DESIGN OF FLIGHT AVOIDANCE MANOEUVRE ALPHABETS FOR MIXED CENTRALISED-DECENTRALISED SEPARATION MANAGEMENT

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Abstract

This paper investigates a mixed centralised-decentralised air traffic separation management system, which combines the best features of the centralised and decentralised systems whilst ensuring the reliability of the air traffic management system during degraded conditions. To overcome communication band limits, we propose a mixed separation manager on the basis of a robust decision (or min-max) problem that is posed on a reduced set of admissible flight avoidance manoeuvres (or a FAM alphabet). We also present a design method for selecting an appropriate FAM alphabet for use in the mixed separation management system. Simulation studies are presented to illustrate the benefits of our proposed FAM alphabet based mixed separation manager.

1 Introduction

Advancements in surveillance and communication technologies combined with growing worldwide air traffic has motivated renewed interest in the automation of air traffic management (ATM). The key task of an ATM system is to maintain safe separation distance between aircraft within a controlled region of airspace, and such task will be termed separation management. Automated separation management has been an active research area over the past decades (see [1] for a survey on automated separation management), and there are two dominating separation management paradigms: centralised approaches [2–6] and decentralised approaches [7–11].

Centralised approaches conduct all air traffic management from a single location based on information from centrally available sensors (for example, a ground-based radar). However, centralised systems tend to be computationally complicated and susceptible to failures when there is a large amount of air traffic [12]. Alternatively, decentralised (or onboard) separation managers allow each aircraft to conduct their own flight planning to avoid other aircraft within the controlled airspace utilizing their own sensors, for example the free-flight concept of the Next Generation Air Transportation System [2]. Nonetheless, decentralised systems can suffer from cascaded or domino failures due to the local nature of available information (a failure mode that is easily avoided in the centralised system) [1,9,12].

One important aspect to realise when considering automated ATM system (whether it is centralised or decentralised system) is that greater reliance is placed on computational, communications, and surveillance infrastructure of the ATM system, and hence an automated system is more likely to suffer failures of some types [2]. In [2], the concept of “graceful degradation” has been proposed which leads to the consideration of how to design an ATM system that maintains some level of performance during degraded conditions (for example surveillance system failures). That is, how can we build an automated ATM system that successfully maintains aircraft separation distances during both nominal and degraded conditions.

To facilitate the concept of "graceful degradation" and to migitate the separate drawbacks of centralised and decentralised separation management approaches, in this paper we consider a recently proposed mixed centralised-decentralised separation management system [13, 14]. One important aspect of such combined or mixed systems is the ability to appropriately switch between the two existing ATM paradigms, and hence exploit the best features of each paradigm whilst ensuring system reliability if one of the systems has degraded performance. Yet, the difficulty of such a mixed system lies in the automatic selection of the appropriate paradigm. In [14], we suggested that selection between a centrally and decentrally generated advice could be made on the basis of a min-max problem. That is, a flight avoidance manoeuvre (FAM) could be selected to ensure that all aircraft maintain reasonable separation, even in the event that the worst case scenario arises (this is called a robust decision approach, and safely handles any uncertainties present). Unfortunately, a key difficulty in solving this min-max approach to ATM is that it requires extensive information sharing between the centralised and decentralised systems (which is impractical over band-limited communication links).

In this paper, we investigate the mixed centralised-decentralised ATM system using a min-max problem posed on a reduced set of admissible FAMs (which will be termed a FAM alphabet) to overcome communication band limits. Our motivation is that consideration of a reduced set of manoeuvre options will lead to a smaller amount of communication traffic. It is then clear that the performance of this mixed ATM system will depend largely on the selected FAM alphabet. Thus, in this paper, we will also propose a design method for FAM alphabet that aims to ensure safe flight behaviour in a broad range of situations.

This paper is structured as follows: Section 2 presents the mixed separation management problem, dynamics, and performance cost. In Section 3, we proposed our FAM alphabet based separation management approach and a design method for FAM alphabets. We then present our simulation studies in Section 4. Some concluding remarks are then presented in Section 5.

