An Aircraft Conflict Resolution Model Based on Geometric Optimization

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Abstract. A geometrically optimal conflict detection and resolution method was proposed to make up for the defect of current methods in engineering applications conflict resolution. Firstly, the conflict resolution point of the problem is defined, at which point the possible flight conflicts between aircrafts are predicted; Secondly, the same direction same angle (SDSA) is adopted to solve the flight conflict, that is, the two aircrafts turn the same angle to the same side at the same time on the original track to obtain a new track crossing point, namely a track recovery point. Thus the minimum separation between the two planes is always maintained. Finally, the simulation results show that the method is simple and efficient.

1. Introduction

In the air traffic control (ATC) operation, pilots usually determine the release method and track recovery time based on the suggestions and experience provided by the controllers. In this "human-in-the-loop" mode, the ATC operation efficiency is relatively low, which is not conducive to the pre-deployment of flight conflicts. Conflict detection and resolution (CD&R) is a key technology in the air traffic management system, which can give early warning and provide an efficient resolution scheme.

Aiming at the engineering application background, this paper focuses on the conflict resolution model based on geometric optimization method. Document [1] gives a path planning method for UAV autonomous obstacle avoidance by using the speed obstacle circular arc method. Document [2] proposes a geometric optimization method for aircraft conflict resolution by using the current position and velocity vector information of the aircraft, which can effectively fly conflicts only through course changes or velocity changes and minimize the deviation between the released trajectory and the nominal trajectory. The above research has a common disadvantage, that is, the solution obtained without considering the track recovery problem. Documents [3]-[5] pay attention to the problem of track recovery after liberation and redirect the plane to its original destination without causing new conflicts. Their research has considered the large-angle maneuver of a single plane to extricate flight conflicts. However, the flight course change is limited and it is difficult to resolve conflicts in many scenarios. Based on the reference to the relevant methods of flight conflict avoidance [6-9], this paper proposes a two-machine same direction same angle (SDSA) relief strategy.

2. Conflict model based on geometric optimization method
2.1 Model simplification
According to the characteristics of civil aviation flight and ATC operation, the model is simplified as follows:

- The plane flies at the same altitude in the course of cruising.
- Assuming that the aircraft was flying at a constant speed when the conflict was resolved.
- In order to avoid conflicts, they usually choose the geometrically optimal way to resolve conflicts, minimize the number of aircraft maneuvers.
- The aircraft safety protection zone is defined as 10 km.
- In this paper, the collision warning distance is set to $s = 100$ km.

2.2 Comparison of the effects of several relief methods
In order to prove the advantages of the proposed SDSA strategy over other release strategies. At first, we derived the relationship between the angle of double aircraft and avoidance cost based on the cost of distance:

![Figure 1. Congestion flight of two aircraft](image)

AC1 is flying from $S_1$ to $S_1'$, and AC2 is flying from $S_2$ to $S_2'$. In Figure 1, the dual-plane simultaneous right-turn heading avoidance strategy is adopted, with angles of $\beta$ and $\alpha$ respectively. They flew to their original destination when the two planes crossed the new track intersection. The distance between the two aircraft at the moment $t_0$ is exactly equal to the warning distance 100 km and the minimum safety separation $d = 10$ km. The distance from the starting point to the destination is $2R$ and the backward distance after heading change is equal to the minimum safety separation $d$.

During the whole conflict resolution process, the sum of the track distances of the two aircrafts:

$$L = S_1'O' + O'S_1' + S_2'O' + O'S_2'$$

New intersection angle:

$$\theta' = \theta + \alpha - \beta$$

$$\frac{S_1S_2}{\sin \theta} = \frac{S_1O}{\sin(\pi - \theta)} \iff \frac{s}{\sin \theta} = \frac{R}{\cos \theta} \iff R = \frac{s}{2 \sin \frac{\theta}{2}}$$

$$\frac{S_1S_2}{\sin \angle S_1O'S_2} = \frac{S_1O'}{\sin \angle S_1S_1'O'} \iff \frac{s}{\sin \theta'} = \frac{S_1O'}{\sin(\pi - \theta - \alpha)} \iff S_1O' = \frac{s \cos(\alpha + \frac{\theta}{2})}{\sin \theta'}$$
Thus:

\[(O'S'_1)^2 = (S'_1 O')^2 + (S_1 S'_1)^2 - 2 \cos \beta \cdot S'_1 O' \cdot S_1 S'_1 \implies O'S'_1 = \sqrt{\frac{s \cos(\beta + \frac{\theta}{2})}{\sin \theta}} \cdot \frac{4R^2 - 4R \cos \beta \cdot \frac{s \cos(\beta + \frac{\theta}{2})}{\sin \theta}}{2}
\]

(5)

Similarly:

\[S'_2 O' = \frac{s \cos(\beta - \frac{\theta}{2})}{\sin \theta'}
\]

(6)

\[O'S'_2 = \sqrt{\frac{s \cos\left(\beta - \frac{\theta}{2}\right)}{\sin \theta'}} + 4R^2 - 4R \cos \alpha \cdot \frac{s \cos(\beta - \frac{\theta}{2})}{\sin \theta'}
\]

(7)

\[
\frac{S_1 S_2}{\angle S_1 P S_2} = \frac{BP}{\angle S_1 S'_1 P} \implies \frac{s}{\cos \left(\frac{\theta + \alpha - \beta}{2}\right)} = \frac{d}{\sin \theta}
\]

(8)

Substitute equation (2) ~ (8) into equation (1), and the expression \(L\) can be obtained.

