A Probabilistic Algorithm for Multi-aircraft Collision Detection and Resolution in 3-D

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Abstract

This paper presents a real-time algorithm for collision detection, collision avoidance and guidance. Three-dimensional point-mass aircraft models are used. For collision detection, conflict probability is calculated by using the Monte-Carlo Simulation. Time at the closest point of approach(CPA) and distance at CPA are needed to determine the collision probability, being compared to certain threshold values. For collision avoidance, one of possible maneuver options is chosen to minimize the collision probability. For guidance to a designated way-point, proportional navigation guidance law is used. Two scenarios on encounter situation are studied to demonstrate the performance of proposed algorithm.

Key Word : Multi-aircraft Collision Avoidance, Monte Carlo Simulation, Probability

Introduction

In present, the satellite navigation system based on ADS-B(Automatic Dependent Surveillance – Broadcast) is being studied in many researches. This research trend makes the conception of 'Free Flight [1]' possible in some aspects and demonstrates the environmental conditions in the ATM(Air Traffic Management). Various researches are accomplished for the 'Free Flight', and many methodologies and skills are published up to present, which find optimal trajectories by using optimal theories, probabilistic modeling, applying potential field, and so on.

'Conflict' can be defined as a "predicted violation of a separation assurance standard" [2]. If the protected zone is violated, each aircraft should solve the violation using proper way to avoid the conflict. For the 'Free Flight', it is very essential task to understand geometric relations between two aircraft in a conflict. Using the conflict conditions, knowledge can be extended to the case for multi-aircraft. In this paper, using time equation to CPA [3], we calculate the closest distance between two aircraft and determine whether each aircraft will be in a violation position or not.

Information for each aircraft from ADS-B is generally not quite exact and should be carefully considered for real applications. To deal with the inaccurate information, it is assumed that position, velocity, and attitude of aircraft have uncertainty with normal distribution characteristics. The information of aircraft differs at every generation for Monte Carlo Simulation, and the conflict probability is obtained as frequency after whole Monte-Carlo Simulation.

This paper presents a collision detection and resolution algorithm which fully utilizes the three dimensional information provided by ADS-B. Resolution to a conflict situation is accomplished non-cooperatively. It means that, except own aircraft, other aircraft move toward the way-points which are pre-designated with constant velocity. Own aircraft can have maneuver options that imply thrust change, lift reduction, and so on to avoid the collision with other aircraft.

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Using the optional maneuvers, own aircraft finds a trajectory which minimizes the probability of collision between own and other aircraft. As mentioned, the probability of collision is obtained from Monte-Carlo Simulation.

This collision avoidance concept using probabilistic method from Monte-Carlo Simulation allows this algorithm to be applied to a tactical use for free flight. The probability from this algorithm is intuitively adopted and easily gives a way to resolve a conflict between aircraft. This paper finally gives a possibility to extension of application for multi-aircraft collision avoidance. It is complicated and has lot of considerations to resolve the conflict situations of multi-aircraft when using other algorithms studied in the past. But own algorithm adopted in this paper can recognize all conflict situations simply without any other severe considerations, and deal with it using one index(conflict probability) for resolution, which is from Monte-Carlo Simulation.

System Modeling

In this paper, the algorithm to be demonstrated for collision avoidance adopts assumptions of 3-D point mass aircraft. When a point mass aircraft is considered, thrust and velocity vectors of aircraft are aligned, and air drag is expressed as drag polar equation. The Cartesian coordinate is chosen for system modeling(Fig. 1) and the equations of motion are described as :

$$\dot{V} = \frac{T-D}{m} - g\sin\gamma \ , \ \dot{\gamma} = \frac{g}{V}(n\cos\phi - \cos\gamma) \ , \ \dot{\chi} = \frac{g}{V}\frac{n\sin\phi}{\cos\gamma}$$

$$\dot{x} = V\cos\gamma\cos\chi \ , \ \dot{y} = V\cos\gamma\sin\chi \ , \ \dot{h} = -\dot{z} = V\sin\gamma \tag{1}$$

In Fig. 1, V, γ, and χ are airspeed, flight path angle, and heading angle, respectively. x, y, h are the position of north, east, and upward direction, respectively. These 6 elements are assumed to be measured from a certain navigation system such as ADS-B. Control inputs needed for minimizing the conflict probability between two or more aircraft are T(thrust), n(load factor), and ϕ(bank angle) in this system.