2 Problem Formulation

2.1 Mixed Separation Management Problem Description

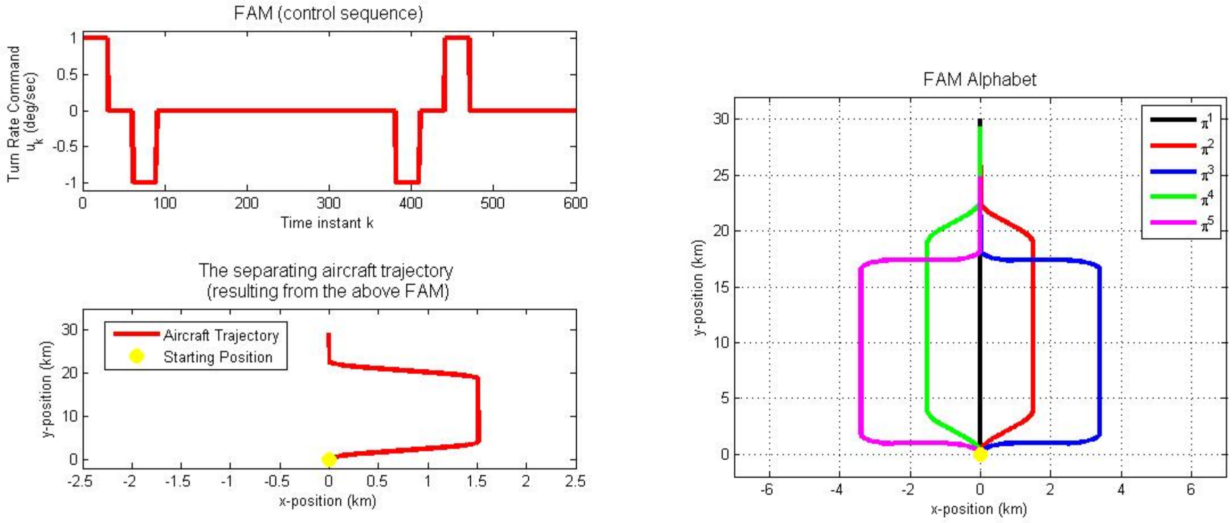
We consider a non-cooperative air traffic separation management problem within one region of airspace, where one aircraft is responsible for all collision avoidance tasks (which we will term the separating aircraft), whilst all other aircraft follow their planned paths. We note that this single separating aircraft assumption is being made for presentation simplicity and the mixed separation management approach can be easily extended so that all aircraft are responsible for collision avoidance tasks.

Now let us consider the following model of air traffic dynamics

$$x_k = f(x_{k-1}, u_k) \tag{1}$$

where $x_k \in \mathbb{R}^d$ describes the state variables containing all air traffic information at time k, and u_k is the flight control action executed by the separating aircraft. We will let $\pi = [u_1, \dots, u_T]$ denotes a sequence of flight control actions or a flight avoidance manoeuvre (FAM), and we will let S_π denotes a set of admissible FAMs. Figure 1a illustrates the difference between a single control action u_k (a command at a particular time instant) and a FAM π. In this figure, the FAM commands the separating aircraft to fly to a parallel track 1.5km to its right, then returns to its original course.

In this paper, we are interested in the problem where control decisions are generated at two different locations: centralised and decentralised



(a) (b)

Fig. 1 Control concepts: (a) single control action u_k, FAM π (sequence of control actions), and the separating aircraft trajectory after executing the FAM π. The FAM commands the aircraft to fly to a parallel track 1.5km to its right, then return to its original course. (b) Aircraft trajectories resulting from the FAM alphabet $\Pi = \{\pi^1, \ldots, \pi^5\}$.

ATM systems, and where the complete air traffic information x_k is not available at either of the two ATM locations (this may be due to sensor limitations, communication limitations, or degradation of the surveillance systems). We will assume that the separating aircraft receives separation instructions from a centralised controller having access to the ground radar, and that the aircraft is also equipped with an onboard separation manager having access to onboard sensors. Hence, in addition to centralised instructions, the aircraft has potential to generate its own instructions based on its own traffic information (which may be different from the information available at the centralised separation management location). We will also assume that the controlled airspace contains aircraft which are not detectable by the ground radar, and other aircraft which are not sensed by the onboard sensors. In this situation, the separating aircraft must select a flight avoidance instruction from a set of candidate instructions generated by both the centralised controller and its onboard controller.

2.2 Mixed ATM Dynamics

For time step $k = 1, \ldots, T$, consider a model of air traffic based on the information separately available at each location as follows:

$$x_k^m = f^m(x_{k-1}^m, u_k) \tag{2}$$

where x_k^m describes the state variables containing all air traffic information available at the mth location at time k (that is, the dynamic states of multiple aircraft). Here, $m = 1$ denotes the air traffic seen by the centralised ATM system and $m = 2$ denotes the air traffic seen by the onboard system. We stress that we have two air traffic pictures in our problem which are separately created at two different ATM locations. Due to the difference in the sensors involved, x_k^1 will often be different from x_k^2.

