Aircraft Self-Separation Algorithm for High Density Air Corridor Operation Based on Flight Intent*

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A fundamental algorithm using the relative position and velocity vector and flight intent for the aircraft self-separation operation in a high density air corridor is presented. A high density air corridor is expected to be an air space where aircraft capable of airborne self-separation are allowed to fly in the same direction. An appropriate self-separation algorithm is indispensable to operate it safely and efficiently. In this study, a typical free-flight algorithm is examined to investigate its suitability for the corridor operation. Through a series of traffic simulations, we clarify that the free-flight based algorithm causes many aircraft to perform excessive heading change maneuvers, and frequent conflict occur against pilots’ intent. To avoid any conflict, the self-separation algorithm is improved by introducing the flight intent in the corridor that all aircraft intend to fly in the same direction. Through the numerical simulation, the improved algorithm facilitates a more intuitive aircraft maneuver to achieve the conflict-free operation with much fewer maneuvers. It is concluded that the flight intent has a significant role to develop a self-separation algorithm capable of the safe and efficient high density corridor operation.

Key Words: Air Traffic Management, Self-Separation, High Density Corridor, Flight Intent

1. Introduction

Recently, the introduction of high density air corridors is being planned to increase the traffic capacity.1,2) These corridors are considered to become long and narrow airspaces connecting the high demand cities and areas. Aircraft will be required to be capable of self-separation using airborne separation assurance systems.3) Because the aircraft in the corridor are able to reach the destination without air traffic controllers’ instruction, the air traffic controllers can allocate their effort for the aircraft outside the corridor. In this way, the concept is expected to enhance both the traffic throughput and the safety in the whole airspace. On the air corridor concept, several preliminary studies have been carried out mainly concerning its design4,5) and operation procedure concept.6) To clarify a feasible self-separation procedure for its safe and efficient operation, the authors have sought an appropriate control algorithm that uses the relative position information. A procedure to appropriately operate a corridor with the maximum traffic volume by heading control7) and a route structure for the safe treatment of air traffic flow with the flight speed distribution have been clarified.8) The influence of the non-uniformity in the separation control behavior on the safety has also been investigated.9)

The self-separation10–13) is also one strong candidate of the airborne surveillance system applications. In typical self-separation algorithms, the conflict detection and resolution are carried out using the relative position and velocity information. One can naturally expect that such a typical self-separation algorithm can also handle a high density air corridor safely. In this study, therefore, to find a more sophisticated and practical algorithm, the relative velocity vector is introduced into a self-separation algorithm, and its effectiveness is examined through numerical air traffic simulations. In addition, as all the aircraft intend to fly in the same direction in the high density corridor, it is also expected to be possible to develop a more appropriate algorithm based on this intent. This is also investigated through numerical simulations.

2. Simulation Models

2.1. Aircraft model

The aircraft is modeled as a mass particle, and only its level motion is considered. The coordinates are shown in Fig. 1. The x and y axes are defined along the flight direction and right hand to it. The aircraft equations of motion are given as follows.

\[
\begin{align*}
\dot{x}_i &= v_i \cos \psi_i \\
\dot{y}_i &= v_i \sin \psi_i \\
v_i &= T - D \\
\dot{\psi}_i &= g \tan \phi_i
\end{align*}
\]

where \(v, \psi \) and \(\phi \) are the aircraft velocity, heading and bank angle. \(i \) denotes the aircraft number. \(T \) and \(D \) are the thrust and drag, and \(g \) is the gravitational acceleration.

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2.2. Self-separation concept

In addition to the minimum separation distance, the separation control distance is introduced for the conflict detection and resolution. These distances are represented by circles around an aircraft as shown in Fig. 2, which are called the minimum separation circle and the separation control circle in this paper. Aircraft in the air corridor perform the conflict detection and resolution referring to the separation control distance in order to avoid any conflict.

2.3. Air traffic model

It is considered that the maximum traffic capacity would be achieved when the aircraft compose a traffic flow with the distance the same as the separation control distance as shown in Fig. 3. This traffic flow is defined as the one with the maximum traffic capacity in this paper. In the following sections of this paper, the separation algorithms are applied to an air corridor with the traffic volume the same as this traffic capacity, and the feasibility to achieve sufficient safety and efficiency is investigated.