Fig. 2 shows relative motions of multi-aircraft. Intruders with constant velocity are on the way to each designated way-point. Own aircraft should approach a designated goal position without violation to the other aircraft's protected zone. The protected zone for general aircraft is the shape of cylinder with 5 nmi(about 9.26 km) radius and 2000 ft (about 0.6 km) height [4].
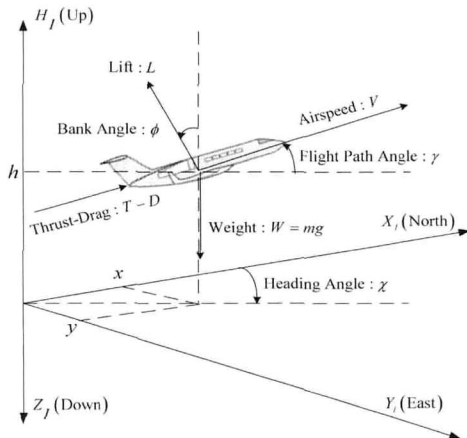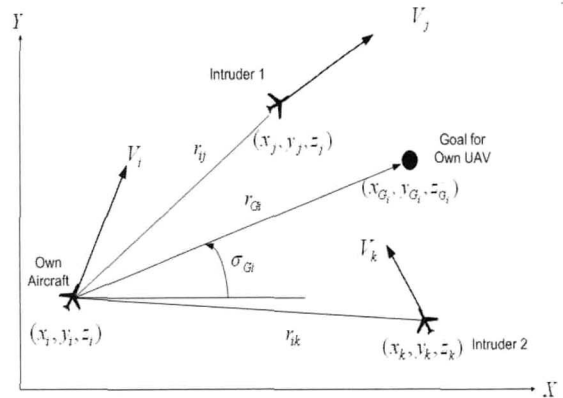

Fig. 1. Aircraft Coordinates

Fig. 2. Relative Motions of multi-aircraft

Table 1. Uncertainty Characteristics

Position	X (m)	N~(mean : 0,　variance : 30)
	Y (m)	N~(mean : 0,　variance : 30)
	Z (m)	N~(mean : 0,　variance : 30)
Velocity	V (m/s)	N~(mean : 0,　variance : 5)
Attitude	γ (deg)	N~(mean : 0,　variance : 0.5)
	χ (deg)	N~(mean : 0,　variance : 0.5)

10 nmi

2000 ft
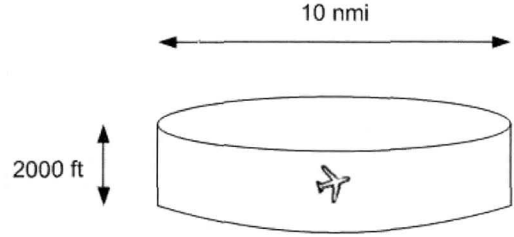
Fig. 3. Cylindrical Protected Zone

Since the information from navigation system like ADS-B is not accurate, it is required to design uncertainties on true values of aircraft's position, velocity, and attitude. For simplicity, every uncertainty is considered to have a normal distribution. Table 1 shows the uncertainty characteristics of the aircraft's information.

These uncertainties are added to the true values when every Monte Carlo Simulation operates. The conflict probability is the frequency of conflict during Monte Carlo Simulation.

$$P(C) = \frac{Number\ of\ Conflict}{Number\ of\ Monte\ Carlo\ Simulations} \qquad (2)$$

Collision Detection, Resolution, and Guidance to the way-point

Let's consider collision conditions of multi-aircraft. Each of them has same protected zone and own aircraft should not intrude the region until the conflict probability is out of concern when own and intruder aircraft are getting farther each other. We determine whether the threat of collision between two aircraft is over or not by calculating time taken to go to CPA position. The time to CPA is expressed as [5]:

$$\tau = -(\vec{r} \cdot \vec{c})/(\vec{c} \cdot \vec{c}) \qquad (3)$$

where $\vec{r}$ is a relative position vector and $\vec{c}$ is a relative velocity vector. In case that two aircraft passed by each other and are getting farther, the time to CPA is negative. Additionally, in case that the time to CPA described in Eq.(3) for all intruders to own aircraft is negative, there is no threat to collide with any of intruders. Therefore in that case it is not necessary to do a labor to detect the conflict with any of them and own aircraft is guided to the way-point by PNG. However if not, own aircraft should accomplish the collision detection and resolution maneuver.

