Dynamic Aircraft Conflict Alert Based on the Markov Decision Process and Simulation of Actual Flight Data

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Abstract. As air traffic flow continues growing, the risk of collision between aircraft is also increasing as well. In order to ensure efficiency of airspace would not reduce due to the increase of the conflict, and thus the accuracy of alerts also has higher requirements. Traditional conflict alerts based on the static threshold method will have a great flight separation redundancy, resulting in reduced operating efficiency of airspace. So it's necessary to study the dynamic threshold alerts approach based on actual flight scenes, which can dynamically adjust the threshold and improve operational efficiency. First in this article, Markov decision processes were introduced. And then proposed a dynamic threshold alert method based on the Markov decision process. Finally, the analysis of alert results were performed through simulation of actual flight data. The results show that this method can reduce the false alert rate and improve the performance of the alert system under the premise of ensuring flight safety.

Keywords: Air traffic management; Markov decision process; Conflict alert; Dynamic threshold.

1. Introduction

The purpose of flight conflict alert is to determine whether the extent of current conflict needs to remind pilots or controllers to take avoidance strategy. The general approach is threshold method, that is, if the current collision probability exceeds this threshold, the potential for conflict is considered a greater threat, alert is necessary for pilots or controllers to take appropriate strategies to avoid conflict. If the current conflict probability is less than the threshold, then that although there is a conflict, the potential threat is not high enough to alert. This can ensure the safety of flying through the air while minimizing the number of alerts and improving flight efficiency[1]. Currently, there are two kinds of threshold selection methods: static threshold and dynamic threshold. Static threshold is a fixed threshold criteria used for judging whether alerting or not. This method is simple, but for complex and intensive flight situations, there may be a high false alert rate. While the dynamic threshold method, combining the current probability of collision with the aircraft's current state, perhaps also based on the state of the close aircraft or the information of process and intention in the future time, dynamically generates current alert threshold. Since this approach comprehensive analysis the current and the projected future state parameters[2], the exact alert threshold in the current time can be obtained in the premise of ensuring flight safety and lowering the false alert rate, reducing unnecessary avoidance strategy.

In the last 20 years, scholars have developed a lot of research on the issue of aircraft conflict alert and most of these methods are based on the probability method[3]. Meanwhile, most of the current domestic and international flight automatic processing systems have a high false alert rate, which adds controllers and pilots’ burden and reduces the capacity of the airspace and restricts airspace
utilization[4]. In addition to James P. Chryssanthacopoulos team's work in 2012[5], other scholars’ work is performed mostly around the frame of static threshold alerts and the research of dynamic alert threshold is relatively little[6]. Thus, dynamically alert threshold method which can set a threshold according to the current state of the aircraft and other information has become a research hotspot. James P. Chryssanthacopoulos’ team proposed a method based on the multiple hypotheses of the next time aircraft state[7], which is very complex and not very apt with actual civil aviation flight condition. For civil aircraft, although the next state is uncertain, we can clearly know the set of states. In this case, Markov decision process can describe the scene well, and then get the accurate conflict probability. This article analyzes the characteristics of the actual civil aviation conflict scenarios and avoidance strategy. And then gives way to generate dynamic threshold based on Markov decision process and validates it by real flight data[8].

2. Problem Definition
This article aims at the issue of dynamic conflict alert problem between two aircraft flying at the same altitude level. Here, the conflict is defined as the distance between two aircraft less than a fixed constant (currently, ICAO provides this distance 5nm)[9]. When the distance between two aircraft is less than the fixed constant, then it’s considered a conflict. Then we calculate the collision probability (with the probability method which domestic and international generally accepted currently). And analyze the usability of avoidance strategy one by one. Combined current conflict probability with the merits of avoidance strategy[10], dynamically generates alert threshold associated with current flight status. In simulation, the real aviation flight data is used as the data source for method validation[11].

The following assumptions and constraints is first given in this problem: (1) All of the states (longitude, latitude, altitude, heading and speed, etc.) of the aircraft in scene can be observed, and flight data is obtained by the same type of monitoring device, which are assumed to have the same error distribution; (2) Since civil aircraft in flight has strict accordance with the assigned route and altitude level flight, it is assumed that the aircraft are flying at a fixed altitude layer and the strategies adopted to avoid conflict do not contain such a climb or descent an altitude layer; (3) Predefined strategy which may be taken to avoid conflict is according to the practical needs of the ATC implementing; (4) There is no conflict between aircraft in data for each aircraft in the initial position; (5) It’s considered the conflict could only occur between two aircraft. That means it is not expected more than two aircraft appear in the same conflict scene; (6) Conflict contained in the data source is limited and countable, which is to analyze the results of the simulation and calculate false alert rate and success alert rates and other indicators.

