of two aircraft conflicts. Liu Yang et al.[4] took low altitude as the research object and constructed the low altitude conflict detection algorithm under the condition of free flight. Most of the above research methods focus on a small number of aircraft. And there is a big gap between them and the actual airspace operation. So it is impossible to comprehensively grasp the flight conflict situation in the complex airspace. In addition, when these methods are used for conflict judgment, all aircrafts in the airspace need to be pairwise judged, and the calculation process is complex.

To improve these problems, this paper converts the conflict relationship between the aircraft to the relationship between network nodes, build a conflict situation network model based on the ACAS flight reserve. And on the basis of the model, we built node comprehensive evaluation index to identify key conflict nodes. It can realize the key conflict nodes in conflict situation network selection. We hoped that this method can quickly find out the aircraft with high conflict level and the conflict location in the airspace, so as to provide information for the air controller to quickly grasp the status of conflict in the airspace.
2. Construction of conflict situation network model

In this paper, the ACAS flight protection area is selected as the criterion for conflict determination. And the conflict situation in the air is abstracted into a complex network.

2.1. Model construction of ACAS flight reserve

ACAS is a device that detects and retrieves the surrounding aircraft, issues queries to the aircraft that may be at risk of invasion.[5]. The detection range of the ACAS antenna is usually set at 15-30 nautical miles in front and 3 kilometers in the longitudinal direction. In this case, ellipsoid conservation area model is usually adopted to establish the flight conservation area model of a single aircraft under the ACAS system. Determine whether the two aircraft there is a conflict or potential conflict rule is: when the horizontal distance is less than the minimum interval standard 10 km, and the vertical distance is less than the minimum vertical interval standard 0.3 km. When the horizontal interval is more than 10 km and less than 15 km, said the potential conflicts between the two aircraft. On the basis of this, the established protected area model is shown in Figure 1.

\begin{equation}
\left( \frac{x-x_0-m}{a^2} \right)^2 + \left( \frac{y-y_0-n}{b^2} \right)^2 + \left( \frac{z-z_0}{c^2} \right)^2 \leq 1
\end{equation}

In the conflict domain equation, offset m and n are introduced. The model also divides the detection levels into the protection zone. It takes the 15 km range of the protection zone as the limit to judge the invasion level according to the invasion distance of the two aircraft. The greater the invasion distance is, the higher the corresponding conflict level will be. At this time, ACAS will make corresponding anti-collision warning or countermeasures.

2.2. Construction of Flight Conflict Network

By building the model of a single aircraft flight protection zone, we can abstract the conflict situation in the airspace into a complex network[6]. Each aircraft is regarded as a node in the network. If there are aircraft intruding into each other's protection zone, there will be an edge between the two nodes. As shown in Figure 2, there are four conflict nodes in the airspace, which are $v_1, v_2, v_3, v_4$. 
Figure 2. Conflict Network Corresponding to Scenarios of Figure 1.

In conflict detection based on ACAS protection zone, the horizontal and vertical spacing between aircraft plays a critical role in aircraft conflict detection. Therefore, we introduce collision edge weights [7] to reflect the influence of two kinds of spacers on the network, and construct the flight conflict weighting network. In Figure 3, when the two aircraft intrude into the protected area, the edge right of the generated conflict is $\omega_{ij}$. According to the fact that the closer the distance between two aircraft is, the greater the probability of conflict between them is, the edge weight designed in Figure 3. Where $d_{LA}$ represents the horizontal distance of the two aircraft from which the invasion occurred, and $d_{LO}$ represents the vertical distance.

$$\omega_{ij} = \frac{1}{d_{LA}} + \frac{1}{d_{LO}}$$

Figure 3. Edge weight setting.

