SEPARATION MANAGEMENT APPROACHES DURING PERIODS OF COMMUNICATION FAILURE

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Keywords: *Conflict resolution, centralized separation management, decentralized separation management*

Abstract

New air traffic automated separation management concepts are constantly under investigation. Yet most of the automated separation management algorithms proposed over the last few decades have assumed either perfect communication or exact knowledge of all aircraft locations. In realistic environments, these idealized assumptions are not valid and any communication failure can potentially lead to disastrous outcomes. This paper examines the separation performance behavior of several popular algorithms during periods of information loss. This comparison is done through simulation studies. These simulation studies suggest that communication failure can cause the performance of these separation management algorithms to degrade significantly. This paper also describes some preliminary flight tests.

1 Introduction

In recent years, air traffic management systems have faced increasing levels of air traffic demands [1]. Current solutions to congestion problems have included building more facilities, hiring more controllers and expanding existing Air Traffic Control technologies. These patchwork solutions have been only marginally effective, at a huge cost [2]. With the expected air traffic to grow from roughly 45,000 daily flights to 61,000 daily flights in the next ten years [2], there is increasing motivation to improve the efficiency of the air traffic management process by investigating the use of automation technologies [3]. In this regard, there has been some notable work in the area of next generation air traffic management; two examples of these programs are the SESAR project in Europe and the NextGen project in US. These two projects are different in scope, but they share a common understanding of a possible future air traffic management capability, which would include automation functions that assist the decision making of air traffic controllers. However if these automated concepts are to be adopted then the safe guards that are present in current operational procedures will no longer be sufficient. Such automated systems require different types of safe guards.

Safety in air traffic operations is generally understood through the five layers of safety processes and systems that are shown in Figure 1 [4]. These layers provide multiple levels of collision protection and, as such, each of these layers would have to fail in order for a mid air collision to occur. This layered approach starts in Layer 1 which contains the basic procedures and structure of airspace management (things like operational altitudes and predefined routes) that provide the basic framework or air-traffic operation. In the 2nd and 3rd layers an air traffic management system performs aircraft traffic separation management. Layers 4 and 5 related to emergency safety systems that are beyond the scope of this study.

This paper is specifically focused on the (automated) separation management system which has the task of maintaining safe separation distances between aircraft and, in the event of a potential conflict arising, this system also has the task of resolving conflicts in a safe manner. However if a communication failure event occurs, there is a possibility that a given separation management system might incorrectly handle the information available, and that these incorrect actions might lead into a mid-air collision. This the issue investigated in this paper.

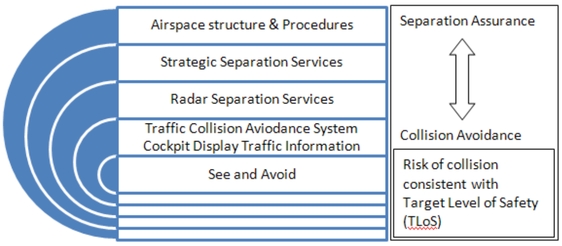

Figure 1: Layers for Air Traffic Separation System

The key contribution of this paper is comparison of performance degradation in separation management during communication failure; this paper outlines the need to develop an automated separation management approach that has robust behavior with respect to the communication issues that arise in realistic environments.

For this purpose, we present a simulation study that investigates the performance of several separation management approaches during communication failure. Whilst the complete loss of a central communication network would clearly cause total failure of centralized separation management, our simulation study also suggests that loss of communication with just one aircraft may significantly reduce the performance of both centralized and decentralized separation management algorithms. The study also suggests that the degree of performance degradation depends on the nature of the air traffic scenario. This paper finishes by presenting details of our initial flight test involving real aircraft. These initial flight tests did not investigate the impact of communication failure, but are precursors to future testing of new air traffic management concepts that are robust to some types of communication problems.

This paper is structured as follows: Section 2 introduces the five separation management approaches that are compared in this comparison study. Section 3 presents the results of our communication failure study. Section 4 provides a description of our initial flight test campaign. Finally, Section 5 summarizes our findings and concludes the paper.

