AUTOMATED CENTRALISED SEPARATION MANAGEMENT WITH ONBOARD DECISION SUPPORT

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Abstract

This paper proposes a novel automated separation management concept in which onboard decision support is integrated within a centralised air traffic separation management system. The onboard decision support system involves a decentralised separation manager that can overrule air traffic management instructions under certain circumstances. This approach allows the advantages of both centralised and decentralised concepts to be combined (and disadvantages of each separation management approach to be mitigated). Simulation studies are used to illustrate the potential benefits of the combined separation management concept.

1 Introduction

Air traffic management (ATM) systems continue to face increasingly high demand for air travel [1–4]. Maintaining separation between two aircraft involves the process of detecting potential collision events and providing separation commands [1]. The existing air traffic separation management system involves human air traffic controllers monitoring all traffic for the possible emergence of potential collisions, and then issuing separation instructions that ensure the safe operation of all aircraft. Such a system seems inadequate for the growing volume of traffic [1–4]. Several concepts have been proposed to overcome the safety risks that are growing for future ATM operations, including automated system in which computer-based separation management is conducted at either central or regional location in a manner that mirrors the current human-centric operation paradigm. This paper investigates new automated air traffic management concepts that extend these proposed automated separation management concepts in a manner that increases system safety.

The primary purpose of ATM operations is to ensure aircraft remain functional and collision-free. Over recent years, many automated separation management techniques have been proposed in the literature; the two dominating approaches are those based on decisions made at a centralised location [1, 4–10] and those based on decentalised decisions [2, 11–15].

Centralised approaches assume that all air traffic management is conducted at a single location and such a completely centralised system can produce more efficient solutions in terms of airspace utilisation [3]. For example, a mixed integer programming (MIP) centralised separation management algorithms is proposed in [5] that seeks to find optimal speed and heading changes. In this MIP approach, speed and heading changes are separately selected and then represented as constraints so that an overall solution can be found using optimisation tools such as CPLEX [5]. Other alternative centralised approaches include genetic algorithm based approaches [6] and approaches in which instructions are selected from a discrete set of predefined maneuvers [2,7].

Alternatively, decentralised separation management approaches allow individual aircraft to make some planning decisions, for example, the free-flight concept of the Next Generation Air Transportation System [4]. For example, in [11], a robust receding horizon control approach is proposed for the horizontal separation management problem where air traffic information is obtained locally by each aircraft. In [12], dynamical game theory is applied to horizontal separation management problem in a situation where each aircraft is assumed to have the knowledge of the current trajectories of every other aircraft but not their intentions (perhaps some aircraft have communication problems). Thus, the proposed algorithm generates collision avoidance maneuvers considering the worst possible actions of the other aircraft. More recently, a decentralised separation management algorithm based on the satisficing game theory is proposed in [2]. This satisficing approach differs from other optimisation approaches in that it does not try to find a single best solution, but rather attempts to obtain a set of acceptable maneuvers by discarding maneuvers that would lead to potential collisions.

Whether considering centralised or decentralised separation management approaches, it is important to realise that increased levels of automation place greater reliance on the computational, communications, and surveillance infrastructure of the ATM system; hence, achieving reliable separation management becomes more difficult (because system failure becomes more likely). Unfortunately, centralised separation management approaches tend to be complicated, to be more susceptible to system failures, and to fail more substantially [3, 16]. Alternatively, although decentralised separation management approaches are more robust to system failures, these approaches can fail in a cascaded manner (in situations easily managed by centralised approaches) due to the local nature of available information [1–3, 11]. For these reasons, neither approach seems completely acceptable, and understanding the concept of "graceful degradation" of an ATM system [4] during system failures becomes more important.

In this paper, we introduce the concept of onboard decision support for the purpose of mitigating the drawbacks of centralised and decentralised systems as well as minimising the impact of system degradation. We highlight that combined centralised and decentralised decisions have previously been proposed for the purpose of automating free flight concepts (where individual aircraft can make decentralise decisions about preferred routes, but safety is maintained by an overall centralised manager) [10]. In this paper, we will consider a different combination of centralised and decentralised decisions. We will propose a new operational concept in which a decentralised separation manager provides an addition layer of separation protection to supplement the protection provided by a centralised separation manager. Our principle motivation for this proposal is to mitigate for the impact of local phenomena that are difficult to handle using a centralised separation approach. In this paper, simulation studies are used to examine the benefits of our proposed algorithm.