The conflict situation in airspace is abstracted as a weighted network. The network can be expressed in the form of the weighting adjacency matrix. For example, the conflict situation weighted network shown in Figure 2 can be expressed as:

$$Q' = \begin{bmatrix}
0 & 0.39 & 0 & 0 \\
0.39 & 0 & 0.65 & 0 \\
0 & 0.65 & 0 & 0.51 \\
0 & 0 & 0.51 & 0
\end{bmatrix} \quad (2)$$

3. Key Conflict Nodes Identification Method

In the conflict situation network, a few aircraft play the role of ‘key nodes’, they can have a key impact on the robustness of the conflict network. For air traffic management activities, the deployment of these key aircraft nodes can quickly alleviate air traffic congestion. How to find out these key conflict nodes accurately is the key problem to be solved in this paper.

3.1. Selection of Evaluation Indicators for Node Importance

In order to effectively evaluate the status of each aircraft node in the entire conflict situation network, we select some indicators to evaluate it. In the selection of indicators, the following factors are mainly considered: 1) the selected indicators can reflect the characteristics of the nodes. 2) the selected indicators can reflect the role of nodes in the network. 3) the selected index can reflect the relationship between nodes and other nodes. Therefore, we selected node degree, near-centrality and PageRank value as evaluation indicators.
**Definition 1** Degree Centrality

The ratio of the number of edges associated with node \( i \) to the maximum number of edges that node \( i \) may have. The expression for degree centrality is:

\[
DC_i = \frac{k_i}{N-1}
\]

(3)

Where \( k_i \) represents the number of edges associated with node \( i \) in the network. The definition of degree centrality indicates the ability of a node to directly associate with other nodes.[8-9] The larger the value, the greater the role it plays in the network. Corresponding to the flight conflict network, the index focuses on reflecting the extent and influence of conflict spread of the aircraft itself.

**Definition 2** Closeness Centrality

Assuming that \( d_{ij} \) represents the number of edges contained in the shortest path with node \( i \) as the starting node and \( j \) as the ending node, the proximity centrality of node \( i \) can be expressed as the reciprocal of the sum of its distances to all other nodes in the network, namely:

\[
CC_i = \frac{N}{\sum_{j=1}^{N} d_{ij}}
\]

(4)

The greater the value of the closeness centrality, the greater the degree of the node in the center of the network, and the more important it is.[10-11] This index can effectively identify aircraft in the core zone of conflict.

**Definition 3** PageRank

PageRank method is realized through a similar voting method. If a node obtains a higher score (weight), the higher the value of the node, and its weight calculation expression is:

\[
Pr(A) = Pr(A) / C(B) + Pr(C) / C(C) + \cdots
\]

(5)

Where, \( Pr(A) \) represents the updated weight value of node A, \( Pr(B) \), \( Pr(C) \) represents the weight value assigned to A by all other nodes connected to node A, and \( C(B) \) and \( C(C) \) represent the number of outlinks of node B and C [12]. This index can effectively identify the important conflict nodes by combining the conflict distance edge weight in airspace conflict situation network.

### 3.2. Evaluation of Node Importance Based on AHP

In this paper, we adopted AHP method to determine the index weight and construct the comprehensive evaluation index for identifying key conflict nodes. This method has low computational complexity and strong systematicness. It can better show the influence of each index on the whole. Among the selected indexes, the PageRank takes into account the connection condition and distance of nodes comprehensively. Here we consider it as the most important, followed by the degree of nodes.

Obtaining a judgment matrix \( A \):

\[
A = \begin{bmatrix}
1 & 3 & 5 \\
1/3 & 1 & 3 \\
1/5 & 1/3 & 1 \\
\end{bmatrix}
\]

(6)

The corresponding eigenvector \( \omega \) of the maximum eigenroot \( \lambda_{\text{max}} \) is calculated and normalized to obtain the weight vector:

\[
W = [W_1, W_2, W_3] = [0.6370, 0.2583, 0.1047]
\]

(7)

Carry out consistency check and calculate the maximum eigenvalue:

\[
\lambda_{\text{max}} = \frac{\sum a_{ij}W_j}{\sum W_i} = 3.0385
\]

(8)

The consistency index \( CI \) is:

\[
CI = \frac{\lambda_{\text{max}} - n}{n-1} = 0.0192
\]

(9)
Consistency specific gravity $CR$ is:

$$CR = \frac{\left(\lambda_{max} - n\right) / (n-1)}{RI} = 0.0370 < 0.1$$

(10)

Where $RI$ is a random consistency index, when $n = 3$, $RI$ is 0.58. This judgment matrix satisfies the consistency test.