2 Separation Management Algorithms

There are several ways to categorize separation management approaches; most of the current separation management systems can be characterized as being either a purely centralized or purely decentralized approach. A centralized separation management approach involves one central decision location with access to all information making decisions for all aircraft. In comparison, a decentralized separation management approach involves individual aircraft making their own individual decisions about how to achieve separation based on on-board information available to the aircraft.

In the study presented in this paper, two centralized separation management (Satisficing Approach [5], Delay Ranking Approach [6]) and three decentralized separation management approaches (Decentralized Reactive Collision Avoidance Approach [7], Myopic Decentralized Approach [8], Look-ahead Decentralized Approach [8]) are examined and compared. We briefly outline these algorithms below.

2.1 Satisficing Approach

The Satisficing separation algorithm is a centralized approach to separation management presented by Archibald *et al* [5]. In this approach collisions are avoided through the joint actions of all aircraft. In response to a potential mid-air collision, each aircraft has five directional options to choose from: ±2.5 degrees, ±5 degrees, 0 degrees. Choice among these options will be made on the basis of two properties of the aircraft involved in the deconfliction process: selectability and rejectability. A suitable direction choice is determined by utilizing these two properties. The fundamental difference between the satisficing approach and other conflict resolution approaches is that the satisficing approach does not attempt to find an optimal solution. Instead, each aircraft determines the set of acceptable avoidance maneuvers by eliminating as many infeasible choices as possible based on safety and efficiency concerns. Aircraft heading can then be chosen from remaining alternatives. Further details on this method are presented in reference [5].

2.2 Delay based Ranking Separation Algorithm

The Delay based Ranking Separation Algorithm was proposed by Qian Hui *et al* [6]. This algorithm is a centralized approach that is similar to Satisficing approach in the sense that the algorithm orders the aircraft by priority and then selects aircraft headings from a discrete set of options. However, in the delay ranking algorithm, the rank of each aircraft is based on their accumulated flight hours and the delay they have already experienced. Figure 2 illustrates this concept.

After the aircraft ranking is determined, their individual responses to a conflict can be selected from 5 different heading change options: 0 degrees, ±2.5 degrees, ±5 degrees. A new heading will be selected to avoid conflicts; however an aircraft only needs to consider conflicts involving higher ranked aircraft. That is, the highest rank aircraft takes no actions; the 2nd highest aircraft only takes actions to avoid the highest ranked aircraft, etc. At any stage, if all five heading changing options for a particular aircraft result in a conflict, then the search will revert up a level and a higher ranking aircraft will be forced to modify its heading choice. This process continues until all aircraft have successfully selected their own heading change. Further details on this method are presented in reference [6].

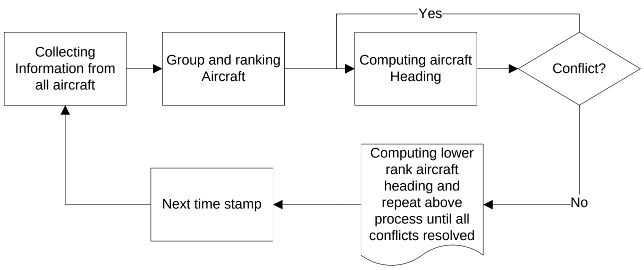

Figure 2: Process of Delay based Ranking Separation Algorithm

2.3 Decentralized Reactive Collision Avoidance Approach (DRCA)

The DRCA method developed by Lalish *et al* [7] adopts the collision cone concept to perform conflict resolution. In this approach, a conflict is defined as occurring when two vehicles at constant velocity will collide at some future point. Safety is achieved in two layers. In the first layer, the DRCA method first resolves current aircraft conflicts using deconfliction maneuvers, which consists of "hard turn left" for any aircraft involved in a conflict. During the second layer, aircraft are instructed in a manner that ensures that they maintain conflict free trajectories until they reach a situation where they can safely revert to their original planned heading. Further details on the DRCA method can be found in [7].