3. Self-Separation Algorithm using Relative Vector

3.1. Relative vector based algorithm

In this paper, the relative velocity vector is introduced in addition to the relative position based self-separation algorithm. The relative vector based algorithm has been developed based on a free-flight self-separation algorithm. The conflict detection and resolution is carried out according to the relative position and velocity vector. Consider a pair of aircraft, A and B, flying on the same level with velocity vectors $V_A$ and $V_B$ at the position $P_A$ and $P_B$ as depicted in Fig. 4. The conflict is detected if the relative velocity vector $V_R$ is expected to pass through the separation control circle. This is evaluated through the following equation.

$$|\alpha| < \beta$$

where $\alpha$ is the direction angle of the relative velocity measured from the relative position vector, and $\beta$ is the width angle of the separation control distance measured from aircraft A. $\alpha$ and $\beta$ are given as follows.

$$\cos \alpha = \frac{(P_B - P_A) \cdot (V_A - V_B)}{|| P_B - P_A || \cdot || V_A - V_B ||}$$

$$\sin \beta = \frac{d_{SC}}{d_{A,B}}$$

where $d_{SC}$ and $d_{A,B}$ are the separation control distance and the distance between aircraft A and B.

To achieve the conflict resolution, the direction angle of the relative velocity vector should be changed by $\gamma \equiv \beta - \alpha$. In this paper it is supposed that both aircraft simultaneously change their heading angle by $\mu_{sc}$ into the opposite direction as shown in Fig. 5. The relative velocity vector after heading change is given as

$$V'_{R} = \left( V_A \cos (\psi_A - \mu_{sc}) - V_B \cos (\psi_B + \mu_{sc}) \right)$$

$$V_A \sin (\psi_A - \mu_{sc}) - V_B \sin (\psi_B + \mu_{sc})$$
where \( V_A = \| V_A \| \), \( V_B = \| V_B \| \), and heading angle of aircraft A and B are denoted by \( \psi_A \) and \( \psi_B \). This vector should be parallel to the one that is rotated by \( \gamma \) from the original relative velocity vector \( V_R \). This is described as

\[
V_R \| \left( \frac{V_A \cos (\psi_A - \gamma) - V_B \cos (\psi_B - \gamma)}{V_A \sin (\psi_A - \gamma) - V_B \sin (\psi_B - \gamma)} \right)
\]

(9)

The maneuver angle \( \mu_{sc} \) is obtained as the following equation to achieve the necessary rotation of the relative velocity vector.

\[
\tan \mu_{sc} = \frac{(V_A^2 + V_B^2 - 2V_A V_B \cos (\psi_A - \psi_B)) \sin \gamma}{(V_A^2 - V_B^2) \cos \gamma + 2V_A V_B \sin \gamma \sin (\psi_A - \psi_B)}
\]

(10)

In the case that the distance between aircraft becomes smaller than the separation control distance, the conflict avoidance maneuver based on the distance\(^9\) is also applied. A heading change angle proportional to the distance below the separation control distance is given in the same direction as \( \mu_{sc} \) as follows.

\[
\mu_u = \frac{d_{sc} - d_{AB}}{d_{sc} - d_{MS}} \frac{\pi}{2}
\]

(11)

where \( d_{MS} \) denotes the minimum separation distance. When the distance reduces to be near the minimum separation distance, the given heading change angle becomes near 90 degrees to achieve swift separation maneuver.

An urgent maneuver is also introduced to recover the aircraft distance in case of the conflict. When the aircraft distance becomes smaller than the minimum separation distance, the following heading change angle is given in the opposite direction to the other aircraft.

\[
\mu_u = \frac{\pi}{2}
\]

(12)

The heading change for the separation control is summarized as follows.

\[
\mu_{A,B} = \begin{cases} 
\mu_{sc} & (d_{A,B} > d_{sc}) \\
\mu_u + \mu_u & (d_{sc} \geq d_{A,B} > d_{MS}) \\
\mu_u & (d_{MS} \geq d_{A,B})
\end{cases}
\]

(13)

### 3.2 Aircraft heading control algorithm\(^8\)

The aircraft heading angle is controlled through the bank angle. The bank angle is given according to

\[
\phi_i = a(\Psi_i - \psi_i)
\]

(14)

where \( a \) is a positive coefficient, and \( \Psi_i \) is the target heading angle of the \( i \)th aircraft. \( \psi_i \) is given as follows.

\[
\Psi_i = \psi_i(y_i) + \sum_{j \neq i} \mu_{i,j}
\]

(15)

The target heading angle \( \psi_i \) is determined so as to lead the \( i \)th aircraft to achieve separation control against plural aircraft, and to turn back to the corridor when it is flying outside it. The bank angle is given proportional to the difference between the heading angle \( \psi_i \) and the target one \( \Psi_i \). The function \( \psi_i(y_i) \) is defined as follows.