This paper is structured as follows: Section 2 formulates the air traffic management problem. Our centralised separation management approach with onboard decision support is described in Section 3. In Section 4, the results of various simulation studies are presented. Finally, some conclusions are provided in Section 5.

2 Problem Formulation

This paper considers the problem of providing en-route separation management support within one region of airspace (and this region may or may not have radar support). We will assume that there may be up to 50 aircraft present in the airspace at any time instant and that the safe separation distance between any two aircraft is $2km$. For simplicity in our simulation studies, these aircraft will be assumed to be flying at similar air speeds with similar turn characteristics (but these two assumptions can easily be relaxed). Further, the airspace is assumed to contain aircraft operating in different states of responsivenesses to ATM instructions. In particular, we assume that three types of aircraft responsivenesses are possible:

A. Fully cooperative aircraft

B. Detectable but non-cooperative aircraft

C. Undetectable aircraft

As the name suggests, fully cooperative aircraft are those which respond to instructions issued to them by a central separation manager. Detectable but noncooperative aircraft are aircraft that do not execute commands issued to them by any separation manager. Undetectable aircraft are aircraft that are not detectable by the centralised separation management system (but are detectable by sensors onboard other aircraft, if within the detection ranges of their sensors). Here, situation B might correspond to an aircraft with communication equipment problems, whilst situation C might correspond to radar or ADS-B failures (or similar).

In this paper, we will assume that a centralised separation manager may only provide heading instructions to aircraft (not speed changes), whilst a decentralised separation management algorithm may instruct both heading and speed changes. The decentralised system under consideration will be assumed to have access to onboard sensors (with limited detection range).

In the next section, we will propose a new automated separation management approach involving centralised separation management with onboard decision support. This additional onboard decision support system provides an additional layer of separation management support between the centralised separation management layer (or standard air traffic control) and the emergency collision avoidance systems such as TCAS. The proposed role of an onboard decision support layer within the operations of an air traffic management system is illustrated in Figure 1.

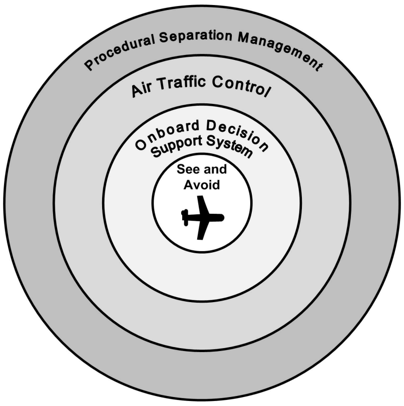

Fig. 1 Region of Operation of Centralised Separation Management and Onboard Decision Support Layers

3 Centralised Separation Management with Onboard Decision Support

Consider the concept of operation involving centralised separation management commands and onboard decision commands that is shown in Figure 2. Specifically, our onboard decision support concept combines centralised and decentralised separation management by an appropriate switch between the two systems. The proposed approach aims to improve separation assurance in an air traffic environment. We highlight that at any time instant, only one separation management is active.

We now outline each of the three major components of our onboard decision support concept.

3.1 Centralised Separation Management

We begin by explaining the centralised component of our candidate system. In this study, we assume that centralised separation management is provided by an algorithm based on the Bramson "tau" criterion for identifying collision threats [17]. An air traffic manager based on this criterion triggers separation commands when the distance at the closest point of approach (CPA), d_{cpa} is less than a predefined distance threshold, d_{th}. The Bramson "tau" criterion τ_b is given by [17]