2.4 Myopic Decentralized Approach

Krozel *et al* in 2001 proposed a decentralized separation management called the Myopic decentralized approach [8]; An aircraft will declare a potential conflict if the "time to closet approach" with another aircraft becomes less than 8 minutes. Myopic decentralized strategy will execute the maneuver that requires the least amount of heading change. If an aircraft detects conflicts with more than one aircraft within the 8-minute window, it resolves them in a sequential pair-wise fashion, beginning with the most immediate conflict. Further details can be found in reference [8].

2.5 Look-ahead Decentralized Approach

Look-ahead Decentralized strategy is an extension of Myopic Decentralized Approach that was proposed by Krozel *et al* [8] in 2001. This strategy works in a manner similar to the myopic decentralized approach except that in the maneuver design stage the look-ahead approach checks if the selected maneuver (either in front or behind the conflict aircraft) creates a new conflict with another aircraft. If no such conflict is found, it executes the selected maneuver and the algorithm yields the same solution as the Myopic Approach. However, if a new conflict is found with a "time to closest approach" value that is less than that of the original conflict, then an alternative maneuver must be selected. This strategy is attempting to identify and avoid a potential domino failure event (which is a sequence of events in which the manoeuvre used to resolve the conflict with one aircraft causes a new conflict with another aircraft). If the above domino failure condition is detected, the look-ahead decentralized algorithm checks if another maneuver leads to a conflict-free path. If so, it executes that solution.

Figure 3 shows the main difference between these two decentralized approaches in a situation when there is a risk of domino failure.

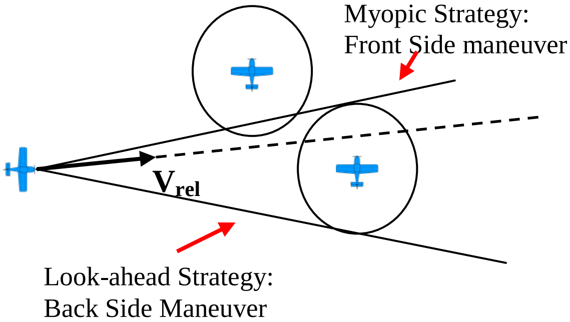

Figure 3: Difference between Myopic and Look-ahead strategy

3 Simulation Study Methodology

We simulated the five separation management algorithms discussed above to evaluate their performance in different scenarios involving communication failure. The evaluation was carried out using the following implementation choices.

3.1 Dynamics

The dynamics of each aircraft was represented using the simplified 3DOF kinematics model [7]:

$$\frac{d}{dt}\begin{bmatrix} x_i \\ y_i \\ \psi_i \end{bmatrix} = \begin{bmatrix} s_i \cos(\psi_i) \\ s_i \sin(\psi_i) \\ u_i \end{bmatrix}$$

where x_i, y_i is the 2D location, s_i is the speed, and ψ_i is the heading of the ith aircraft. The control inputs u_i are restricted to $u_{i,min} \le u_i \le u_{i,max}$ where $u_{i,min}$ and $u_{i,max}$ represents the minimum and maximum turning rate of the aircraft.

3.2 Traffic pattern Scenarios (Four Aircraft)

Figures 4, 5 and 6 show the three scenario types were examined this study: the choke point scenario, the cross passing scenario and the 4 vehicle mixed benchmark scenario. All aircraft used are simulated to have constant speed s_i =100m/s (which corresponds to 360km/hour and is roughly representative of a GA Class aircraft). Control limits $u_{i,min}$ and $u_{i,max}$ were assumed to be -5 degree/second and +5 degree/second, respectively (see [6] for justification).