The function \( \psi_i(y_i) \) is defined as follows.

\[
\psi_i(y_i) = \begin{cases} 
-b(y_i - y_{edge}^i) & (y_i > y_{edge}^i) \\
0 & (y_{edge}^i \leq y_i < y_{edge}^i) \\
b(y_i - y_{edge}^i) & (y_i < y_{edge}^i)
\end{cases}
\]

(16)

where \( y_{edge}^i \) and \( y_{edge}^i \) are the \( y \) positions of the corridor edges. In order to enable all the aircraft to fly at their optimum flight speed, no deceleration or acceleration are considered in the separation control, and \( T = D \) and \( \dot{v}_i = 0 \).

### 4. Numerical Analysis

#### 4.1 Parameters and assumptions

In the numerical simulations, the minimum separation distance \( d_{MS} \) and the separation control distance \( d_{sc} \) are set as 10NM (=18,520 m) and 10.5NM (=19,446 m), respectively. It is assumed that the conflict detection and resolution are carried out against aircraft within 50NM. The air traffic flow is composed of 20 aircraft. The aircraft are placed along the \( x \) axis with intervals equal to the separation control distance, and placed randomly along the \( y \) axis for the initial condition as shown in Fig. 6. In this figure, the circles surrounding each aircraft denote the minimum separation circles, and the arrows exaggeratingly denote the flight speed and direction, where the aircraft heading angles are exaggerated five times. The analysis range and the corridor width are also shown in Fig. 6. The analysis range is fixed, and the front of this range is considered linking to the end to simulate an infinite length traffic flow. When an aircraft’s separation control distance exceeds the front of the analysis range, the aircraft takes the aircraft around the corridor, and placed randomly along the \( x \) axis. Each aircraft flight speed is given randomly according to the uniform distribution between 230 m/s and 250 m/s. The corridor width is given as three times of the separation control distance. Table 1 shows the simulation parameters.

In the following sections of this paper, the aircraft behaviors are illustrated to grasp the traffic situations. The aircraft situations are depicted as follows: the aircraft with circles are performing a separation control against other aircraft shown connected by narrow lines, the aircraft with gray-filled circles are close to another aircraft below \( d_{sc} \) in distance, the aircraft with black-filled circles are in the conflict...
situation, and the aircraft without circles are performing no separation control and close to no other aircraft. These situations are illustrated in Fig. 7.

The air traffic behavior converges to some steady state flow as the simulation time progresses. To focus on the traffic behavior difference between the two separation control algorithms, long term simulations are necessary to eliminate the influence of the initial condition and to evaluate the steady state traffic behavior. In addition, the larger numbers of aircraft are introduced as follows.

The following indices are applied to evaluate the air traffic simulation result using the initial condition shown in Fig. 6 is presented in Fig. 10, where the aircraft positions, heading change. The example illustration of the 20 aircraft traffic simulation result using the initial condition shown in Fig. 10 is presented in Fig. 10, where the aircraft positions, velocity and heading angles are depicted every 25,000 s.

The result shows that the conflict occurred in 32 cases of the 50-case simulations. A typical conflict situation is depicted in Fig. 11, where the heading angles are shown with no exaggeration. The conflict occurs between aircraft A, B and C. The conflict resolution maneuver between aircraft B and D is the trigger of the conflict. In Fig. 11(a), although aircraft D is about to overtake aircraft B and C, the separation distances between them are insufficient. This causes aircraft B and D to get close below the separation control distance as shown in Fig. 11(b), and they make swift turns for conflict resolution. However, a large heading change of aircraft D causes aircraft A and C to make large heading changes as shown in Fig. 11(c). Aircraft C turns left for the conflict resolution between aircraft D, and this causes aircraft A to turn right to resolve the conflict with aircraft C. Such fast maneuvers in a lateral direction result in the urgent maneuver resolves the conflict soon as shown in