$$\tau_b = -\frac{r - \frac{d_{th}}{r}}{\dot{r}} \qquad (1)$$

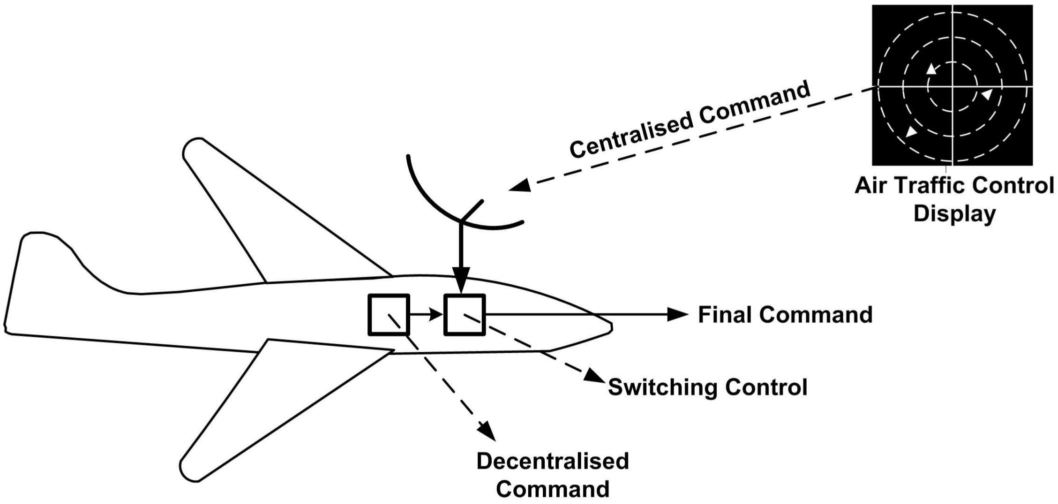

Fig. 2 Concept of Centralised Separation Management with Onboard Decision Support

where r is the range between the two aircraft and $\dot{r} = -v_{rel} \cos\theta$ is the range rate. Here, θ is the incident angle and v_{rel} denotes the relative velocity of the two aircraft. The geometry of the distance at CPA is illustrated in Figure 3. It is noted that this Bramson "tau" criterion is most effective when the range rate is constant [18]. It can be shown that when d_{cpa} is equal to d_{th}, that τ_b is equal to time to CPA, t_{cpa} [17]. When d_{cpa} is less than d_{th}, $\tau_b < t_{cpa}$.

In this study, the predefined distance threshold is set to be $2km$. If a potential collision has been declared, then the centralised system under study here selects a prescribed separation heading command for each aircraft from a predefined set depending on the range, the incident angle, and relative speed of the two aircraft (as shown in Tables 1 and 2). Table 1 details the prescribed heading changes for aircraft interacting with a fully operative aircraft. Table 2 details the prescribed heading changes for aircraft interacting with a detectable but noncooperative aircraft. We highlight that it makes sense that larger heading instructions might be required to safely avoid noncooperative aircraft (because only one aircraft is maintaining separation rather than separation being a shared responsibility between both aircraft).

In addition to the instructions provided in Table 1 and 2, the separation manager will also consider the aircraft's next destination in its calculation of heading instruction. In particular, the final heading instruction is produced by adding the heading change selected from Table 1 or 2 to the heading required to reach the next waypoint. In the case of multiple collision threats, heading changes are chosen for each potential collision pair. The final command for an aircraft is produced by adding together all selected heading changes for each of this aircraft's collision pairs, and then adding this total heading change to the heading required to reach the aircraft's next waypoint.

3.2 Onboard Decision Support Component

We now describe the decentralised component of our proposed separation management approach. In our study, a decentralised separation manager is assumed to operate independently on each aircraft and to have access to suitable onboard sensors (with an assumed sensing range of $2.5km$). Thus, this decentralised separation manager gives each aircraft an independent, but limited, ability to detect collision threats that might be missed by the centralised system (such as small aircraft or UAV). Moreover, we will assume that if an aircraft detects a potential collision within the prescribed range, then the decentralised separation manager can trigger collision avoidance maneuvers.