In order to eliminate the order of magnitude difference among the three indicators, the maximum and minimum normalization method is adopted:

$$DC_i = \frac{DC(v) - \min DC(v)}{\max DC(v) - \min DC(v)}$$

(11)

The node importance comprehensive evaluation $P_i$ result is obtained:

$$P_i = 0.6370 \times Pr + 0.2583 \times DC_i + 0.1047 \times CC_i$$

(12)

4. Key Conflict Node Identification Process

Through the description in the first three sections, the key conflict node identification process of the training airspace conflict situation network established in this paper is presented as shown in Figure 4.

The identification of key conflict nodes in conflict situation network mainly consists of three parts: data acquisition, construction of conflict situation network, and evaluation and identification of key conflict nodes.

Part I: Data acquisition, collection of real-time flight parameters of all aircraft in the current airspace, including flight speed, space coordinate position, etc.

Part II: Construction of flight conflict network. On the basis of the acquired aircraft flight data and the ACAS protection area of each aircraft, the connection and edge weight between nodes are determined to construct the conflict network.

Part III: identification of key conflict nodes. The degree centrality, closeness centrality and PageRank were used to evaluate the importance of each node in the conflict situation network and identify the key conflict nodes.

5. Experimental analysis

In this paper, Matlab is used to generate an appropriate number of node sets in three-dimensional space to simulate the space position of aircraft in normal flight. It is assumed that the airspace range is a space with a length and width of 400 km and a height of 1500 m. In Figure 5, there are 50 aircrafts in the airspace.
According to the position relationship of all aircraft in the airspace, the conflict situation network model in the airspace is constructed according to the ACAS flight protection zone model, as shown in Figure 6.

On the basis of the airspace conflict situation network, we respectively analyzed the degree, closeness centrality and PageRank value of the network. And the comprehensive importance evaluation $P_i$ value through AHP were obtained. The results are shown in Table.1.

| Aircraft number | Degree Centrality | Closeness Centrality | PageRank | $P_i$ |
|-----------------|-------------------|----------------------|----------|------|
| A1              | -                 | -                    | -        | -    |
| A2              | 0.2857            | 0.4401               | 0.1421   | 0.3105 |
| A3              | -                 | -                    | -        | -    |
| A4              | 0.4286            | 0.9940               | 0.1977   | 0.5505 |
| A5              | 0.1000            | 0.0844               | 0.0561   | 0.0913 |
| A6              | -                 | -                    | -        | -    |
| A7              | -                 | -                    | -        | -    |
| A8              | 0.3000            | 0.9172               | 0.1402   | 0.4426 |
| A9              | 0.2000            | 0.4910               | 0.0950   | 0.2642 |
| A10             | 0.1423            | 0.0001               | 0.0791   | 0.0990 |
| ...             | ...               | ...                  | ...      | ...  |
| A20             | 0.3000            | 0.5893               | 0.1270   | 0.3566 |

In Table.1, each nodes’ the conflict situation was evaluated. There are some nodes lacking importance evaluation index values. Because they are not the nodes in a conflict situation network. Their importance evaluation indexes can not be calculate. We found that one node that has a high value of index may not the important node. We also need to combine the results of the other two indexes to

![Figure 5. Simulation training airspace state.](image)

![Figure 6. Construction of flight conflict network.](image)
draw a conclusion. According the values of $P$, we choose the top 10 conflict nodes as the key conflict nodes, which can be used as the focus of flight conflict adjustment. The results are shown in Figure 7:

![Figure 7. Identification results of key collision nodes.](image)