We also highlight that each ATM location could solve the separation management problem on the basis of its own dynamic model x_k^m to select the most appropriate FAM (and hence the best u_k) from the perspective of its air traffic information. We will denote the FAM posed by the mth ATM location as $\pi^*(m)$. Unfortunately, neither of the separately designed solutions, $\pi^*(1)$

and $\pi^*(2)$, can guarantee safety due to the incomplete nature of information available at either location. This observation motivates the mixed centralised-decentralised ATM problem of determining a FAM π^* that takes due consideration of all available air traffic information, and ensures acceptable aircraft separation if either $m=1$ and $m=2$ is a true description of the real air traffic situation.

2.3 Performance Cost

In this paper, we are interested in determining an appropriate FAM to achieve some performance objectives, especially maintenance of aircraft separation distances. Let $J(m,\pi)$ denote the cost function for using an admissible FAM $\pi=[u_1,\dots,u_T]$ in the mth system (where a large penalty occurs if possible collision events remain in the mth system). For example, this cost function might be described by

$$J(m,\pi)=\sum_{k=1}^{T-1} h(x_k^m,u_k)+g(x_T^m) \tag{3}$$

where $h(\cdot)$ is some running cost and $g(\cdot)$ is some terminal cost. However, more general cost functions may also be considered.

In the standard separation management problem involving no system uncertainties (both ATM locations share the same air traffic information), the optimal mixed control problem can be defined as a problem of finding a FAM π^* such that

$$\tilde{J}(\pi^*)=\inf_{\pi\in S_\pi} J(m,\pi). \tag{4}$$

where $m=1$ or $m=2$ will give the same solution (because ATM locations share the same air traffic information). However, this paper considers the separation management problem where air traffic information available at the two ATM locations are different and possibly conflicting. Hence, in the next section, we will propose a mixed separation management problem of finding the best FAM π^* when there are uncertainties due to the incomplete nature of information that is separately available at the two ATM locations.

3 Proposed Mixed Separation Management

3.1 Robust Decision Approach

In the situations involving system uncertainties, it is often useful to consider a robust or min-max decision problem. Hence, we pose the min-max problem of finding m^* and π^* such that

$$J(m^*,\pi^*)=\inf_{\pi\in S_\pi}\max_{m\in[1,2]} J(m,\pi). \tag{5}$$

This optimised FAM π^* corresponds to a good compromised solution in the sense that, if possible, all collision events in both systems $m=1$ and $m=2$ are avoided even when important air traffic knowledge is spread between the two ATM locations.

Unfortunately, the difficulty in solving this min-max problem is that it requires extensive information sharing between the two locations. That is, all information from one system must be sent to the other system (the costs of using each of the admissible FAMs $\pi\in S_\pi$).

To reduce the amount of shared information, we consider the benefits of restricting admissible FAMs to a small (finite) pre-agreed set of manoeuvres, which will be called a FAM alphabet; this alphabet is denoted as $\Pi\subset S_\pi$, and $\Pi=\{\pi^1,\dots,\pi^N\}$ is a finite set of N admissible FAMs. Figure 1b illustrates an example of aircraft trajectories resulting from a FAM alphabet which consists of 5 FAMs (or control sequences).

The agreed FAM alphabet will be assumed to be available at both ATM locations. Once a FAM alphabet has been agreed, the min-max mixed separation management problem (5) becomes

$$J(m^*,\pi^*)=\inf_{\pi\in\Pi}\max_{m\in[1,2]} J(m,\pi) \tag{6}$$

which will be called the FAM alphabet based mixed separation management problem. We highlight that solution of this alphabet version of the min-max problem only requires transmission of the cost of using each FAM in the FAM alphabet. However, there remains a question of how to design an appropriate FAM alphabet Π, which replaces the set of admissible control actions S_π, such that the robust design problem (5) is reasonably represented by the min-max mixed separation problem (6).

In the next subsection, we present a design method for FAM alphabets.

3.2 Design of Flight Avoidance Manoeuvre Alphabet

The performance of the FAM alphabet based mixed separation management method (6) depends largely on the agreed FAM alphabet Π (see Figure 1b for an example of Π). Thus, we will now present a design method for selecting an appropriate FAM alphabet.

Let S_Π denote a set of candidate FAM alphabets. For a candidate FAM alphabet $\Pi \in S_\Pi$, we define the alphabet criterion $\bar{J}^a(\Pi)$ as

$$\bar{J}^a(\Pi) = \inf_{\pi\in\Pi} \sup_{x_0} J^a(\pi, x_0) \qquad (7)$$

where $J^a(\cdot)$ is the cost function based on the complete air traffic model (1). Since one FAM is used at a time, this criterion determines the cost of a candidate FAM alphabet Π by finding the best min-max cost of the FAM over all initial air traffic engagements x_0.