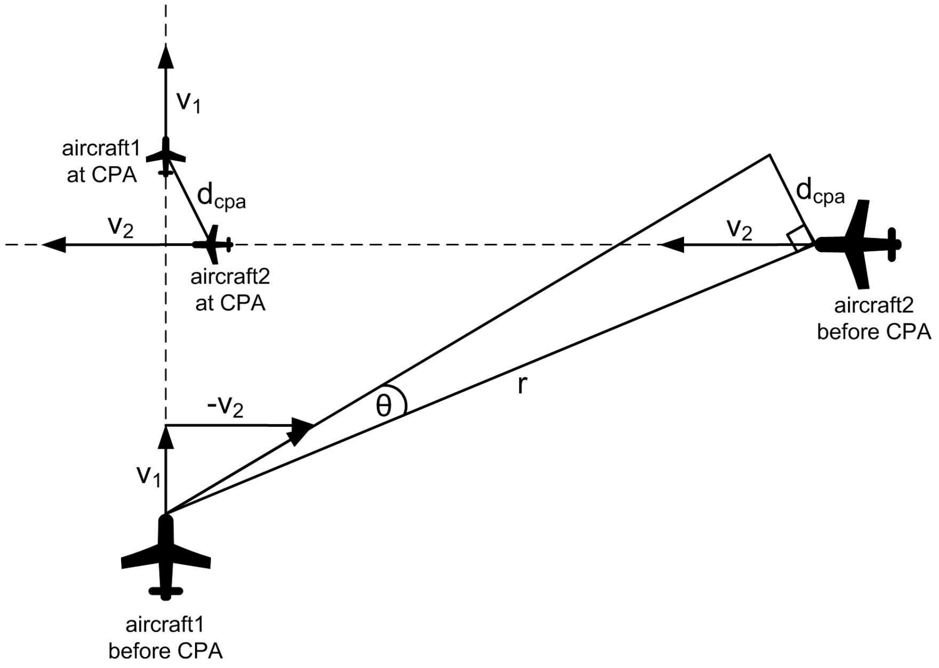

Fig. 3 Distance at the Closest Point of Approach

In a manner similar to above, if our proposed decentralised separation manager detects a potential conflict, then prescribed separation instructions are issued as described in Table 3. As before, in the case of multiple collision threats, a separation command is chosen for each potential collision pair. The final command for the aircraft is produced by adding together all separation maneuvers. We highlight that aircraft's next destination is not considered in the heading instructed created by the decentralised separation manager.

We stress that due to the range of detection considered in our study the concept presented here is different from emergency collision Furthermore, avoidance systems such as TCAS. In some sense, our proposed decentralised system can be considered to trigger moderate separation maneuvers rather than the extreme maneuvers triggered by an emergency collision avoidance system.

3.3 Switching Rule

Finally, we complete the description of our proposed separation managenment approach by describing the rule for selecting between centralised and decentralised instructions. For the purpose of this study, we assume that the centralised separation manager is active for the majority of the flight. A switch from centralised to decentralised system occurs only when the separation distance between the aircraft and a potential collision is less than $2.3km$ and the system switches back to commands from the centralised separation management system when the separation distance is more than $2.3km$. This switching method is illustrated in Figure 4.

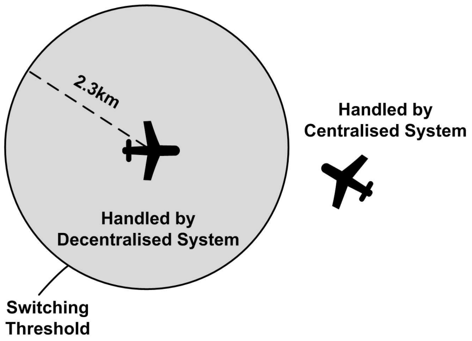

Fig. 4 Switching Method

4 Simulation Studies

In this section, we present our simulation studies of the proposed centralised separation man-

Table 1 The Prescribed Centralised Separation Commands for Aircraft in Conflict with Fully Cooperative Aircraft

Separation Distance	Incident Angle	Relative Speed	Separation Maneuver (Heading Change)
$\geq 1km$	$< 45^o$	Slower/Same Speed	Turn 60^o away from the other aircraft
$\geq 1km$	$< 45^o$	Faster	Stay on course
$\geq 1km$	$\geq 45^o$	Any	Turn 90^o to the right
$< 1km$	Any	Any	Turn 180^o

Table 2 The Prescribed Centralised Separation Commands for Aircraft in Conflict with Detectable but Noncooperative Aircraft

