A Self-separation Algorithm using Relative Speed for a High-density Air Corridor

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This paper discusses algorithms for the self-separation of aircraft operating in a high-density air corridor. An air corridor is a tube or band-shaped piece of airspace that connects congested airports, high-demand city areas, etc. Aircraft in the corridor all fly in the same direction, and only aircraft capable of self-separation may operate in the corridor. An appropriate self-separation algorithm is indispensable for realizing high traffic throughput while maintaining safety. In this paper, we augment a previously developed basic self-separation function with a new algorithm that determines heading changes based on the relative speed of other traffic. The basic self-separation function uses the relative lateral positions of other aircraft to determine heading changes for conflict avoidance assuming that all aircraft intend to fly along the corridor. Numerical traffic simulations show that the new algorithm, based on relative speed, leads to the formation of groups of aircraft with similar speed. It is clarified that the introduction of a simple common rule concerning turn direction achieves a drastic improvement in the degree of control while maintaining safety. It is also found that the control amount is equalized regardless of the flight speed and its variability.

Key Words: Air Traffic Management, Traffic Flow, Air Corridor, Self-separation

Nomenclature

\( RMS \): minimum separation distance
\( RSC \): separation control distance
\( x, y \): cartesian coordinates
\( V \): flight speed
\( a \): acceleration in flight direction
\( \psi \): heading angle measured from \( x \) axis
\( \Psi \): target heading angle
\( \varphi \): bank angle
\( \mu \): maneuver angle for separation control
\( d \): distance
\( g \): Earth gravity acceleration
\( \alpha, \beta \): positive coefficient
\( t \): simulation time frame

Subscripts
\( i, j \): aircraft number

1. Introduction

To accommodate future air traffic demand while maintaining safety, the capabilities of air traffic management (ATM) systems must be improved along with advanced communication, navigation, and surveillance technologies. The air corridor is an operational concept proposed in the Next Generation Air Transportation System (NextGen)1) and Collaborative Actions for Renovation of Air Traffic Systems (CARATS)2) programs to increase ATM capacity. The air corridor is a long, narrow tube or band of airspace connecting high-demand areas. The corridor is unidirectional, and only aircraft capable of self-separation are permitted to operate in the corridor. Self-separation means that separation assurance is achieved by aircraft on-board control without air traffic control (ATC) intervention. Separation is technically enabled by the use of Automatic Dependent Surveillance Broadcast (ADS-B),3) whereby aircraft periodically broadcast their position, altitude, velocity vector, etc. This enables each aircraft to monitor nearby traffic and self-separate from them. Self-separation potentially reduces separation minima, which results in an increase in airspace capacity. As the corridor is segregated from conventional airspace, ATC provides instructions only to aircraft outside of the corridor, which reduces ATC workload and consequently improves both safety and capacity. Air corridor operations will be effectively able to manage airspace in which both self-separation capable and non-capable aircraft are mixed.

Safe and efficient operational procedures are required to implement air corridor operations. Although the geometry and allocation of air corridors have been studied,4–6) details of the self-separation procedures had not been studied prior to the authors’ investigations.7–10) The authors intend to clarify the feasibility of self-separation in the corridor, and have previously investigated a self-separation algorithm for one-way, high-density traffic flow that uses heading changes7) and route structures for safer and more efficient traffic flow.8) Additionally, a basic self-separation algorithm for air corridor operation based on the assumption that all aircraft fly in the same direction has been proposed.9,10) In this

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paper, an additional rule to determine the turn direction for conflict avoidance according to relative speed is newly introduced. The effectiveness of this rule is investigated through numerical simulations.

2. Simulation Models

2.1. Basic self-separation concept

In this study, only the level motion of aircraft is considered. For conflict detection and resolution, a minimum separation distance and a separation control distance are introduced. In Fig. 1, minimum separation distance is shown by a circle with radius $R_{MS}$ centered on an aircraft, and the separation control distance is shown by a dashed circle with radius $R_{SC}$. Aircraft perform conflict detection and resolution referring to the separation control distance $R_{SC}$. Violation of the minimum separation distance constraint is considered to be a conflict.

It is desirable that all aircraft fly at their optimum speed, so self-separation algorithms that use only heading change are developed. It is assumed that conflict detection and resolution are carried out against other aircraft within the range of surveillance, so all aircraft perform self-separation based on the position and speed information of other traffic within their surveillance range.