We then propose that a FAM alphabet Π^* should be selected from the set S_Π so that it minimises the alphabet cost (7) in the sense that Π^* satisfies

$$\bar{J}^a(\Pi^*) = \inf_{\Pi\in S_\Pi} \bar{J}^a(\Pi). \qquad (8)$$

Hence, this design selects the best FAM alphabet over all complete air traffic configurations.

4 Simulation Studies

In this section, we will present a study of our proposed FAM alphabet design method in a standard separation management problem involving two aircraft before presenting a study of our proposed FAM alphabet design method and our FAM alphabet based mixed separation management approach in a three aircraft problem. We consider separation management in a 20km × 20km region of airspace. For simplicity, we assume that the aircraft are flying at the same altitude and speed with similar turn characteristics. We model our aircraft through 3-DOF equations of motion and aircraft's turn rates are limited to $5^\circ/s$. Here, we consider the total control time $T = 600$ seconds and sampling period (time between each time step) of 1 second.

4.1 Ex 1: Design of FAM Alphabet for Standard Separation Management

For illustrative purposes, this first example compares the performance of candidate FAM alphabets with the optimal control solution for a standard ATM problem involving two aircraft. This is the ATM problem examined in [15] using dynamic programming techniques. The purpose of this example is to examine the suitability of reducing the control options to a FAM alphabet, by examining how much performance is lost (compared to the optimal solution, with access to all control commands).

For evaluation purposes, we will consider the following performance cost $J^a(\pi, x_0)$ proposed in [15],

$$J^a(\pi, x_0) = \sum_{k=1}^{T-1} h(x_k, u_k) + g(x_T) \qquad (9)$$

where $u_k \in \pi$ and x_k is the dynamic state of the real air traffic picture at time k starting from x_0.

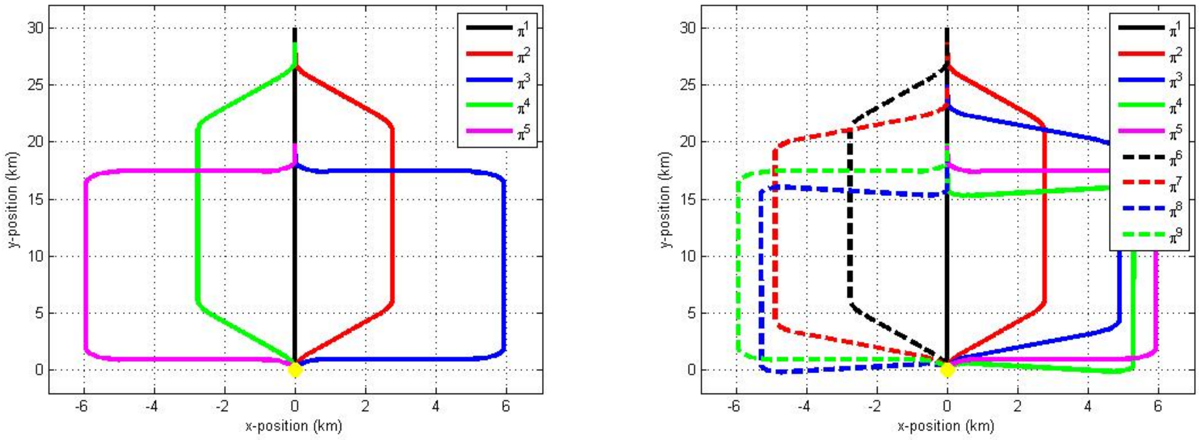
We consider the running cost $h(\cdot)$ which is given by

$$h(x_k, u_k) = u_k^2 + \delta(x_k)^2 + B(x_k) \qquad (10)$$

where $\delta(x_k)$ is the distance in *km* from initial flight path to the separating aircraft (measured perpendicular to the planned flight path) at time k, which will be termed crosstrack error. Here, $B(x_k)$ is the penalty for violating the safe separation distance R_s which is given by

$$B(x_k) = \begin{cases} C^R, & \text{if } r_k < R_s \\ 0, & \text{otherwise} \end{cases} \qquad (11)$$

where r_k is the minimum distance at time k between the separating aircraft and all other aircraft, and $C^R = 1 \times 10^9$ is a large constant chosen to penalise likely collision events.



(a) Π^a

(b) Π^b

Fig. 2 The separating aircraft trajectories when executing each FAM in the FAM Alphabets Π^a and Π^b where the yellow dot is the starting position of the aircraft

Also, we consider the terminal cost $g(\cdot)$ which is given by

$$g(x_T) = 500(\psi_T^a)^2 + 500\delta(x_T)^2 + B^T(x_T) \quad (12)$$

where ψ_T^a is the separating aircraft's heading at time T, and $B^T(x_T)$ is the terminal penalty applied to FAM which leads the separating aircraft to other potential collision events at time T. Here, $B^T(x_T)$ is given by

$$B^T(x_T) = \begin{cases} 0, & \text{if } |\theta_T^i| > 90^\circ \text{ and } \dot{r}_T^i > 0 \\ C^T, & \text{otherwise} \end{cases} . \quad (13)$$

Here, θ_T^i is the heading of the separating aircraft at time T with respect to the line connecting the separating aircraft to the ith other aircraft, and $\dot{r}_T^i$ is the range rate between the separating aircraft and the ith aircraft. Also, $C^T = 1 \times 10^6$ is a terminal cost penalty chosen to be greater than the total of a typical running cost (when no collision events occur).