Separation Distance	Incident Angle	Separation Maneuver (Heading Change)
$\geq 1km$	$< 45^o$	Turn 60^o away from the other aircraft
$\geq 1km$	$\geq 45^o$	Turn 180^o
$< 1km$	All	Turn 180^o

agement with onboard decision support. This study compares the proposed system with a pure centralised separation management approach and a pure decentralised separation management approach. Our simulations are limited to horizontal aircraft dynamics and hence, we utilise 3-DOF equations of motion in our aircraft trajectory generation. We assume that the maximum turning rate of each aircraft is $3^o/s$. We also assume that the maximum speed of each aircraft is $65m/s$ and the minimum speed of each aircraft is $35m/s$. To avoid creating extreme maneuvers, we will limit the acceleration of each aircraft to $1m/s^2$.

4.1 Test Scenarios

This simulation study involves a varying number of aircraft in six different air traffic engagement configurations: head-on collision, star configuration, wall configuration, trail collision, closely paralleled, and converging trail collision. These six configurations are described below:

- Head-on collision: this scenario involves two aircraft flying directly towards each other, for more information see [19].

- Star configuration: this engagement is when more than two aircraft are flying towards a common position in the airspace at the same speed i.e. the aircraft are converging to a centre point. An example of star configuration is illustrated in Figure 5. This configuration is introduced in [13]. We also consider two special sub-cases of this engagement type:
  - Small incident angle: this engagement is when aircraft are flying towards a common position at the same speed and the incident angle between adjacent aircraft is less than 15 degrees.
  - Large incident angle: similar to the small incident angle but the aircraft are flying towards a common position at the incident angle between adjacent aircraft is more than 60 degrees.

- Wall configuration: this scenario involves an aircraft flying towards a wall of two or more aircraft that are flying at the same speed in the opposite direction as shown in Figure 6. This configuration is also introduced in [13].

- Trail collision: this scenario involves two or more aircraft flying in the same direction in a straight line and the aircraft at the back

Table 3 The Prescribed Decentralised Separation Commands

Separation Distance	**Incident Angle**	**Relative Speed**	**Heading Change**	**Speed Change**
$< 1km$	$< 45^o$	Same Speed	Turn 180^o	No Change
	$< 45^o$	Slower		$30m/s$
	$< 45^o$	Faster		$-30m/s$
	$\geq 45^o$	Any		$-30m/s$
$1 - 1.5km$	$< 45^o$	Slower/Same Speed	Turn 90^o away from the other aircraft	No Change
	$< 45^o$	Faster	Stay on Course	
	$\geq 45^o$	Slower/Same Speed	Turn 150^o away from the other aircraft	
	$\geq 45^o$	Faster	Turn 90^o away from the other aircraft	
$\geq 1.5km$	$< 45^o$	Slower/Same Speed	Turn 60^o away from the other aircraft	No Change
	$< 45^o$	Faster	Stay on Course	
	$\geq 45^o$	Slower/Same Speed	Turn 90^o away from the other aircraft	
	$\geq 45^o$	Faster	Turn 60^o away from the other aircraft	

is flying faster than the aircraft in front of it, for more information see [19].

- Closely paralleled: this engagement is when aircraft are flying next to each other in the same direction and the distance between adjacent aircraft is less than the safe separation distance.

- Converging trail collision: this scenario combines the Star configuration with the Trail collision engagements together as illustrated in Figure 7. This scenario is introduced in [10].