2.2. Air traffic model

In this study, the standard traffic volume is defined as the volume of traffic within which all aircraft form a line with the in-trail distances equal to the separation control distance, as shown in Fig. 2. A simple straight corridor is considered, and all aircraft are supposed to fly in the same direction at their optimum speeds, as shown in Fig. 3. Self-separation algorithms are investigated through numerical simulations of the air corridor with a standard traffic volume.

2.3. Equations of motion

An aircraft is modeled as a point mass which moves in the coordinate system shown in Fig. 4. The $x$ axis is defined as the direction parallel to the corridor, and the $y$ axis is perpendicular to the $x$ axis. The equations of motion are given as follows:

\[
\begin{align*}
\dot{x}_i &= V_i \cos \psi_i \\
\dot{y}_i &= V_i \sin \psi_i \\
\dot{V}_i &= a_i \\
\psi_i &= \frac{g \tan \psi_i}{V_i}
\end{align*}
\]

Since aircraft are assumed to fly at constant speed, acceleration is zero. Additionally, a bank angle limit is introduced to prevent aircraft from generating unsafe bank angle. The limit is set at 18 deg, which is the standard bank angle defined in the Required Navigation Performance Authorization Required (RNP-AR) Procedure Design Manual.11) Aircraft change their bank angle within the operationally safe range.

2.4. Basic self-separation algorithm

The basic self-separation algorithm was developed based on the assumption that all aircraft intend to fly in the same direction.9,10) Consider the case of aircraft $A$ overtaking aircraft $B$ shown in Fig. 5, where $d_{AB}^x$ and $d_{AB}^y$ are the distances between these aircraft along the $x$ and $y$ axes. If $d_{AB}^y$ is greater than $R_{SC}$ or $V_B$ is greater than $V_A$, these aircraft can maintain sufficient separation without any maneuvers. When $d_{AB}^y$ is less than $R_{SC}$ and $V_B$ is less than $V_A$, the aircraft should perform maneuvers for conflict avoidance. In this study, aircraft $A$ and aircraft $B$ change their headings in opposite directions by the same angle, expressed by $\mu_{AB}$. It is preferable that aircraft $A$ overtakes aircraft $B$ with a minimum heading change, keeping the distance greater than $R_{SC}$.

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![Fig. 1. Minimum separation distance and separation control distance.](image1)

![Fig. 2. Standard traffic volume.](image2)

![Fig. 3. Traffic flow in the air corridor.](image3)

![Fig. 4. Coordinate system.](image4)
Hence, in the situation shown in Fig. 5, aircraft A, on the left side, changes its heading to the left, and aircraft B, on the right side, changes its heading to the right.

For conflict resolution, three types of angles depending on the situation are introduced: \( \mu_{SC} \) for distant aircraft, \( \mu_a \) for aircraft within the \( R_{SC} \) radius and outside of the \( R_{MS} \) radius, and \( \mu_u \) for aircraft within the \( R_{MS} \) radius. The relative velocity vector must be directed along the line tangential to the circle, as shown Fig. 5, to maintain the distance greater than \( R_{SC} \). Consequently, the required heading change, expressed by \( \mu_{SC} \), should satisfy the following equation:

\[
R_{SC} \cos \gamma - d_{AB}^t = \frac{d_{AB}^t - R_{SC} \sin \gamma}{(V_A - V_B) \cos \mu_{SC}}
\]

This equation determines the time required for aircraft A to reach the separation control circle of aircraft B along the tangential line. The left side of the equation is the lateral distance divided by the lateral relative speed, and the right side is the longitudinal one. From the above equation, the heading change angle \( \mu_{SC} \) is obtained as follows:

\[
\tan \mu_{SC} = \frac{R_{SC} \cos \gamma - d_{AB}^t}{d_{AB}^t - R_{SC} \sin \gamma} \frac{(V_A - V_B)}{(V_A + V_B)}
\]

Consider the case of an aircraft within the \( R_{SC} \) radius of other aircraft, where the distance between aircraft A and B becomes shorter than \( R_{SC} \). In that case, aircraft should change their heading swiftly to separate from the other aircraft. As shown in Fig. 6, the tangential direction is given as \( \gamma' \) in Eq. (7). In the same way as above, angle \( \mu_a' \) is derived from Eq. (8) so that the relative velocity vector turns \( \gamma' \).