3.1 Collision Detection

Collision detection is performed by own aircraft only because non-cooperative maneuver is assumed. For the collision detection, information update rate of 2 sec is assumed in this algorithm. When all information of intruders is given, the probability of conflict for each encounter is calculated by Monte-Carlo Simulation. In this process of the Monte Carlo Simulation, the relative position vector at CPA is calculated and decomposed into horizontal and vertical part. Then the conflict is defined as follows :

$$Relative\ CPA\ position\ vector : \vec{r_i} = \vec{r_{hi}} + \vec{r_{vi}}, \quad with\ i-th\ intruder$$
$$Conflict\ condition : \|\vec{r_{hi}}\| \leq 5\ nmi \approx 9.26\ km\ \&\ \|\vec{r_{vi}}\| \leq 1000\ ft \approx 0.3\ km \qquad (4)$$

Table 2. Threat Level(TL)

P(C)	Level
0~5%	Level 0
5~20%	Level 1
20~40%	Level 2
40~60%	Level 3
60~100%	Level 4

With the result(conflict probability) from the Monte-Carlo Simulation, threat level is classified from level 0 to 4 according to the conflict probability in Table 2 . In this algorithm, own aircraft avoids the intruder with the maximal probability of conflict. In case of level 0, own aircraft is guided to a goal position(designated way-point).

3.2 Collision Resolution

To resolve all conflict including the conflict which has the maximal probability, there are six maneuver options at each level. The magnitude of maneuver is defined with respect to the threat level and is more strengthen as the threat level is higher because an agile maneuver is required to resolve more urgent situation. The details are described in Table 3.

Table 3. Six Acceleration Options w.r.t TL

Maneuver Options	Level 1	Level 2	Level 3	Level 4
$\Delta a_x (m/s^2)$	± 0.1	± 0.5	± 1	± 3
$\Delta a_y (m/s^2)$	± 0.1	± 0.5	± 1	± 3
$\Delta a_z (m/s^2)$	± 0.01	± 0.05	± 0.1	± 0.3

Before final control inputs for thrust, load factor and bank angle, we test the acceleration options first through the Monte-Carlo Simulation . When the best maneuver is found by the test, the final control inputs are to be applied. The reason of adoption of "Acceleration Options" is that it gives easy understanding of the physical meaning and the flight path of own aircraft more than the actual control inputs such as thrust, load factor or bank angle.

In case of acceleration maneuver for z-axis, the magnitude is smaller than one for x and y-axis. The reason is that the radius of protected zone is much wider than the height of it. After testing all options, the best acceleration option is chosen to minimize the conflict probability. The acceleration chosen is added to the current acceleration. The acceleration command is expressed to the practical control inputs(thrust, load factor, and bank angle). The relation of the present accelerations and the control inputs is shown as [6] :

$$\phi = \tan^{-1} \left[\frac{a_y \cos \chi - a_x \sin \chi}{(a_z + g) \cos \gamma - (a_x \cos \chi + a_y \sin \chi) \sin \gamma} \right]$$

$$n = \frac{(a_z + g) \cos \gamma - (a_x \cos \chi + a_y \sin \chi) \sin \gamma}{g \cos \phi} \qquad (5)$$

$$T = \left[(a_z + g) \sin \gamma + (a_x \cos \chi + a_y \sin \chi) \cos \gamma \right] m + D$$

