A conflict detection and resolution approach for military aircraft passing through airlines

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Abstract. Aiming at solving the conflict of military aircraft passing through airlines, after modeling and analyzing the scenario that aircraft flows fly to converge, a conflict detection and resolution approach is proposed. When the aircraft flow enters the pre-designated control zone, the conflict in the forward looking time is determined by a ‘sliding detection window’, which moves with the military aircraft. After analyzing resolution boundary condition, a conflict resolution model is established. In this way, the avoidance action, heading and speed change maneuvering, would not cause the domino effect. The analytical mathematics result has shown the viability.

1. Introduction

In recent years, with the rapid growth of civil aviation traffic volume and the heavy military aviation training tasks, the collision avoidance work within civil and military aviation has attracted more and more attention. Once some special circumstances happen, such as fighter ferry flights, major military maneuver tasks, long-distance training over the open sea, and even the use of airspace in the wartime, the aircraft conflict probability will greatly increase while military aircraft fly through the airline. At present, the military aircraft usually cross the routes on prearranged fixed crossing zones. There are many shortcomings in the above methods: 1. Involving air traffic controllers of both sides is easy to make mistakes; 2. It has poor flexibility to suit high-intensity air combat; 3. The efficiency is low to meet the request of ‘safe and efficient’ in air traffic management (ATM).

The conflict detection and resolution in the scenario of aircraft flow passing through the air route is a complex systems engineering, which involves some knowledge including traffic flow theory, safety assessment and conflict detection and resolution (CD&R) techniques. In the study of aircraft flow model: Zhi-Hong Mao and others[1-3] analyzed the stability of intersecting aircraft flow using offset model and heading change maneuvers resolution, and found that this method has strong robustness and does not produce domino effect, and proposed a compact aircraft flow crossing air route method. Troy Hand[4] discusses the effect of sequential conflict resolution maneuvers of an infinite aircraft flow through a finite control volume. Kyle Treleaven[5] proposes a general framework to study the conflict resolution for multiple intersecting flows of aircraft in planar airspace. Ahmed H. Dallal[6] uses Lyapunov analysis to analytically prove the convergence of conflict resolution dynamics under the proposed rule. Their researches laid the foundation for this problem.

In this paper, we propose a conflict detection method based on sliding detection windows to group potential conflict aircraft. By adjusting the aircraft weight, civil aviation aircraft will assist in avoidance at a lower cost, while military aircraft will maneuver at a higher maneuvering. Moreover, we put a mathematical statement of resolution boundary constraint to ensure the safety. We hope to
improve the operational efficiency of military aircraft crossing the route.

2.Conflict detection model in intersecting aircraft flow

2.1 Sliding detection window model

Air traffic controllers usually identify conflicts by comparing the two-aircraft interval with the safety interval, but in CD&R problem, protected zones should be established for accuracy. Since the flight height has been prearranged, the conflicts in height are beyond considerations. Thus, protected zone is simplified to a circle of radius $a$ as shown in figure 1. According to the safety interval standard, the radius of the protected zone is 2.5 nm. If the protection zones of a pair of aircraft overlap, there will be a conflict.

Military aircraft fly in a straight formation, while civil aircraft fly over an air route with a width of $L' = 20$ km. A control zone can be set up in any route to be crossed. When the aircraft flow enters the control zone, the military aircraft projects a rectangular ‘sliding detection window’ (a rectangular shaded area) with a width of $a$ (equal to the radius of the protected zone) along the protected zone, and it moves (translates) with the aircraft. If the detection window overlaps with the protected zone of civil aircraft, there will be a conflict when the pair of aircraft reaches the intersection.

Military aircraft avoid conflicts by heading change and speed adjusting. At this time, the detection window also moves (rotates) with the aircraft. The conflict detection scenario can be shown in figure 2.

Figure 1. Protected zone  
Figure 2. Conflict detection scenario

For observing clearly, the aircraft are magnified in figure 2 and do not maneuver after entering the control zone. In particular, when the velocity magnitudes of two aircraft flow are equal, the angle between the sliding detection window and the aircraft flow is 45°. The radius $R$ of the control zone is determined by the radius of the protected zone, the velocity of the aircraft and the maneuverability of the aircraft. According to the above analysis, the potential conflict relationship between the aircraft in figure 2 can be described in figure 3.

In figure 3, the hollow circle represents the military aircraft, the solid circle represents the civil aircraft, and the dashed lines represent the potential conflict relationship. It can be seen that there is no conflict within the same category aircraft, and conflicts between military and civil aircraft can take many forms, such as ‘one-to-one’, ‘many-to-one’, ‘one-to-many’ and ‘many-to-many’.