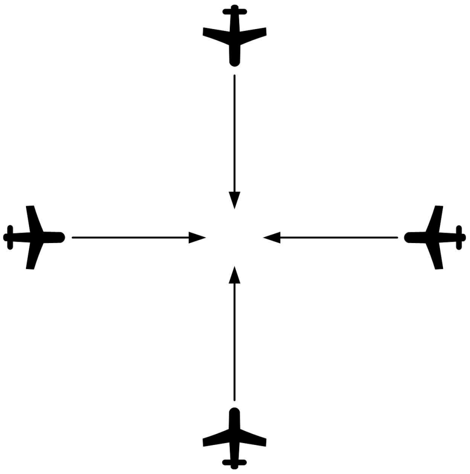

Fig. 5 Test Scenarios: Star Configuration

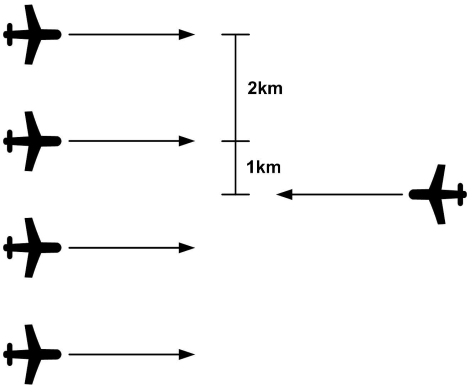

Fig. 6 Test Scenarios: Wall Configuration

4.2 Performance Metrics

Comparison between different separation management approaches can be made on the basis of two performance metrics: minimum separation distance and path deviation. Minimum separation distance metrics relate to the smallest distance between any two aircraft while path deviation metrics measure the total amount of heading changes made by all aircraft within the controlled airspace. The idea is that a good separation management approach will ensure minimum distance does not violate some lower bound whilst also ensuring that aircraft do not deviate too much from their planned path. In the following examples we will actually employ four different metrics to understand separation performance: the instantaneous minimum distance, the (overall) mini-

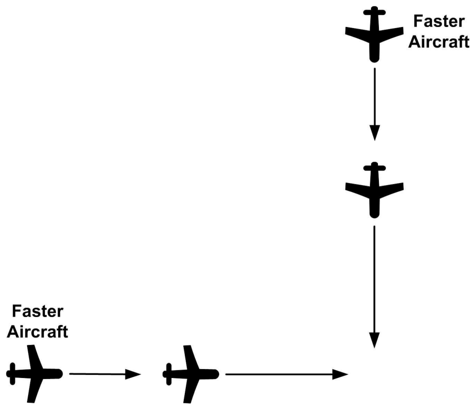

Fig. 7 Test Scenarios: Converging Trail Collision

mum distance, the accumulated path metric and the (overall) path metric cost. For N aircraft, the instantaneous minimum distance D_k, at time k, is the smallest distance given by

$$D_k = \min_{i,j\in[1,\ldots,N]} d_k^{ij} \qquad (2)$$

where d_k^{ij} is the distance between the ith and the jth aircraft at time k. The (overall) minimum distance can then be defined as the minimum distance over the whole period being considered.

We also define the accumulated path metric cost J_k of N aircraft to be the cost of path deviation up until k, which can be expressed as

$$J_k = \sum_{\ell=1}^{k}\sum_{i=1}^{N}\left(\psi_i^c(\ell)-\psi_i^p(\ell)\right)^2 \Delta t(\ell) \qquad (3)$$

where $\psi_i^c(k)$ and $\psi_i^p(k)$ are the commanded heading and the original (if no conflict occurred) heading of the ith aircraft at time k, respectively. Here, $\Delta t(k) = t(k) - t(k-1)$ is the time in seconds between the commanded heading sent at time k and the previous command at time $k-1$.

Finally, if there are a total of T commanded headings, the path metric cost function is defined as J_T.

4.3 Results

We will first present an illustrative example that compares the performance of

- A pure centralised separation management approach (the bramson "tau" criteria approach described in Section 3.1),
- A pure decentralised separation management approach (the approach described in Section 3.2), and
- Our proposed onboard support separation management approach.

After presenting this illustrative approach, we will present an overall comparison study of the same algorithms.

4.3.1 *Fully Cooperative Trail Collision Engagement*

Consider an illustrative case involving a potential trail collision with 3 fully cooperative aircraft. In this fully cooperative scenario, we expect the pure centralised approach to achieve the most efficient air traffic management. Figure 8 shows the instantaneous minimum distance whilst Figure 9 shows the accumulated path metric achieved by all three candidate approaches during the encounter. Figure 8 highlights that all three seperation manager successfully maintain separation at the 2km level; however, Figure 9 highlights that the pure decentralised approach achieves this traffic management outcome with the smallest amount of path deviation.