Additionally, limits on the quantity of controls [6] are set like below :

$$4448 \, N < \ Thrust < \ 213500 \, N$$
$$0.7 < Load \ Factor < 1.3$$
$$-30° < Bank \ Angle < 30° \qquad (6)$$
$$103.63 \, m/s < \ V < 274.32 \, m/s$$
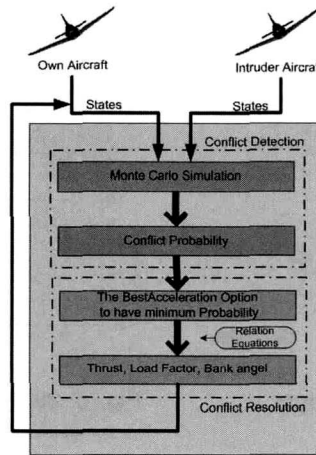
A whole algorithm scheme is shown in Fig. 4.

Fig. 4. Algorithm Scheme

3.3 Guidance to the way-point

In the case that the conflict probability is in level 0 or the time to CPA is negative value, own aircraft is guided to the way-point. The acceleration command of PNG is given as :

$$\vec{a_g} = N \vec{\sigma_G} \times \vec{V} \tag{7}$$

Numerical Results

※ Specifications for Own aircraft : mass = 83 tons, S = $158m^2$, $C_D = 0.05$

4.1 Scenario #1 : Own aircraft vs Two Intruder aircraft

Own aircraft and one intruder maintain level flight, and the other intruder is ascending. The conflict between 'own' and 'intruder 2' is occurred in intial phase of the scenario 1.

Fig. 5-1 indicates the scenario conception. As expected, 'own aircraft' avoids the conflict with 'intruder 2' and goes through the space between two intruders. To avoid the conflict with intruders, the bank maneuver is chosen sometimes as shown in Fig. 5-2.

The conflict probability is illustrated in Fig. 5-3. When two intruders get closer to own aircraft, the probability is higher. But the effective resolution maneuver reduces the probability and makes own aircraft avoid the conflict. Fig. 5-4 shows the control input history. To avoid the conflict, the bank and thrust commands mainly are used in this scenario. From Fig. 5-5 and Fig. 5-6, it is observed that any conflict does not occur. It means there is no simultaneous violation on the horizontal and vertical plane.
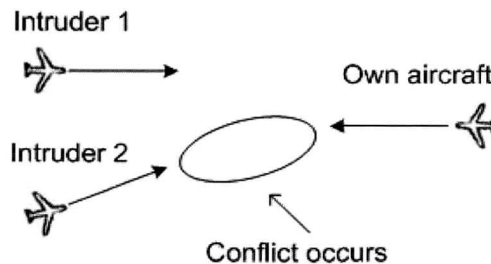
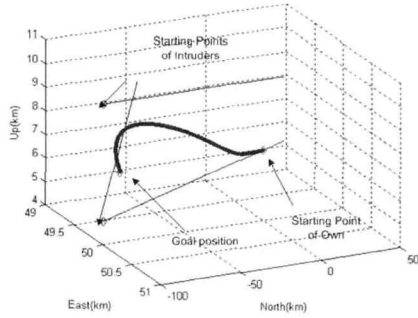Fig. 5-1. Scenario Description

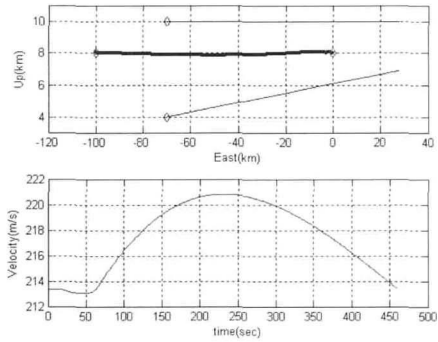Fig. 5-2a. Result Trajectory

Fig. 5-2b. Result Trajectory(XZ-plane)
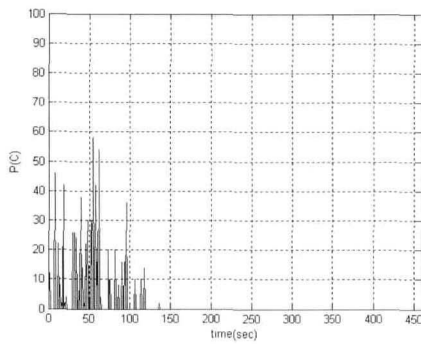& Velocity History