In this study, we will compare the optimal solution with 2 candidate FAM alphabets Π^a and Π^b consisting of 5 FAMs and 9 FAMs, respectively, as illustrated in Figure 2. The two alphabets involve straight flight, left turns, and right turns. We highlight that Π^b includes all of the FAMs in Π^a, and these alphabets are considered to illustrate the benefits that larger alphabet may have over smaller alphabet.

To illustrate the suitability of FAM alphabets in a standard ATM problem, we use the performance measure (9) in the test cases involving air traffic engagement scenarios with 2 aircraft starting at the same distance from a common waypoint with the incident angle α, and both aircraft flying towards the common waypoint at the same speed, as shown in Figure 3. In Figure 4, we compare the performance of the two FAM alphabets with the optimal solution for the test scenarios with incident angles $\alpha = [40, 45, \ldots, 180]^\circ$. Note that angles less than 40° were not considered due to the limitations in the optimal solution (see [15] for implementation details and limitations).

Figure 4 suggests that the optimal control solution generally performed better than the FAM alphabets (lower costs), and thus illustrates that there is some performance loss in the replacement of S_π by either Π^a or Π^b (but not too much). We also note that Π^b performed better (or no worse than) Π^a, and this suggests that system performance may be increased with the inclusion of FAMs that more closely match the optimal solutions. Note that the costs are large (over 1000 for most cases) as they represent the sum of crosstrack errors squared.

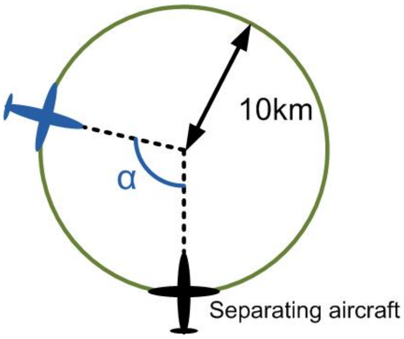


Fig. 3 Test Scenario involving 2 aircraft: separating aircraft (black) and the other aircraft (blue) are on the same circle of radius 10km with incident angle between the two aircraft α, and the two aircraft are approaching each other.

4.2 Ex 2: Design and Performance of FAM Alphabet for FAM Alphabet Based Mixed Separation Management

We now examine our proposed design approach to an FAM alphabet based mixed separation management problem with three aircraft. The purpose of this example is to illustrate the suitability of our proposed alphabet design approach, and also the suitability of our proposed mixed ATM method.

We will first describe the test cases and performance metrics, before presenting an evaluation of the system performance.

4.2.1 Mixed Separation Management Test Cases

For design and simulation purposes, we consider separation management problem between 3 aircraft:

- a separating aircraft sensed by both centralised and decentralised systems,
- an aircraft detectable by the ground radar but undetectable by sensors onboard the separating aircraft, and
- an aircraft undetectable by the ground radar but sensed by sensors onboard the separating aircraft.

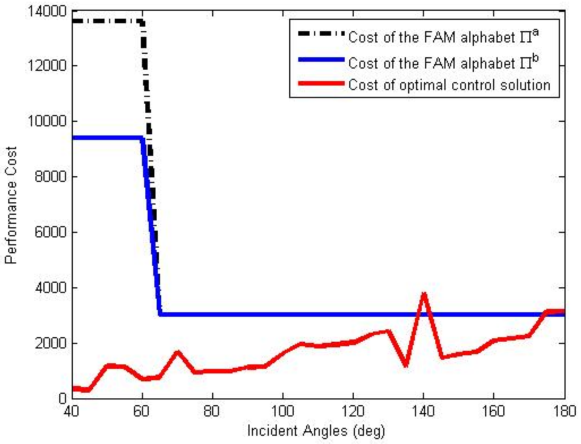


Fig. 4 Comparison of performance costs $\bar{J}^a(\cdot)$ of the optimal control solution and the FAM alphabet Π^a and Π^b

We consider air traffic engagement scenarios where all 3 aircraft are flying towards the same location (centre of the circles) as shown in Figure 5.