3. Algorithm Explanation

3.1. Algorithms Outline
For flight conflict concerned, dynamic alert system based on the Markov decision process complete the following functions. The real-time states of all aircraft in the scene are stored and observed constantly. When conflicts arise, the system analyzes pre-set strategies’ usability one by one and evaluates the optimal avoidance strategy[12]. At the same time, combined the current conflict probability with the behavior revenue of the optimal avoidance strategy, system gains current alert threshold. If the current conflict probability is less than the threshold, no alert is generated; otherwise, the alert is generated, and system gives the current optimal avoidance strategy[13]. Common indicators (behavior revenue) to measure the merits of the strategy contain discount indicator and average indicator[14]. Discounts indicator refers to the expected total revenue of the long-term discount (converted unit revenue at time t into βt (β <1) times of units revenue at time 0)[15]. Average indicator refers to the average expected revenue of unit time. Markov decision process adopted discount indicator is called discount model. And Markov decision process adopted average indicator is called average model.

In the analysis of the aircraft conflict, the conflict process can be considered as a first order Markov process (for the conflict between two aircraft, the first order Markov process is sufficient for analysis),
and the aircraft's state space and avoidance strategies sets are limited. More importantly, the average model reflects the revenue of current state adopted a strategy more accurately. Based on the above, this article uses the average model to describe and analyze the conflict scene.

3.2. Algorithm Flow

Because the alert threshold is dynamically given based on the current aircraft state, aircraft conflict dynamic alert based on the Markov decision process, can improve the alert accuracy. Alert threshold selection is crucial. Low threshold will cause excessive false alert rate and reduce flight efficiency, so that pilots or controllers would take some unnecessary avoidance strategy. High threshold, although reduces the false alert rate, will generate alert only in the case collision probability is very high, which would leave pilots or controllers little reaction time. At the same time, communication delays coupled with flight performance also make avoidance strategy extremely limited and urgent. It results in the increasing of collision incidents.

The flow chart of getting dynamic alert threshold based on Markov Decision is shown below. After analyzing all of the actions can be taken, Markov decision process approach can pick preferably out the action which makes current revenue most in the principle of maximum revenue. Combined current most revenue with failure alert probability, we can gain an alert threshold (It will be explained in detail below.). Since all possible actions and action revenue in future are analyzed in this method at the same time, this method can effectively reduce the false alert rate when it is used on conflict alert.

![Figure 1. Dynamic alert flow chart.](attachment:dynamic_alert_flow.png)

As shown above, first, we describe the aircraft conflict scenarios with the state set, collection of behaviors, the state transition function and the revenue function, then we obtain Markov model (S, A, T, R). According to revenue function R(s, a), by traversing the overall behavior of the aircraft can be taken in the avoidance strategy set, we build the maximum revenue set \( \pi (s) \) of all aircraft state. Next, we can get the total revenue function:

\[
U(s,a) = R(s,a) + \sum_{s' \in S} T(s,a,s')U(s',a)
\]  

(1)

It should be noted that the revenue function R(s, a) indicates the revenue gained by a direct action in the s state, without considering the state transition. Thus the above formula represents the total revenue obtained by conducting action a in state s, which has considered the state transition revenue. Thus, the Markov model has been established.

Based on an average model principle and the maximum expected revenue criterion, dynamic alert threshold associated with the current state can be obtained:
\[
\min_{a \in S} P(E|s,a) - R(s,a) \tag{2}
\]

When the conflict probability of not taking any action (strategy) is greater than the equation above, an alert is generated. The converse situation is not an alert. The first term in the equation above, the selection range of \(s\) is the overall behavior (strategy) in addition to not alert. While the selection range of \(a\) in the second term is maximum benefit set \(\pi(s)\).

3.3. Markov Model of the Scene

3.3.1. Establishing the aircraft state space. According to the location coordinates, trajectory and flight routes heading of aircraft in the airspace, aircraft state can be divided into a variety of flight conditions. Since aircraft conflict occurs in pairs, it hasn’t practical significance to discuss the state of one aircraft alone. Thus, we need to discuss the state between two aircraft. Since this article only researches flight conflict of civil aircraft flying at a fixed altitude layer, and thus we only discuss several flight conditions which exist in two-dimensional flight path. Classification is based on the conflict severity, which is constant or progressive larger or little, and where we are appropriate aware of strategy can be used based on current state.

(1) Two aircraft flight path parallels (same direction flight) or coincidence that two aircraft are flying in the same or parallel routes: conflict on this state has essentially the same form and size, so the strategies generally is deceleration.

(2) Two aircraft have opposite flight path and depart away from each other, or heading angle between aircraft increases: the latter has the following two possible states:

![Figure 2. Heading angle between aircraft increases.](image)

That indicates flight conflict between two aircraft is decreasing or discharged. Generally, no alert need to be conducted in this state.

(3) Two aircraft have opposite flight path and close to each other, or aircraft heading angle between aircraft reduces: the latter condition is shown below:

![Figure 3. Heading angle between aircraft decreases.](image)

This state indicates flight conflict increases. Generally, strategy is acceleration or deceleration or left deflection, right deflection, etc.
3.3.2. Establish a collection of conflict avoidance strategy. According to the actual operation of civil aviation needs, we set only four kinds of conflict avoidance strategy to change track in the form of a two-dimensional at the same height layer in addition to climb or descend flight level strategy, as follows.