In Figure 7, there are ten key conflict points with high conflict situation level in the conflict situation network. They are node 4, 8, 12, 20, 27, 33, 34, 41, 44 and 46. Nodes of the comprehensive evaluation of node 33 is 0.8925. It is the highest of all nodes’ $P_i$. It can be seen that there are three key position around node 33. And the number of aircraft with the adjacent has four. Although No.4 aircraft did not identify the conflict in current, but can be used as a potential conflict object. In addition, No.33 aircraft’s local conflicts situation is very complex. The local density is big. We need to focus on. These key conflict nodes often conflict with multiple aircraft and require the attention and priority of controllers. Through the construction of conflict network, this paper effectively avoids the repeated conflict judgment between two aircrafts in the airspace. and reduces the complexity of controller conflict detection in the complex airspace with a large number of aircrafts. In particular, the identification method of key conflict points can provide controllers with high-value conflict situation information. And it assists them to make reasonable deployment plans according to different conflict levels.

6. Conclusion
Firstly, this paper netted the aircrafts with conflicts and potential conflicts in the airspace and constructed the airspace conflict situation network model based on the ACAS conservation area model. Then, the AHP method was used to construct the evaluation index of node comprehensive importance by using three key node identification indexes of degree centrality, closeness centrality and PageRank. The key conflict nodes in the simulated airspace situation network were found out. And the conflict situation in the airspace is classified according to the index. The experimental results show that the nodes with higher conflict level are surrounded by multiple additional conflict nodes. The location change of the core conflict aircrafts will have a great influence on the local conflict network. By providing air traffic controllers with conflict situations in the airspace, the method optimizes their attention distribution and provides assistance for the formulation of targeted conflict resolution schemes quickly and efficiently.

References
[1] Han D, Zhang X, Nie Z, et al, A conflict detection algorithm for low-altitude flights based on SVM, Journal of Beijing University of Aeronautics & Astronautics, 2018.
[2] Krozel, J., & Peters, M., Conflict detection and resolution for free flight, Air Traffic Control Quarterly, 5(1997) 181-212.
[3] Liu X, Yang X P, Tian S J, et al, Flight collision detection algorithm based on ADS-B information spherical model, Transducer & Microsystem Technologies, 6 2017) 1-15.
[4] Liu Y, Xiang J W, Luo Z P, et al, Short - term Conflict Detection Algorithm for Low - altitude Free Flight, Journal of Beijing University of Aeronautics and Astronautics, 43(2017) 1873-1881.

[5] Jeannin J B, Ghorbal K, Kouskoulas Y, et al, A formally verified hybrid system for safe advisories in the next-generation airborne collision avoidance system, International Journal on Software Tools for Technology Transfer, 230(2015) 1-25.

[6] Newman, M. E., Mathematics of networks. The new Palgrave dictionary of economics, 23 (2016) 1-8.

[7] Muldoon, S. F., Bridgeford, E. W., Bassett, D. S., Small-world propensity and weighted brain networks, Scientific reports, 6 (2016) 22057.

[8] Lü, L., Chen, D., Ren, X. L., Zhang, Q. M., et al, Vital nodes identification in complex networks, Physics Reports, 650(2016) 1-63.

[9] Liu, Y., Wei, B., Du, Y., Xiao, F., & Deng, Y, Identifying influential spreaders by weight degree centrality in complex networks, Chaos, Solitons & Fractals, 86(2016) 1-7.

[10] Du, Y., Gao, C., Chen, X., Hu, Y., et al, A new closeness centrality measure via effective distance in complex networks, Chaos: An Interdisciplinary Journal of Nonlinear Science, 25(2015) 033112.

[11] Park, M., Lee, S. H., Kwon, O. M., & Seuret, A., Closeness-centrality-based synchronization criteria for complex dynamical networks with interval time-varying coupling delays, IEEE transactions on cybernetics, 48(2018) 2192-2202.

[12] Ishii, H., & Suzuki, A. Distributed Randomized Algorithms for PageRank Computation: Recent Advances, In Uncertainty in Complex Networked Systems, Birkhäuser, Cham (2018) 419-447.