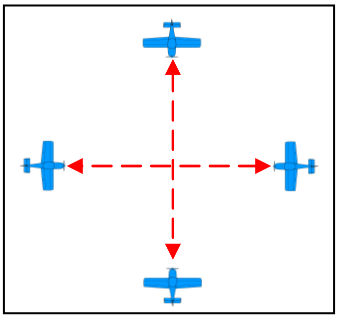

Figure 4: the choke point scenario

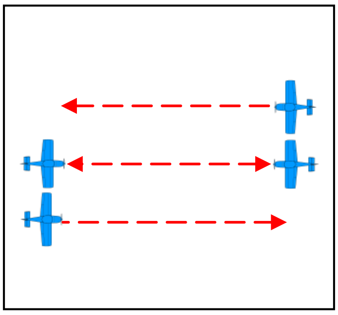

Figure 5: the cross passing scenario

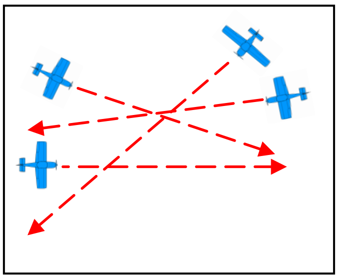

Figure 6: 4 vehicle mixed benchmark scenario

3.3 Performance Metrics

This paper will compare algorithms on the basis of minimum separation distance. We acknowledge that other metrics are meaningful (traffic complexity metric, route planning efficiency) but minimum separation distance describes the most important algorithm characteristic.

3.4 Simulation Studies of Communication Failure

This section describes the results of our simulation study in which we compare the performance of the five algorithms is a situation when a communication failure related to one of the aircraft has occurred. We conducted two sub-studies for this purpose. The data update rate of 2Hz was used in both studies and the desired separation distance was set to 400m.

3.4.1 Centralized Separation Management

In this part of the simulation study we compare the two centralized approached described earlier: satisficing approach and delay ranking approach. Each of these separation algorithms was examined in the three traffic pattern scenarios described in section 3.2. For each traffic pattern scenario, the algorithms were examined in two information situations: perfect information situation, and in the presence of a single uncooperative aircraft. An uncooperative aircraft is defined as an aircraft that does not follow the separation instructions issued by the central controller (perhaps this instruction was not received due to equipment failure on the aircraft). Table 1 shows the separation distances achieved by the centralized separation management algorithms. Note that both algorithms managed separation correctly when full information was available. (Separation is maintained if distance is greater than 400m)

Table 1: Performance of Centralized Separation Management Approaches.

Performance	Centralized Approach	
	Satisficing	Delay Based
Choke Point	**456.4 m**	**436.3 m**
Cross Passing	**413.1 m**	**434.1 m**
Four vehicle mixed b/m	**453.1 m**	**434.1 m**

We next evaluated the impact of having a single uncooperative aircraft in these traffic patterns. Table 2 shows the effective reduction in minimum separation distance caused by the single uncooperative aircraft (that is, minimum separation distance in the prefect information case minus the minimum separation distance achieved in the presence of a single uncooperative aircraft).

Table 2: Centralized Separation Management: the reduction in separation distance due to an uncooperative aircraft

Performance Degradation	Centralized Approach	
	Satisficing	Delay Based
Choke Point	**247.6 m**	**159.3 m**
Cross Passing	**133.6 m**	**35.0 m**
Four vehicle mixed b/m	**130.0 m**	**27.0 m**

3.4.2 Decentralized Separation Management

In this part of the simulation study we compare the three decentralized approached described earlier: DRCA approach, Myopic approach and the look-ahead (LA) approach. Each of these separation algorithms was examined in the three traffic pattern scenarios described in section 3.2. For each traffic pattern scenario, the algorithms were examined in two information situations: perfect information, and in the presence of a blind aircraft. A blind aircraft is defined as an aircraft whose on-board sensors are not functioning correctly, and this aircraft cannot perform decentralized separation management. Such an aircraft is assumed to maintain straight flight. Table 3 shows the separation distances achieved by the decentralized separation management algorithms when all three aircraft all fully operational. We highlight that both the Myoptic and Look-ahead approaches failed in the cross passing pattern (even when all aircraft at fully operational).

Table 3: Performance of Decentralized Separation Management approaches.