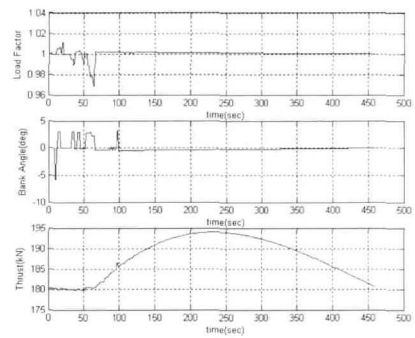Fig. 5-3. Probability

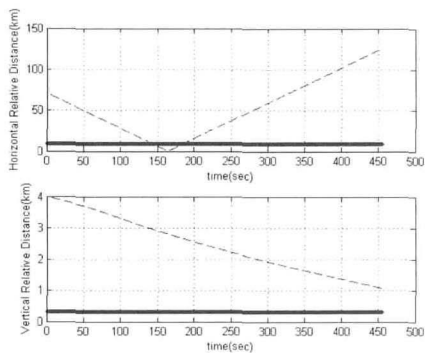Fig. 5-4. Control Input History

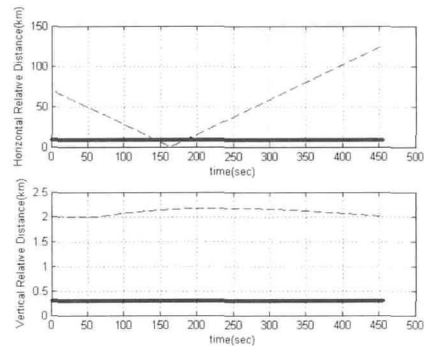Fig. 5-5. Relative distance
(Own & Intruder 1)

Fig. 5-6. Relative distance(Own & Intruder 2)

4.2 Scenario #2 : Own aircraft vs Three Intruder aircraft

Own and intruder 1 & 3 maintain level flight. Intruder 1 is coming perpendicular and intruder 3 is in head encounter. Intruder 2 is descending from a higher altitude.

From the result shown in Fig. 6-2a, own aircraft chooses the trajectory below the intruders. Since there is a risk to be in conflict with the 'Intruder 2' when own aircraft chooses upper trajectory than the trajectories of 'Intruder 1' and 'Intruder 3', own aircraft maneuvers downward to avoid all intruder's protected zone.
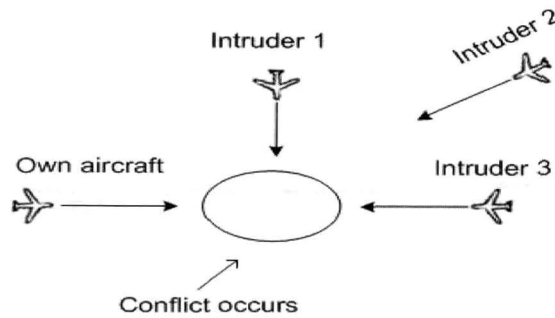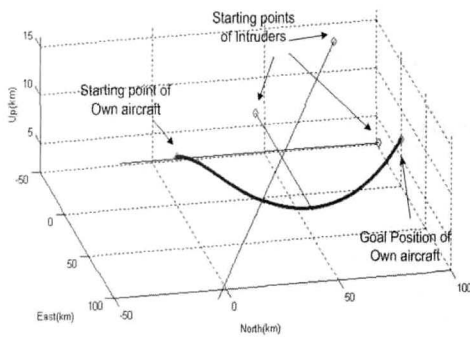
Fig. 6-1. Scenario Description
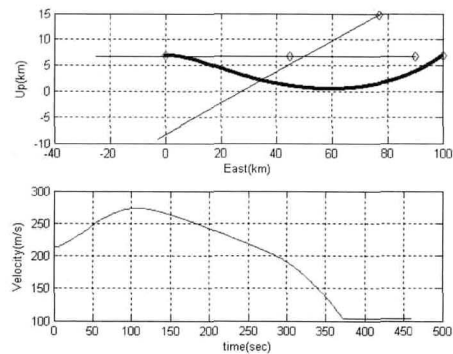