In Figure 5, the separating aircraft (black) and the centrally detectable aircraft but unseen by onboard sensor (blue) are placed on the same circle with a radius of 10km while the centrally undetectable aircraft (red) is on an outer circle with a radius of R km centred at the same location as the first circle. Here, we consider 2 different values of R: 13km and 15km. For each R, we consider 4824 test cases with different incident angles $\alpha_1 = [15, 20, \ldots, 345]^\circ$ and $\alpha_2 = [0, 5, \ldots, 355]^\circ$. Note that the incident angles $\alpha_1 < 15^\circ$ and $\alpha_1 > 345^\circ$ are not considered because the two aircraft would be violating the safe separation distance R_s at time $k = 0$.

4.2.2 Performance Measures

In this study, we use two performance metrics to evaluate our proposed mixed ATM method: separation assurance and flight path deviation. The key task of an ATM system is to maintain certain separation distance between aircraft, and hence, separation assurance is an important metric used in evaluating ATM systems. However, it is also desirable that aircraft closely follow their planned flight paths (which may have been designed to

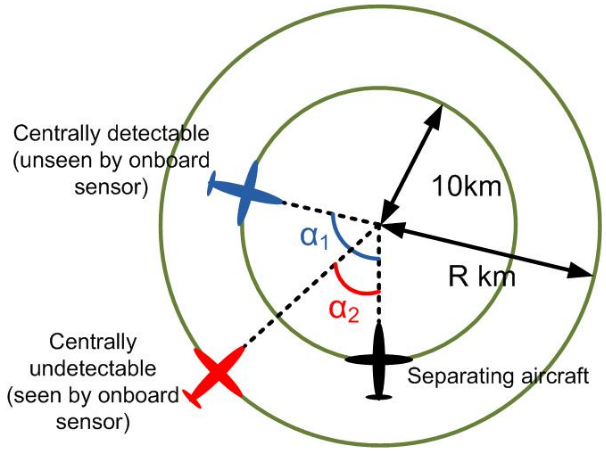


Fig. 5 Test Scenario: separating aircraft (black) and centrally detectable aircraft are on the same circle of radius 10km with incident angle between the two aircraft α_1 while centrally undetectable aircraft (red) is on an outer circle of radius R km with incident angle between the aircraft and the separating aircraft α_2

optimise other flight conditions e.g. flight time).

As the separating aircraft is responsible for all collision avoidance tasks, distances between the separating aircraft and the other two aircraft will be used as an indication of separation assurance. That is, we will use the term "near miss" to refer to an event where the smallest distance between the separating aircraft and the other aircraft (at any time during the entire flight) is less than the safe distance R_s. We will also use the term "collision" to refer to an event where the smallest distance (any time during the entire flight) is less than $R_c = 0.5km$. We will use the numbers of near misses and collisions to evaluate our separation manager in terms of separation assurance.

Moreover, we define flight path deviation Ψ_d as

$$\Psi_d = \sum_{k=1}^{T} (\psi_k^p - \psi_k^a)^2 \Delta t. \qquad (14)$$

where ψ_k^p and ψ_k^a are the planned heading and the actual heading of the separating aircraft at time k, respectively. Here, Δt is the sampling time in seconds. In the following simulation studies, we will use the path deviation averaged over all test scenarios (average path deviation) as a performance measure.

4.2.3 Design of FAM Alphabets for Mixed Separation Management

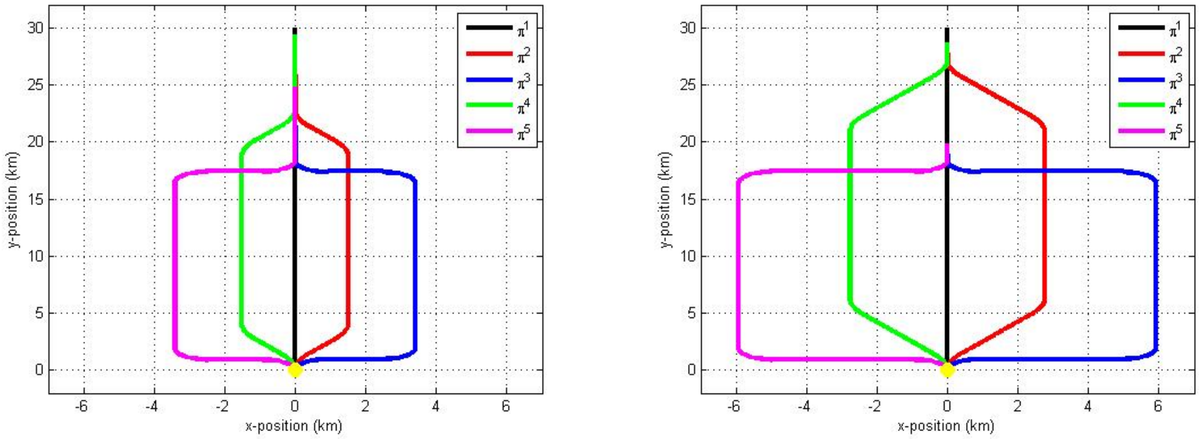
We consider the FAM alphabet based mixed ATM problem (6) with the performance cost $J(m, \pi)$ which is in the form of (3) where $h(\cdot)$ and $g(\cdot)$ are given by (10) and (12), respectively. We note that the running cost $h(x_k^m, u_k)$ and the terminal cost $g(x_T^m)$ are now based on the air traffic seen by the mth controller.