\[
E_{\text{conf}} = \frac{1}{N} \sum_{i,j} \int d_{ij}^{\text{conf}} \, dt \quad (i < j)
\]

\[
E_{\text{ctrl}} = \frac{1}{N} \sum_{i,j} \int d_{ij}^{\text{ctrl}} \, dt \quad (i < j)
\]

where \(N\) is the number of aircraft. \(E_{\text{conf}}\) and \(E_{\text{ctrl}}\) are defined as the average of the time integration of the aircraft distances below the minimum separation distance and the separation control distance, respectively. Because the conflict between aircraft must be avoided for safety assurance, \(E_{\text{conf}} = 0\) is mandatory throughout numerical simulations. In addition, it is desirable that \(E_{\text{ctrl}}\) has a smaller value so as to minimize the conflict possibility.

It is also desirable for the feasibility of the separation control algorithm that the pilots’ workload is as small as possible. In this paper the workload is roughly evaluated by the amount of the heading angle change, and the index \(E_{\text{work}}\) is defined as follows.

\[
E_{\text{work}} = \frac{1}{N} \sum \int |\dot{\psi}| \, dt
\]

To eliminate the influence of the initial conditions as much as possible, the evaluation indices are calculated after 20,000 s.

### 4.3 Numerical simulation and evaluation

Figure 8 shows the basic conflict resolution maneuver. Aircraft A is flying at 250 m/s at the center of the corridor overtaking another aircraft B flying at 230 m/s at 5 NM right and 40 NM ahead. In this case, aircraft A and B begin turning left and right, respectively, to achieve the required separation cooperatively. The conflict resolution is achieved in a different manner when the aircraft have initial heading angles. In Fig. 9, aircraft B is initially heading left by 0.05 rad. In this case these aircraft begin turning in the opposite direction to achieve conflict resolution with the smaller heading change. The example illustration of the 20 aircraft traffic simulation result using the initial condition shown in Fig. 6 is presented in Fig. 10, where the aircraft positions, velocity and heading angles are depicted every 25,000 s.

The result shows that the conflict occurred in 32 cases of the 50-case simulations. A typical conflict situation is depicted in Fig. 11, where the heading angles are shown with no exaggeration. The conflict occurs between aircraft A, B and C. The conflict resolution maneuver between aircraft B and D is the trigger of the conflict. In Fig. 11(a), although aircraft D is about to overtake aircraft B and C, the separation distances between them are insufficient. This causes aircraft B and D to get close below the separation control distance as shown in Fig. 11(b), and they make swift turns for conflict resolution. However, a large heading change of aircraft D causes aircraft A and C to make large heading changes as shown in Fig. 11(c). Aircraft C turns left for the conflict resolution between aircraft D, and this causes aircraft A to turn right to resolve the conflict with aircraft C. Such fast maneuvers in a lateral direction result in the conflict as shown in Fig. 11(d). Even in this situation the urgent maneuver resolves the conflict soon as shown in
right to perform an appropriate conflict resolution. Such an intuitive supposition is implicitly based on the flight intent that all aircraft in the corridor intend to fly in the same direction. Therefore, it is expected that the flight intent introduction facilitates an appropriate self-separation algorithm.

5. Flight Intent Introduction

5.1. Lateral position based algorithm

The flight intent in the corridor corresponds with the recognition that all aircraft intend to fly in the same direction. It is expected to be possible to implement this intent into the self-separation algorithm by focusing on the lateral position difference instead of the heading angle information in the conflict detection. Consider aircraft A overtaking aircraft B as shown in Fig. 12. The conflict is detected if aircraft A is flying faster than aircraft B and its lateral position is within the lateral separation control circle width of aircraft B. To avoid conflict, in the same way as the relative vector based algorithm, it is supposed that both aircraft make heading change maneuver in the opposite direction by $\mu_{sc}$ as
shown in Fig. 13. To achieve the conflict resolution with the minimum heading change, the relative velocity vector should be directed toward the tangential line of the separation control circle as shown in Fig. 12.