\[
\cos \gamma' = \frac{d_{AB}^t}{\sqrt{d_{AB}^t + d_{AB}^t}}
\]

\[
\tan \mu_a' = \frac{R_{SC} \cos \gamma' - d_{AB}^t}{d_{AB}^t + R_{SC} \cos \gamma'} \frac{(V_A - V_B)}{(V_A + V_B)}
\]

Additionally, an angle proportional to the distance below the \( R_{SC} \) is given to \( \mu_u' \) for spacing, as shown in Fig. 7. Consequently, angle \( \mu_u \) for spacing is defined as follows:

\[
\mu_u = \mu_u' + \frac{R_{SC} - d_{AB}}{R_{SC} - R_{MS}} \left( \frac{\pi}{2} - \mu_u' \right)
\]

Finally, \( \mu_u \) for urgent heading change is introduced in case the distance becomes shorter than \( R_{MS} \) as follows:

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

Fig. 5. Heading angle for conflict avoidance in the basic algorithm.

Fig. 6. Heading angle for tangential direction.

Fig. 7. Heading angle for aircraft within \( R_{SC} \).

2.5. Self-organizing algorithm

This section describes the algorithm augmented with an additional rule that determines turn direction according to the relative speed. In the basic algorithm, aircraft turn in the direction based on the lateral position to overtake other aircraft with minimum heading change. On the other hand, it is also possible to overtake a distant aircraft with small heading change in the opposite direction. In this study, it is assumed that the faster aircraft overtakes another one on the right side.
Consider the case of two aircraft, shown in Fig. 8, for example. Unlike the basic algorithm, aircraft A is overtaking aircraft B on the right side, and the required heading change angle is expressed by $\mu_{SC}^*$. In the same way as in the previous section, Eq. (12) is derived from the time for aircraft A to reach the separation control circle of aircraft B. Then, Eq. (13) is obtained from Eq. (12) as follows:

$$
R_{SC} \frac{\cos \gamma^* + d_{AB}^y}{(V_A + V_B) \sin \mu_{SC}^*} = \frac{d_{AB}^x - R_{SC} \sin \gamma^*}{(V_A - V_B) \cos \mu_{SC}^*}
$$

(12)

$$
\tan \mu_{SC}^* = \frac{(R_{SC} \cos \gamma^* - d_{AB}^y)(V_A - V_B)}{(-R_{SC} \sin \gamma^* + d_{AB}^y)(V_A + V_B)}
$$

(13)

Heading angle $\mu_{SC}^*$ is determined according to the relative position and speed to keep the distance greater than $R_{SC}$. As an example, Fig. 9 shows the angles required to overtake on the right side at each position, assuming $V_A = 500 \text{ kt}$, $V_B = 450 \text{ kt}$, and $R_{SC} = 5 \text{ NM}$. As aircraft A is on the left side and the longitudinal distance is short, the heading angle shown in Fig. 9 is extremely large. Since many aircraft fly in the same direction in the high-density air corridor, large heading changes might result in an increase in conflict risk.\(^9,^{10}\) Hence, in this study, a threshold is introduced to change the turn direction based on the situation. Aircraft overtake another aircraft in the direction designated only when $\mu_{SC}^*$ is less than threshold angle $\mu_a$, otherwise aircraft avoid each other in the same direction as the basic algorithm. Consequently, heading angle $\mu_{SC}^d$ for self-separation is defined as follows:

$$
\mu_{SC}^d = \begin{cases} 
\mu_{SC}^* & (V_A \leq V_B \text{ and } \mu_{SC}^* \leq \mu_a) \\
\mu_{SC}^* & (V_A > V_B \text{ or } \mu_{SC}^* > \mu_a)
\end{cases}
$$

(14)

If the distance between aircraft A and B becomes shorter than $R_{SC}$ and $R_{MS}$, a swift heading change is additionally applied in the same way as the basic algorithm. The heading changes for the separation control in this algorithm are summarized as follows:

$$
\mu_{AB} = \begin{cases} 
\mu_{SC}^d & (d_{AB} > R_{SC}) \\
\mu_a & (R_{SC} \geq d_{AB} > R_{MS}) \\
\mu_a & (R_{MS} \geq d_{AB})
\end{cases}
$$

(15)