Fig. 6-2a. Result Trajectory

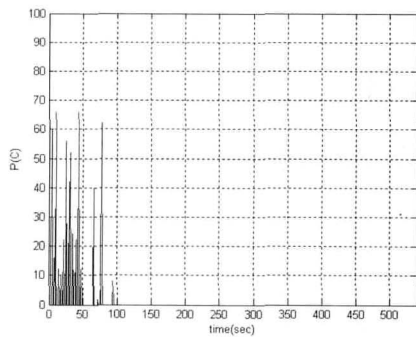Fig. 6-2b. Result Trajectory(XZ-plane)
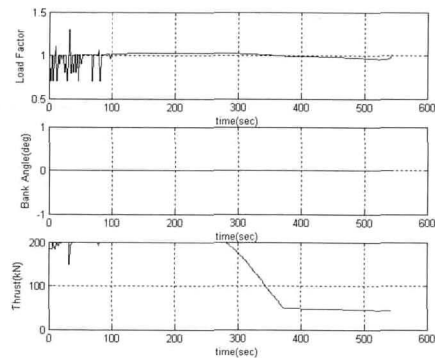& Velocity History

Fig. 6-3. Probability

Fig. 6-4. Control Input History

In Fig. 6-2b, it is observed that the velocity is saturated at the minimal value. When own aircraft uses the acceleration option with the negative direction of altitude, the thrust and the velocity are decreased consequently. After the resolution maneuver, own aircraft is guided to the goal position. Since the altitude of the goal position is higher than one of own aircraft at that time, the velocity maybe decrease for going up to the goal position. However in this algorithm it is guaranteed that own aircraft maintains the velocity up to a certain level(103.63m/s). Therefore, to sustain the velocity level, the thrust level also remain at a certain level(Fig. 6-4).

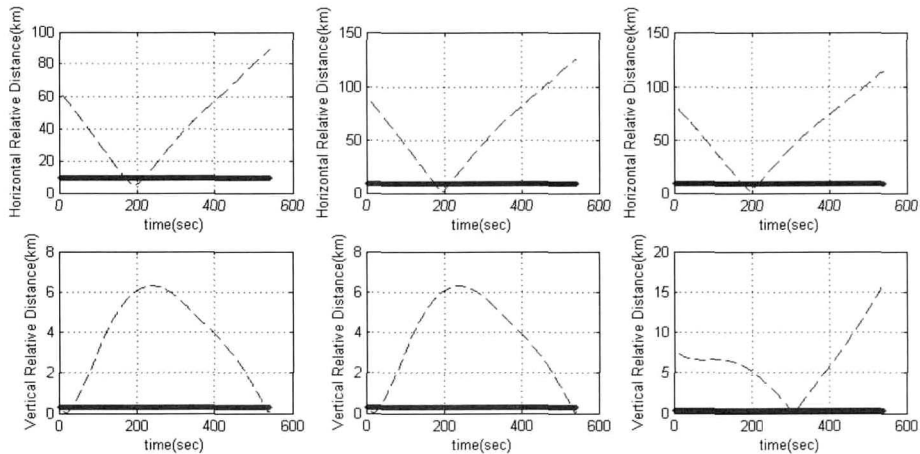From Fig. 6-3 and 6-5, it is known that there's no conflict occurred.

Fig. 6-5. Relative distance(Own & Intruders)

Conclusions

In this paper, we proposed the algorithm for the collision detection and resolution of the unmanned aircraft systems. Using the Monte-Carlo Simulation, a conflict probability is calculated and, according to a threat level, six maneuver options are introduced.

The best maneuver to avoid the collision is selected, and the acceleration command is transformed into three control inputs, thrust, load factor, and bank angle. By using the selected control inputs, the conflict probability is minimized. After the resolution maneuver, own aircraft is guided to pre-designated point(way-point) by using PNG. In this paper, multi-aircraft encounter scenarios are considered, and the maneuvering of own aircraft is that as expected. This means that, without any other considerations for conflict situations between multi-aircraft, it can be resolvable using this algorithm. From the results, we can verify the possibility to the demonstration of the 'Free Flight' which is ultimate goal of this study.

Acknowledgement

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