2.2 Conflict orientation analysis

As can be seen from Figure 2, the position relationship between the two aircraft while a conflict existing can be divided into two cases in figure 4:
In figure 4, the solid line is the projection of the aircraft AC1’s protected zone and the dashed line is the projection of the aircraft AC2’s protected zone. Although there are conflicts in both cases, the positions between the two aircraft are slightly different: In figure 4 (a), the right boundary of the two aircraft’s protected zone projects cross the other aircraft’s protected zone, and there is a conflict on the right side. If the aircraft maneuvers to the left side in the direction of the dashed line (optimal maneuver direction), it can be quickly avoid the conflict; In figure 4 (b), the left boundary of the two aircraft’s protected zone projects cross the other aircraft’s protected zone, and there is a left conflict. Right side is the optimal maneuver direction.

If there are conflicts on both sides, the longest distance from the aircraft on both sides to the long edge of the sliding detection window should be examined:

\[
\text{Direction} = \begin{cases} 
1 & d_{l,\text{max}} > d_{r,\text{max}} \\
0 & d_{l,\text{max}} = d_{r,\text{max}} \\
-1 & d_{l,\text{max}} < d_{r,\text{max}} 
\end{cases}
\]

(1)

where direction is the optimal maneuver direction, 1 corresponds to a left turn, 1 corresponds to a right turn, and 0 corresponds to no maneuver. \(d_{l,\text{max}}\) (\(d_{r,\text{max}}\)) is the longest distance to the long edge of the detection window in the set of left (right) touch’s aircraft. The aircraft pays the least maneuvering cost if they fly in the optimal maneuvering direction.

With the best maneuver direction, the airplane.

3.Conflict resolution model

3.1 Resolution strategies and objective function

Because changing altitudes makes the problem more complicated, the heading and speed change strategies are selected in this paper.

a) Heading changes: Civil aircraft are required to not make heading maneuver; The military aircraft’s heading changes range is \([-20^\circ, 20^\circ]\), and the change range is discretized as a set of strategies with a difference of \(5^\circ\).

b) Speed changes: Assume the military and civil aircraft can speed up/down 10%, 20% and 30%.

After a maneuver, if the civil aircraft leave the new detection windows, it is considered that the resolution is successful. Military and civil aircraft maintained their current flight posture through the control zone, then military aircraft assemble according to the regulations, and civil aircraft adjust to previous speed.

The objective function is the avoidance cost of the aircraft in conflict resolution, and it is a function of the turn angle and speed. In this model, the objective function is expressed by the following formula:

\[
U(\theta, v) = k_1 \sum_{i=1}^{n} \int_{0}^{t_f} [w_1 \sin^2(\Delta \theta) + w_2 (\Delta v/\bar{v}_i)^2] dt,
\]

(2)

where \(t_0\) is the beginning time of the resolution; \(t_f\) is the time of leaving from the control zone.
\( \frac{\Delta v}{v_0} \) is the speed change ratio; \( \Delta \theta \) is the angle change; \( w_1 \) is the weight coefficient for angle change, and \( w_2 \) is the weight coefficient for speed; \( k_i \) is the weight coefficient for different aircraft categories.

### 3.2 Resolution boundary constraint

Equation (2) specifies the objective function. However, the aircraft that chooses not to avoid will pay the least avoidance cost. Therefore, in order to ensure flight safety, it is necessary to set constraints and eliminate the infeasible solutions in the strategies. We use the experience from heading change maneuvers resolution method in reference [1], introduce the situation that two aircraft arrive at different time, and extend it to the judgment of heading-speed maneuver resolution boundary. The schematic diagram of the model is shown in figure 5.

![Figure 5. Resolution boundary of two aircraft conflict](image)

At initial time \( t_0 \), aircraft \( AC_1 \) and \( AC_2 \) are at initial positions \( S_1 \) and \( S_2 \) with the speeds \( v \) and \( kv \). \( AC_1 \) is left \( AC_2 \) \( l \) behind from the initial positions to the collision point. The radius of the protected zone is \( a \), and there is a left touch between them. The sufficient conditions for successful resolution can be obtained from the following derivation:

In \( \angle OS_1 S_2 \):

\[
\frac{d(O, S_1) = d(O, S_2) = R}{\angle S_1 OS_2 = \theta} \Rightarrow d(S_1, S_2^{'}) = 2R \sin \frac{\theta}{2};
\]

After entering the control zone, the two aircraft turn right to avoid collision and the turn angles are \( \eta \) and \( \phi \) respectively. The intersection changes from \( O \) to \( O' \), and the track crossing angle changes from \( \theta \) to \( \theta' \):