(1) Acceleration (+20nm/ h) 20 ~ 60 seconds, then return to the original speed:
Adjust specific acceleration time according to crisis proportions;
(2) Deceleration (-20nm/ h) 20 ~ 60 seconds, then return to the original speed:
Adjust specific acceleration time according to crisis proportions;
(3) To the left deflection:
Avoid conflict by an arc-shaped trajectory starting with a deflection angle of 30 degrees and finally return back to the original route;
(4) To the right deflection:
Avoid conflict by an arc-shaped trajectory starting with a deflection angle of 30 degrees and finally return back to the original route.

3.3.3. Obtain the state transition probability function. Flight conflict dynamics alert is based on conflict detection and track prediction has error during conflict detection. Thus when we treat flight conflict as the first order Markov process, estimates of future aircraft position is biased. From the point of view of Markov model, when an aircraft in some state takes a strategy, it isn’t certain to enter the next state we expected. There is a certain probability into some other state. So in order to get the state transition probability function, it is necessary for the aircraft position error analysis.

Predicted track position error grows with prediction time. Such a position error obeys a certain probability distribution in each direction: lateral position error component obeys normal distribution with constant mean and root-mean-square \( \sigma_{lp} \); vertical position error component obeys normal distribution with constant mean and root-mean-square \( \sigma_{vp} \); along the track direction, the root-mean-square \( \sigma_{hv} \) increases linearly with time. Thus, the predicted aircraft position error model can be seen as an ellipsoid and its center is aircraft nominal position and its half axle long respectively for three directions is \( \sigma_{lp}, \sigma_{vp}, \sigma_{hv} \), as shown below.

Figure 4. Ellipsoid prediction error probability distribution.

According to the aircraft position error distribution above, ignoring flight technology error and other errors (it is considered any strategy adopted does not have any error), we can calculate the probability of state which aircraft may enter into and then obtain the state transition probability function.

3.3.4. Revenue function construction. Revenue function is a quantitative indicator to evaluate each strategy in the current state. After considering the collision probability, fuel economy and the actual needs of the ATC operation, we construction revenue function as follows:

\[
R(s, a) = 10\Delta P + \Delta L + b
\]
In the formula above, $\Delta P$ is positive revenue, which means the reduced probability after strategy adopted ($\Delta P = P - P'$, where $P$ represents a conflict probability value after strategy adopted); $L$ is negative revenue, which means distance difference between the original trajectory and the trajectory after taking strategies and its unit is nautical miles ($\Delta L = L - L'$, where $L$ indicates original route distance when strategy is not adopted; $L'$ indicates track distance from beginning of strategy to ending of strategy when some strategy is adopted); $b$ is a positive revenue and it is the ATM operational impact factor and it represents impact of actual air traffic control operation. When there are a number of strategies available, but if one of these strategies is more in line with demand for the avoidance strategy during actual air traffic control operation, this strategy will have higher $b$ values ($0 < b < 1$).

4. Simulation
When we conduct simulation based on the method below, we use the real aviation flight data and intercept data around the terminal area (where have high conflict probability) as the data source. The ATC platform is our simulation environment. Finally, we can get the collision probability and alert thresholds.
Two aircraft have no conflict each other in the initial, as shown below.

![Figure 5. Initial position of two aircraft.](image)

Two aircraft are flying straight direction and there is intersection along extension cord. There will be a potential flight conflict.
When an alert is generated, the aircraft symbol turns yellow. The current collision probability is the current alert threshold. The following picture shows the location of the two aircraft and collision probability curve when the alert generates.

![Figure 6. The location of the two aircraft when the alert generates.](image)
Collision probability curve indicates a trend of future conflict increasing, which matches the decreasing of the distance between two aircraft. At this point the collision probability is 0.1. Although the probability of a collision between two aircraft is not much, the liberation strategy can be taken is limited in current state and two aircraft flight direction is similar perpendicular to each other. So it results in larger distance. If generates alert in the future, revenue will drop substantially. When alert removes, the location of two aircraft and collision probability curve are shown below.

Collision probability curve indicates a trend of future conflict gradually reducing, which matches the increasing of distance between the two aircraft. At this point the collision probability is 0.28. It is different with the alert threshold of 0.1 when the two aircraft is close, current alert threshold becomes large. Although the conflict probability between two aircraft is larger, the two aircraft is moving away from each other. It results in the threshold raise, leading to false alert rate lower.
5. Conclusion
According to the actual operation characteristics of civil aircraft, this paper proposes a revenue function in the dynamic flight conflict alert problem based on Markov decision process. The simulation result shows aircraft conflict dynamic alert based on Markov Decision Process can generate dynamic alert threshold combined present aircraft status and conflict probability with conflict-avoidance strategies. When conflict occurs, if the conflict-avoidance strategy has high revenue, the dynamic threshold is low, tending to generate an alert to avoid conflict. Contrary, if the conflict-avoidance strategy has low revenue, the dynamic threshold is high. Alert will not be generated to reduce the false alert rate.

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