Performance Degradation	Decentralized Approach (m)		
	DRCA	Myopic	LA
Choke Point	**399.6 m**	**399.8 m**	**398.5m**
Cross Passing	**423.6 m**	**26.5m**	**33.5m**
Four vehicle mixed b/m	**401.4 m**	**398.6 m**	**400.4 m**

We next evaluated the impact of having a single blind aircraft in these traffic patterns. Table 4 shows the effective reduction in minimum separation distance caused by the single blind aircraft (that is, minimum separation distance in the prefect information case minus the minimum separation distance achieved in the presence of a single blind aircraft). We highlight that the two cases in which the separation distance increased actually correspond to case when separation failed in the fully operational case.

Table 4: Decentralized Separation Management: the reduction in separation distance due to a blind aircraft

Performance Degradation	Decentralized Approach (m)		
	DRCA	Myopic	LA
Choke Point	**131.9 m**	**1.3 m**	**0.0 m**
Cross Passing	**23.0 m**	**-72.2 m**	**-65.2 m**
Four vehicle mixed b/m	**0.7 m**	**231.3 m**	**15.5 m**

3.4.3 Summary of Communication Loss Simulation Study

The results given in Tables 1 and 2 suggest that centralized separation approaches tend to have degraded performance if there is communication loss in one of the aircraft in the airspace. The main reason for this degraded performance is that these approaches assume perfect communication. We would expect performance to be even worse if additional aircraft have communication problems. Tables 3 and 4 highlight that some traffic patterns are difficult for decentralized approaches (even for fully operational aircraft); however, there is some suggestion that decentralized approaches may be slightly less sensitive to communication failure.

4 High-fidelity Simulation and Flight Testing Architecture: Initial Testing

We are currently designing an architecture that provides a common environment for the development of candidate next generation separation management concepts. This development environment allows both high-fidelity simulation testing (6DOF dynamic models) and flight testing of proposed algorithms, and includes:

- Several computers hosting parts of the system (remote hosting is possible),
- Specialized communication layers to manage air-traffic communication (both software protocol interfaces and hardware), Communication occurs over 3.5G telephone data networks (or satellite networks).
- Specialized automated separation management approaches (based on satisficing approach, but conforming to interfacing requirements) ,
- Specialized 6DOF simulation models for virtual aircraft (conforming to interfacing requirements),
- [Optional] a Cessna 172R aircraft (equipped with specialized avionics such as high-grade IMUs and various data connections).

The relationship between the components in this architecture is shown in the Figure 7. We highlight that communication layer and other aspects of this architecture were developed as part of the Smart Skies Project.

The primary advantage of the developed architecture is that it allows us to first perform rapid algorithm developments in a friendly simulation environment. Once verified in simulation, we can the easily transition to actual flight testing (because our architecture will work with both simulated hardware and real hardware).

The primary purpose of our initial flight tests was to provide preliminary verification of our new architecture. A secondary purpose was to evaluate how well our simulation models (primarily our 6DOF) match the real interactions that occur during real conflict resolution. We stress that these tests did not aim to investigate the impact of communication loss, and hence these first tests involved only simple conflicts involving two aircraft approaching at a variety of different angles (from 22.5 degrees to 180 degrees in increments of 22.5 degrees). One aircraft was our specially equipped Cessna 172R aircraft. The other aircraft was a computer simulation of an aircraft (that mimicked all the required interfaces, the aerodynamic behavior and the response to separation instructions).