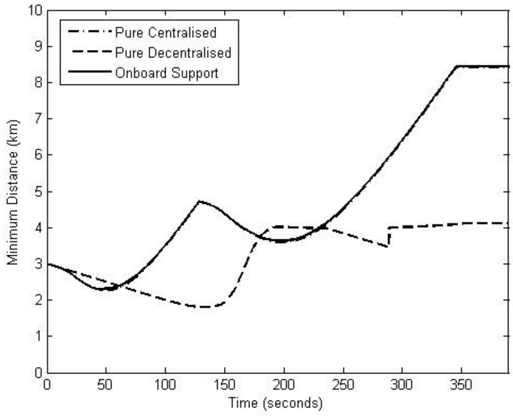

Fig. 8 Illustrative Test Case: Minimum Distance Performance for Trail Collision with 3 Fully Cooperative Aircraft

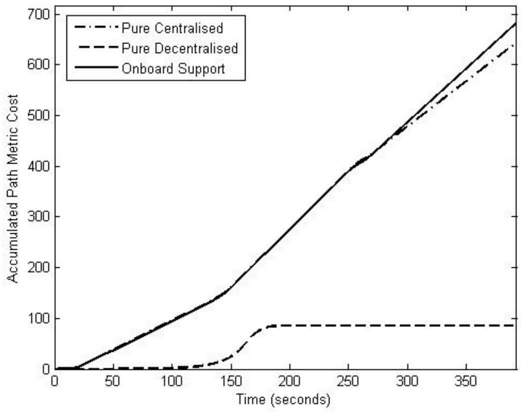

Fig. 9 Illustrative Test Case: Flight Path Deviation Performance for Trail Collision with 3 Fully Cooperative Aircraft

4.3.2 Comparison Study: Trail Collisions

We will now provide a more extensive comparsion study of the trail collision traffic pattern. Each separation management algorithm under consideration was examined in three test scenarios: all fully cooperative aircraft, cooperative aircraft plus one detectable but noncooperative aircraft, and cooperative aircraft plus one small centrally undetectable aircraft. A comparison study of the separation management algorithms is presented in Table 4. For the case of all fully cooperative aircraft, the pure centralised approach outperforms the other systems in terms of minimum distance while the pure decentralised system leads to the smallest amount of path metric cost. However, for other test cases, our onboard decision support approach outperforms the pure centralised system in terms of minimum distance and outperforms the pure decentralised system in terms of flight path deviation. We highlight that the centralised system fails to maintain separation whenever there are any aircraft that are not fully cooperative (during the investigated trail collision engagements).

4.3.3 Other Collision Geometries

The results of the above comparison studies were repeated in the Head-on collision (2 aircraft), Star configuration (4 and 8 aircraft), Small incident angle configuration (2, 3, 4, and 5 aircraft), Large incident angle configuration (2 and 3 aircraft), Wall configuration (3 and 5 aircraft), Closely paralleled configuration (3 and 5 aircraft) and Converging trail collision (4 aircraft).

In all these cases, the pure centralised approach was most efficient in the fully cooperative scenario. However, the centralised with onboard support was most efficient when in the single detectable but noncooperative aircraft scenario, and a single undetectable target scenario.

Our results suggest that our proposed onboard decision support concept successfully mitigates the drawbacks of pure centralised system when noncooperative or undetectable aircraft is present. The proposed system also manages the collision threats with a smaller amount of deviation than the pure decentralised system in the noncooperative and undetectable aircraft cases.

5 Conclusion

In this paper, we examine the potential benefits of including onboard decision support within a centralised air traffic management environment. Our simulation studies examined an extensive number of scenarios to illustrate that an onboard decision capability allows some of the positive characteristics of decentralised management concepts (especially redundancy) to be combined with the overall optimality of centralised management concepts.

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Table 4 Comparison study: Trail Collision—3 Aircraft

Aircraft Configuration	Separation Management	Minimum Distance (km)	Path Metric Cost
Fully Cooperative	Centralised	2.27	644.2395
	Decentralised	1.80	85.4562
	Onboard Support	2.29	683.0636
One Noncooperative	Centralised	0.95	210.2046
	Decentralised	1.80	117.4229
	Onboard Support	1.64	87.0174
One Undetectable	Centralised	0.00	0.000
	Decentralised	1.80	117.6132
	Onboard Support	1.65	85.3397

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