Moreover, we consider 6 candidate FAM alphabets $S_\Pi = \{\Pi^1, \Pi^2, \ldots, \Pi^6\}$ in our study; the candidate alphabets are shown in Figure 6. The first 3 candidate alphabets consist of 5 FAMs representing straight flight, 2 left turns, and 2 right turns. The candidate alphabets Π^4 and Π^5 consist of 7 FAMs representing straight flight, 3 left turns, and 3 right turns. The last candidate alphabet consists of 9 FAMs representing straight flight, 4 left turns, and 4 right turns. We highlight that the last 3 candidate alphabets were selected to investigate the effects larger alphabets have on the performance of the separation manager. Note that Π^4 involves all the FAMs from Π^3 and the smaller left and right turns from Π^2, and Π^5 involves all the FAMs from Π^3 and the larger left and right turns from Π^2. The last FAM alphabet Π^6 combines the FAMs from Π^4 and Π^5.

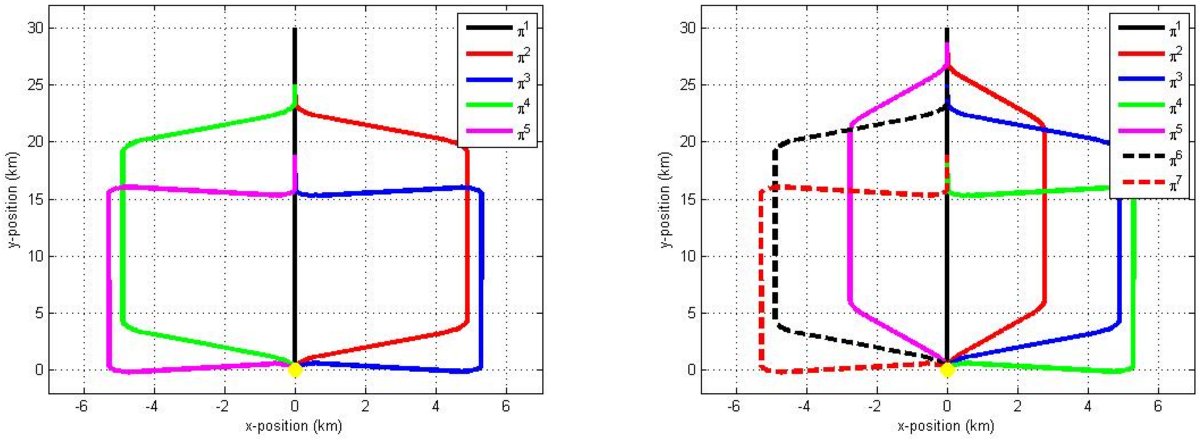
We applied our FAM alphabet criterion (7), where $J^a(\cdot)$ is described by (9), to the set of 6 candidate alphabets taking into consideration the air traffic configurations described in Section 4.2.1. The value of the criterion of each candidate alphabet is shown in the first column in Table 1. It can be seen that the alphabet Π^3, Π^4, Π^5, and Π^6 satisfy our design (8). We highlight that these 4 alphabets share 2 common FAMs, and hence it is possible for the alphabets to have the same costs because our criterion (7) finds the cost of the best FAM for the worst air traffic configuration.