In this paper, the resolution strategy of turning right \(\alpha\) for AC2 and not maneuvering for AC1 is called single aircraft large angle release, as shown in Figure 2. (a); The resolution strategy turning right \(\beta\) for dual-aircraft is called same direction same angle (SDSA) release, as shown in Figure 2 (b); When the track intersection angle \(\theta\) is fixed, there must be two planes turning right at a certain angle, making the distance between the two aircraft from conflict identification to recovery of the original route the shortest, that is, the track at this time is the optimal track; The worst case is the flight path with the longest flight path when the two planes turn right at different angles.

![Figure 2. Congestion flight of two aircraft](image)

(a) AC2 turns right \(\alpha\), AC1 keeps heading  
(b) AC1 and AC2 turn right \(\beta\) individually

The payment difference between the track and the optimal track distance under different relief strategies is given below:

![Figure 3. Comparison of the resolution pay-off in different heading crossing angle](image)

![Figure 4. Comparison of the resolution pay-off in different strategy](image)

As shown in Figure 3, when the crossing angle is less than 30°, the flying approximately parallel, only through the course maneuvering deployment cost is very high, so it is not considered. In Figure 3,
it can be clearly seen that dual-aircraft and same-angle relief are close to the optimal level in several release strategies. Meanwhile, the conflict relief angle under this strategy can be obtained by using the formula above, which is conducive to the controller's command and avoid the controller's human error.

In Figure 4, the difference of payment between the large angle relief of single aircraft and the same angle relief of double aircraft is compared, and the function $f(\theta) = L_1 - L_2$ is always greater than 0. That is, no matter how the intersection angle changes, the large angle maneuver avoidance of single aircraft is more costly than the same angle maneuver avoidance of two aircraft at the same time, i.e. SDSA relief mode is better. In addition, the smaller the intersection angle is, the more the advantage of dual avoidance can be reflected.

The SDSA release model is relatively simple to establish. The corrected flight path after release can not only ensure a sufficient safety distance between the aircraft, but also give the conflict release point. When the aircraft reaches the conflict release point, it will resume its course and fly directly to the destination. In the process of conflict resolution, the model only changes the direction of the speed, which is applicable to flight conflicts in different scenarios. The main process of SDSA conflict resolution is shown in Figure 5.

3. Simulation and analysis

In order to verify the effectiveness of SDSA conflict resolution strategy, in this section, we use Matlab: R2016a to simulate four scenarios respectively. The starting and ending positions of aircraft 1 and 2 are determined, and the optimum cruising speed is 800 km / h direct to the destination. For an example, in scenario 1, AC1 flies from (0,200) to destination (400,200):

| Scene | AC.1      | AC.2      | Conflict? |
|-------|-----------|-----------|-----------|
| 1     | (0,200)-(400,200) | (400,200)-(0,200) | Y         |
| 2     | (0,200)-(400,200) | (200,0)-(200,400) | Y         |
| 3     | (0,200)-(400,300) | (200,0)-(300,400) | Y         |

The simulation has only been run for a few preliminary test cases to check the validity of the methodology. In each scenario, the flight trajectories of the two aircraft (left in the figure) and the interval between the two aircraft (right in the figure) were given.

- Scenario 1:
Scenario 2:

Figure 7. Heading change resolution for 90deg intersection conflict

Scenario 3:

Figure 8 Heading change resolution for intersection conflict

From the above simulation, it can be found that after the conflict was resolved, the two planes kept a safe distance of more than 10 km. At the same time, the point of conflict relief and the point of track recovery are defined, and the timing of aircraft maneuver is defined, so that the course can be resumed after resolution. This method uses the geometric model, and only twice maneuvers are needed to resolve the conflict and recover.

Table 2. Comparison of simulation results

|                      | Time | Head-on | 90deg | Closed angle | Obtuse angle |
|----------------------|------|---------|-------|--------------|--------------|
| Resolution time/s    | 0.861| 0.858   | 0.865 | 0.924        |
| Flight time(conflict)/h | 0.444| 0.444  | 0.458 | 0.497        |
| Flight time(resolution)/h | 0.450| 0.450  | 0.465 | 0.503        |
| Around time/h        | 0.006| 0.006   | 0.007 | 0.006        |

The simulation results under various modes are compared above. Take the head-to-head flight conflict as an example, the conflict resolution calculation time is 0.861 s, when no resolution is performed, the direct flight time to the destination is 0.444 h, and after the conflict resolution, the flight time only increases to 0.450 h. Compared with the simulation results, it is found that the time caused by SDSA release strategy is less than 0.007 h (30 s), i.e. Less than 10km.

4. Conclusions
This paper proposes the CD&R model based on flight trajectory prediction, and combines minimum maneuver in basis of geometric optimization. The CD&R modes of the two aircraft in different scenes and the calculation method of each parameter are given in detail, and the effectiveness of the method is verified by simulation. The model is simple and reliable, and can be used in the actual operation process, providing CD&R methods for flight conflicts. The conflict resolution (detection) point and
recovery point in flight are clearly defined, which has not been specifically given in previous studies. SDSA method is easy to operate, effectively solve conflicts, convenient for controllers and pilots to operate, as well as ensure flight safety.

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