2.6. Aircraft control models

The heading change angle is controlled by the bank angle. The bank angle is given as follows:

$$
\psi_i = \alpha(\psi_i - \psi_j)
$$

(16)

$$
\psi_i = \psi_r(y_i) + \sum_{i \neq j} \mu_{i,j}
$$

(17)

$$
\psi_r(y_i) = \begin{cases} 
-\beta(y_i - y_{edge}^+)(y_{edge}^+ \leq y_i) & \\
0 & (y_{edge}^- \leq y_i \leq y_{edge}^+) \\
-\beta(y_i - y_{edge}^-)(y_i < y_{edge}^-)
\end{cases}
$$

(18)

where $\psi_i$ is introduced to lead the aircraft toward the corridor inside when it is flying outside. $y_{edge}^+$ and $y_{edge}^-$ are the $y$ positions of the corridor edges. The target heading angle $\Psi$ is determined so as to lead the $i$th aircraft to achieve separation control with plural aircraft, and to turn back to the corridor. The bank angle is given proportional to the difference between heading angle $\psi$ and target angle $\Psi$.

3. Numerical Simulations

3.1. Simulation parameters

To examine the effectiveness of the additional rule, two algorithms are compared through numerical simulations. Table 1 summarizes simulation parameters and Fig. 10 depicts an example of initial conditions, where arrows denote velocity vectors, and the circle centered at an aircraft with radius $R_{MS}$. In the figure, the heading angles are magnified five times. To identify the traffic behavior and eliminate

| Table 1. Simulation parameters. |
|---------------------------------|
| No. of aircraft | 80 | Corridor width, NM | 15 |
| Speed range, kt | 450–500 | Surveillance range, NM | 100 |
| $R_{MS}$, NM | 3 | $\alpha$ | 1.0 |
| $R_{SC}$, NM | 5 | $\beta$, rad/m | 0.1 |
the influence of the initial conditions, long-term simulations are necessary. Hence, the air corridor model shown in Fig. 10 is used in the numerical simulations, where the right and left edges are assumed to be linked and the aircraft on the right edge monitor those on the left edge, and vice versa. The length of the corridor is 400 NM, and air traffic flow is composed of 80 aircraft. The behavior of aircraft for 100,000 s is computed. The aircraft are placed along the x-axis with intervals equal to the separation control distance, and randomly along the y-axis for the initial condition. The aircraft flight speeds are given randomly according to uniform distribution between 450 kt and 500 kt. The scenario with a large standard deviation in flight speed corresponds to a traffic flow where multiple types of aircraft of various weights fly. Minimum separation distance $R_{MS}$ and separation control distance $R_{SC}$ are set to 3 NM and 5 NM, respectively. It is assumed that conflict detection and resolution are carried out against aircraft within 100 NM. The corridor width is given at three times as wide as the separation control distance. Numerical simulations are carried out using 50 sets of initial conditions.

3.2. Evaluation indices

To evaluate air traffic, the following indices are introduced to roughly determine safety and control amount. All aircraft are required to maintain a minimum separation distance to avoid conflict. Hence, $d^c$ is introduced to compute distances below the minimum separation distance as follows:

$$d^c_{ij} = \begin{cases} R_{MS} - d_{ij} & (d_{ij} < R_{MS}) \\ 0 & (d_{ij} \geq R_{MS}) \end{cases}$$

(19)

As the index of safety, $E_s$ is defined as hourly average distance $d_i^c$ per pair as follows:

$$E_s = \frac{1}{N(N-1)} \sum_{i<j} \int_0^t d_{ij}^c dt \ (i < j)$$

(20)

It is also desirable for a feasible self-separation algorithm that the control amount is as small as possible. In this paper, the amount of heading change $h^c$ is investigated and $E_c$ is defined as the index of total amount of control as follows:

$$E_c = \frac{1}{N} \sum_i h_i^c$$

(21)

(22)

To eliminate the influence of the initial conditions as much as possible, the evaluation indices are computed from 20,000 s after the start of the simulations.

4. Numerical Results and Analyses

4.1. Corridor traffic improvement

Examples of traffic behavior computed using the basic algorithm and the self-organizing algorithm are shown in Figs. 11 and 12, where the congested area is denoted by the dashed circle. The heading change angle required to avoid other aircraft becomes larger as the flight speed difference increases, especially in a congested area, as shown in Fig. 11. In the traffic simulation that uses the basic algorithm, almost all aircraft perform self-separation within a range of 10 deg of heading change, while 13 deg is the largest in the 50 scenarios. Therefore, the threshold used in the self-organizing algorithm is set at 10 deg.