\( \theta' = \theta + \phi - \eta \);

Assuming that the conflict resolution is accomplished at time \( t_1 \), \( AC_1 \) flies forward by distance \( s \) at point \( M \). If \( AC_2 \) is at point \( N \) or \( N' \), there will be no conflict. The sliding detection window can be shown in the Fig. 5. Let \( S_iQ || MP \) intersect \( O'S_2^{'}, \) at point \( Q \), then:

\[
\sin \beta = \frac{d(O', S_i) = d(O', Q)}{\angle QS_1Q';}
\]

Let \( d(O', S_i) = x \), then \( d(O', Q) = kx \), and the above formula can be denoted as:

\[
\frac{x}{\sin \beta} = \frac{kx}{\sin(\pi - \beta - \theta')};
\]

\[
\sin \beta = \sin \beta \cos \theta' + \cos \beta \sin \theta';
\]

The left and right sides of the formula are divided by \( \sin \beta \), then \( \tan \beta = \frac{\sin \theta'}{1 - \cos \theta'} = \cot \frac{\theta'}{2} \).
\[ \alpha = \beta + \theta + \frac{\varphi - \pi}{2} = \arctan(\cot \frac{\theta'}{2}) + \frac{\theta}{2} + \varphi - \frac{\pi}{2}; \]

Because \( P \) is the midpoint between \( N \) and \( N' \), then:
\[ d(N, P) = d(N', P) = \frac{a}{\sin \beta} = \frac{a}{\sin[\arctan(\cot \frac{\theta'}{2})]}; \]

At this time, \( AC2 \) is at the edge of the detection window and maintains safety separation exactly:
\[ r_1 = d(S_2', P) - d(N, P) \quad \text{(3)} \]
\[ \text{or} \quad r_2 = d(S_2', P) + d(N', P) \quad \text{(4)} \]

In order to find out \( d(S_2', P) \), according to the sine theorem:
\[ \frac{d(S_2', Q)}{\sin \alpha} = \frac{d(S_1, S_2')}{\sin(\pi - \beta)}; \]
\[ d(S_2', Q) = d(S_1, S_2') \frac{\sin \alpha}{\sin \beta} \]
\[ = -2R \sin \frac{\theta}{2} \left[ \cos \beta \cos(\theta' + \varphi) - \sin \beta \sin \frac{\theta}{2} \right] \]
\[ = -2R \sin \frac{\theta}{2} \left[ \cot \beta \cos(\theta' + \varphi) - \sin \frac{\theta}{2} + \varphi \right] \]
\[ = -2R \sin \frac{\theta}{2} \left[ \tan \frac{\theta'}{2} \cos(\theta' + \varphi) - \sin \frac{\theta}{2} + \varphi \right] \]

Because of \( d(S_1, M) = s \), then
\[ d(Q, P) = ks, \]
\[ d(S_2', P) = d(S_2', Q) + ks \]
\[ = -2R \sin \frac{\theta}{2} \left[ \tan \frac{\theta'}{2} \cos(\theta' + \varphi) - \sin \frac{\theta}{2} + \varphi \right] + ks \quad \text{(5)} \]

Substitute Formula (5) into Formulas (3) and (4) to obtain the boundary condition for resolution:
\[ r_1 = -2R \sin \frac{\theta}{2} \left[ \tan \frac{\theta'}{2} \cos(\theta' + \varphi) - \sin \frac{\theta}{2} + \varphi \right] + ks + \frac{a}{\sin[\arctan(\cot \frac{\theta'}{2})]} \]
\[ r_2 = -2R \sin \frac{\theta}{2} \left[ \tan \frac{\theta'}{2} \cos(\theta' + \varphi) - \sin \frac{\theta}{2} + \varphi \right] + ks + \frac{a}{\sin[\arctan(\cot \frac{\theta'}{2})]} \]

To sum up, in the case of \( AC1 \) forward distance \( s \), as long as AC2 forward distance \( s' < r_1 + l \) or \( s' > r_2 + l \), there will be no conflict.

4. Conclusion

In this paper, the problem of aircraft passing through route is modeled and analyzed, and a detection model based on sliding window is proposed to group potential conflict aircraft, so that distributed resolution can effectively reduce the complexity of the algorithm. Furthermore, we calculate a boundary constraint for the solution meeting the requirement of safe interval. In the next period, we will analyze the influence of aircraft flow’s crossing angle, aircraft initial interval and control zone on the resolution condition. Ultimately, the general rules can be summarized.

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