4.2.4 Evaluation of Proposed FAM Alphabet Based Mixed Separation Management

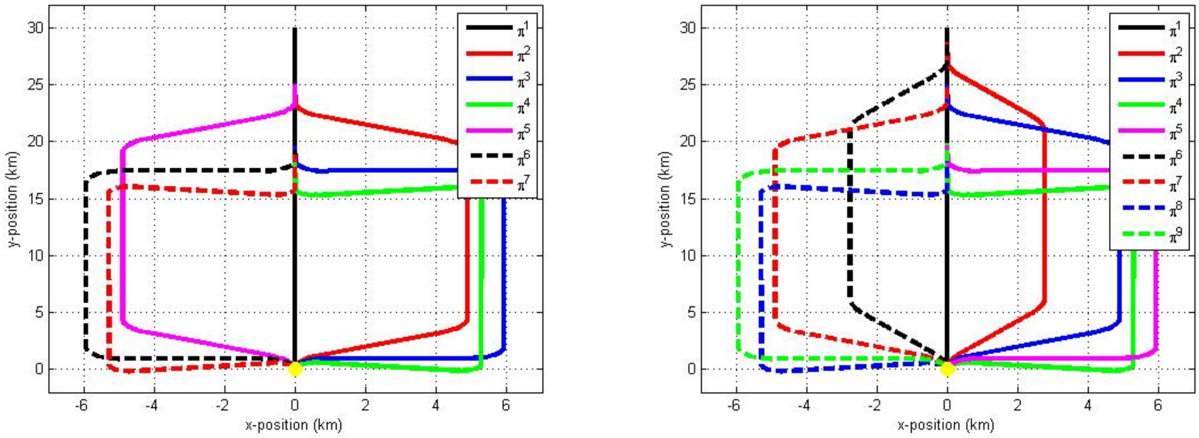
To evaluate our proposed mixed separation management technique and the FAM alphabet design,



(a) Candidate FAM alphabet 1, Π^1 (b) Candidate FAM alphabet 2, Π^2



(c) Candidate FAM alphabet 3, Π^3 (d) Candidate FAM alphabet 4, Π^4



(e) Candidate FAM alphabet 5, Π^5 (f) Candidate FAM alphabet 6, Π^6

Fig. 6 The separating aircraft trajectories when executing each FAM in each candidate FAM Alphabets where the yellow dot is the starting position of the aircraft

Table 1 FAM alphabet design and performance of mixed separation manager

FAM Alphabet	Alphabet Criteria ($\times 10^{11}$)	Near Misses	Collision Events	Average Path Deviation Cost	Message Size (Bytes)
1	2.56	3344	48	208.62	40
2	1.50	432	0	225.85	40
3	1.42	240	0	296.84	40
4	1.42	112	0	202.89	56
5	1.42	224	0	296.98	56
6	1.42	110	0	203.07	72

Table 2 Performance comparison between mixed centralised-decentralised, purely centralised, and purely decentralised separation managers where all separation managers use the FAM alphabet Π^6

Separation Manager	Near Misses	Collision Events	Average Path Deviation Cost
Mixed	110	0	203.07
Purely Centralised	2205	736	124.80
Purely Decentralised	1602	5286	43.41

we conducted simulation studies involving 9648 test scenarios, as described previously. The performance of each candidate FAM alphabet and the mixed separation management method (6) is also illustrated in Table 1. In terms of separation assurance, it can be seen that our simulated performance corresponds well with our FAM alphabet design. That is, the alphabets with smaller costs lead to the smaller numbers of near misses and collision events. The results also suggested that the separation manager performed better as the number of FAMs in the alphabet increases. That is, Π^4 and Π^5 outperformed Π^3 (which performed the best out of the FAM alphabets with 5 FAMs) in terms of separation assurance, and Π^4 outperformed other alphabets in terms of path deviation. Also, Π^6 outperformed Π^4 and Π^5 in terms of separation assurance and perform comparably well in terms of path deviation.

Table 1 also illustrates the size of a message required to send the costs of each FAM (a double-precision number) in each candidate FAM alphabet. Although the performance of the mixed system improves with the number of FAMs in the alphabet, we note that the amount of information sharing is also increased with the number of FAMs as illustrated in Table 1. Hence, this result suggests that there is a trade-off between performance and communication bandwidth in mixed separation management system.

Now, to illustrate the benefits of our proposed FAM alphabet based mixed ATM system, we compare the performance our mixed ATM approach with purely centralised and purely decentralised approaches; the results are shown in Table 2. From Table 2, it can be seen that our proposed mixed ATM system outperformed the purely centralised and purely decentralised separation managers in terms of separation assurance. That is, our mixed ATM system is the only separation manager which led to no collision events. Also, our proposed mixed system led to the smallest number of near misses (110 near misses). However, the mixed separation manager resulted in larger path deviation cost. This is because the purely centralised and purely decentralised systems were unable to detect a number of potential collision events and hence, did not guide the separating aircraft away from its original path (when it was probably desirable to do so).

5 Conclusion

In this paper, we proposed a mixed centralised-decentralised air traffic management system utilising a min-max decision approach based on a reduced set of pre-agreed flight avoidance manoeuvres (termed a FAM alphabet). We also presented a design method for selecting a suitable FAM alphabet. Studies were presented that illustrated the superior performance of our proposed FAM alphabet based mixed separation management approach compared to existing centralised and decentralised ATM methods, and also showed that the performance of our proposed approach depends on the pre-agreed FAM alphabet.

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