In the traffic with the self-organizing algorithm, it is possible to find that the aircraft are well-organized according to their flight speed; the faster aircraft fly on the right side and the slower ones fly on the left side, as shown in Fig. 12. Consequently, overtaking with a large flight speed difference is reduced considerably. It is also found that only small heading changes are required, even in congested areas. Figures 13 and 14 show examples of conflict resolution among aircraft in a congested area. In the basic algorithm cases, the relative speeds to adjacent aircraft are relatively larger, and the heading change angles also become larger. On the other hand, in the traffic based on the self-organizing algorithm cases, aircraft have plenty of time to get close since the speed difference is much smaller. Consequently, little heading change is required to maintain the distance.

The evaluation indices are summarized in Table 2. There was no conflict throughout the simulations. $E_s$ was reduced drastically, by about 80%. It has been clearly demonstrated that the introduction of simple rules that designate the turn direction has achieved a safer traffic flow using a small amount of control.

4.2. Control amount and standard deviation of flight speed

In this section, the relation between control amount and speed variability on traffic is investigated in detail. The relation between control amount and standard deviation of flight speed in 50 scenarios is shown in Fig. 15, where the lateral and vertical axes indicate the standard deviation and the control amount index, respectively.

In the basic algorithm, the control amount increases as the standard deviation increases. In the traffic with large standard deviation, aircraft have to change their heading frequently because overtaking occurs more often. This results in increasing the amount of control required. On the other hand, the self-organizing algorithm achieves a well-organized traffic flow. In the traffic, overtaking occurs between the aircraft with similar flight speeds. This enables all aircraft to achieve conflict-free traffic with only small heading changes. It is further found that the algorithm facilitates not only the reduction, but also equalization of the control amount.

4.3. Control amount and flight speed

The relation between control amount and flight speed of
individual aircraft is also examined in detail. The flight speed and $h^c$ values of each aircraft in one typical scenario are presented in Fig. 16. Table 3 shows the average and standard deviation of speed and $h^c$ values of 80 aircraft in the selected scenario.

In the basic algorithm, the control amount increases as the aircraft flight speed deviates from the average. The aircraft flying at the maximum or minimum speed in the scenario...
have to change their heading angles more than twice that of the aircraft flying at the average speed. In the self-organizing algorithm, all aircraft realize separation with approximately the same small heading change angles. It has been clearly shown that the self-organizing algorithm decreases and equalizes the control amount required regardless of flight speed.

5. Conclusion

In this paper, the algorithms for self-separation of aircraft operating in a high-density air corridor were discussed, especially focusing on the effectiveness of conflict avoidance direction determination based on the relative speed. Through traffic simulation using the basic algorithm, it has been clarified that the average control amount index inevitably increases as flight speed variability increases. It has also been clarified that aircraft flying at the speed with a large gap from the average speed are obliged to change their heading frequently. On the other hand, the self-organizing algorithm leads to the formation of groups of aircraft with similar flight speeds. Consequently, all aircraft are able to perform self-separation with little heading change regardless of their speed and variability.

In the case of conflict resolution with a preceding aircraft, it is reasonable that aircraft overtake the preceding one in the direction based on the lateral position to complete overtaking with the smallest heading change. However, it is found that the traffic where all aircraft follow the above rule results in a frequent occurrence of overtaking and a larger heading angle for conflict avoidance. This simulation demonstrates that the introduction of a simple common rule that determines the turn direction based on relative speed achieves a drastic improvement in control amount while maintaining safety. The control amount is not only reduced, but also equalized. This equalization contributes to equity among all the aircraft.

To bring high-density air corridor operation into practical use, much future work is required. Since airspace is finite and aircraft operate within certain airspace, an algorithm that prohibits any deviation from a width-limited air corridor should be developed. Additionally, more practical procedures including altitude change and corridor configuration with entrance, exit and junction point should be investigated. Furthermore, allocations of the air corridor are an important issue for efficient implementation, and emergency procedures are indispensable. In addition, the traffic flow should be evaluated from a more practical viewpoint, such as fuel consumption and punctuality.

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