The condition that the relative velocity rotates by $\gamma$ to be tangential to the separation control circle is given as

$$d_{SC} = d'_{A,B} \sin \gamma + d''_{A,B} \cos \gamma$$  \hspace{1cm} (20)$$

where $d'_{A,B}$ and $d''_{A,B}$ are the distances between these aircraft along the $x$ and $y$ axes. The heading change angle $\mu_{sc}$ should satisfy the following equation.

$$d_{SC} \cos \gamma - d'_{A,B} = \frac{d'_{A,B} - d_{SC} \sin \gamma}{(V_A + V_B) \mu_{sc}}$$  \hspace{1cm} (21)$$

This equation means the necessary time for aircraft $A$ to reach the separation control circle of aircraft $B$ along the tangential line. The left hand side is the lateral distance divided by the lateral relative velocity, and the right hand side is the longitudinal one. From the above equations the heading change angle $\mu_{sc}$ is obtained as follows.

$$\tan \mu_{sc} = \frac{(d_{SC} \cos \gamma - d'_{A,B})(V_A - V_B)}{(-d_{SC} \sin \gamma + d''_{A,B})(V_A + V_B)}$$  \hspace{1cm} (22)$$

Likewise for the relative vector based algorithm, when the distance between aircraft becomes smaller than the separation control distance, the following heading change is given in addition to $\mu_{sc}$ for the swift conflict avoidance maneuver.

$$\mu_a = \frac{d_{SC} - d_{A,B} \pi}{d_{SC} - d_{MS} \pi}$$  \hspace{1cm} (23)$$

The same urgent maneuver as the relative vector based algorithm is also introduced.

$$\mu_u = \frac{\pi}{2}$$  \hspace{1cm} (24)$$

The heading change for the separation control is summarized as follows.

$$\mu_{A,B} = \begin{cases} \mu_{sc} & (d_{A,B} > d_{SC}) \\ \mu_{sc} + \mu_u & (d_{SC} \geq d_{A,B} > d_{MS}) \\ \mu_u & (d_{MS} \geq d_{A,B}) \end{cases}$$  \hspace{1cm} (25)$$
As a result, the self-separation based on the flight intent potential conflict against aircraft in the lateral direction enabled the aircraft pilots to trust other ones suggested through numerical simulations. The flight intent operation with a large traffic throughput was clearly demonstrated through numerical simulations, it was proven that the self-separation velocity vector and flight intent application. Through numerical simulations especially focusing on the relative flow in a high density air corridor was investigated through three-dimensional maneuver for conflict avoidance, dynamic configuration change of corridors. Investigations of emergency procedures are also indispensable. It is also an important subject to find simplified separation control strategies so that the human pilots are actually able to make appropriate maneuvers for conflict resolution. The evaluation indices must also be improved so that they can evaluate the self-separation procedure from a more practical viewpoint.

### 6. Conclusion

The fundamental behavior of self-separated air traffic flow in a high density air corridor was investigated through numerical simulations especially focusing on the relative velocity vector and flight intent application. Through numerical simulations, it was proven that the self-separation algorithms using heading change for free-flight inevitably leads the aircraft to detect and resolve the potential conflict against other ones with even a small heading angle difference, even though they are flying almost parallel. This results in aircraft large heading changes causing conflict frequently in the high density corridor. This numerical result suggested that typical self-separation algorithms for a free-flight using heading control are unsuitable for the high density corridor operation. To avoid such excessive maneuvers, the self-separation algorithm was improved by applying the corridor flight intent that all the aircraft are flying in the same direction. Its effectiveness to achieve the conflict-free operation with a large traffic throughput was clearly demonstrated through numerical simulations. The flight intent introduction enabled the aircraft pilots to trust other ones to fly in the same direction and to omit monitoring the potential conflict against aircraft in the lateral direction. As a result, the self-separation based on the flight intent achieved the conflict-free high density corridor operation with one-sixth amount of the heading change. This can be regarded as one of counter-intuitive results; an algorithm with less information and less control achieves better performance.

There are many future works required to bring the self-separated high density corridor into practical use; e.g., three-dimensional maneuver for conflict avoidance, dynamic configuration change of corridors. Investigations of emergency procedures are also indispensable. It is also an important subject to find simplified separation control strategies so that the human pilots are actually able to make appropriate maneuvers for conflict resolution. The evaluation indices must also be improved so that they can evaluate the self-separation procedure from a more practical viewpoint.

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