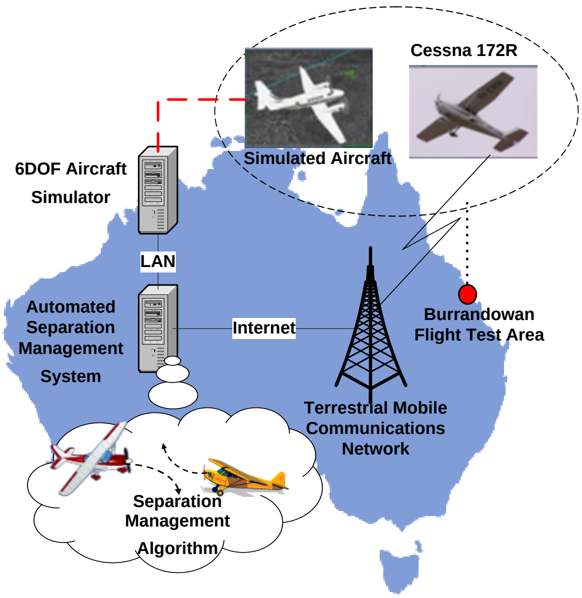

Figure 7: The automated separation management system architecture

Table 5 shows a comparison, for different approach angles, between pure simulation tests and flight tests involving one real aircraft (with real communication links) and one simulated aircraft. In this table, in the 2nd and 3rd columns, a tick means satisfactory separation was achieved in that test case; a cross means that the minimum required separation distance was not maintained. In the last column, the tick/cross denotes whether similar behavior was seen in both the simulation and the flight tests.

Table 5: A comparison study of simulation and real flight behavior

Case	Simulation	Flight Trial	Similar
22.5 degree	x	√	x
45 degree	√	√	x
67.5 degree	√	√	√
90 degree	√	x	x
112.5 degree	√	√	x
135 degree	√	√	√
157.5 degree	√	√	x
180 degree	√	√	√

To highlight some of the features present in real flight tests we will now describe some of the data collected in the 67.5 degree approach angle case (other approach angles exhibited similar features). Figure 8 shows the trajectories followed by the aircraft during this scenario. The red trajectory corresponds to the real aircraft and the blue trajectory corresponds to the simulated aircraft. We highlight that in this scenario both aircraft received commands to change heading for the purposes of avoiding the potential collision identified; the red aircraft is instructed to turn right so that it passes ahead of the blue aircraft (which is also instructed to turn right so that it passes behind the red aircraft). Once the potential conflict has been resolved, both aircraft head towards their original waypoints.

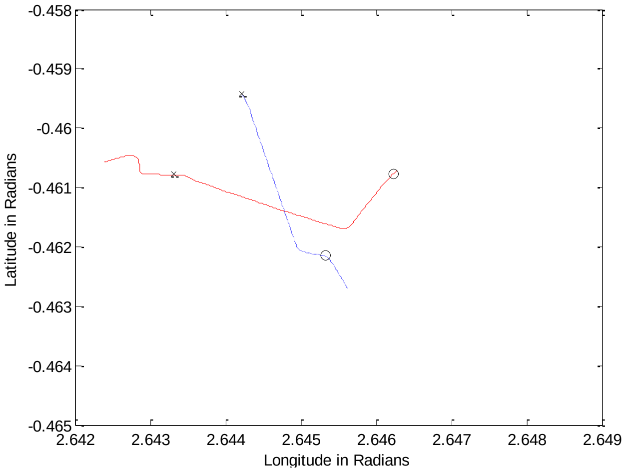

Figure 8: The resolved trajectories in the 67.5 degree scenario (real flight test). The real aircraft is denoted in red (starting from the left end of its shown trajectory) and the simulated aircraft is denoted in blue (starting from the top end of its shown trajectory). Initial points of the aircraft are denoted with "x" and destination waypoints of the aircraft are denoted with "o". At the very left, some of the red (real) aircraft's trajectory prior to the experiment is shown (and should be ignored).

In Figure 9 we show the commands issued and response behavior of the real (red) aircraft. In this figure the red tick marks correspond to time instants in which the centralized separation manager issues a heading instruction to the real aircraft (the size of the tick corresponds to the value of the heading instruction). These instructions are issued between 150s and 175s. The aircraft's actual heading is denoted by the blue line. In the shown scenario, the separation instruction is issued several times, and adjusted, until the algorithm is happy that the aircraft is on a conflict-free trajectory (in an approximate sense, this corresponds to aircraft's heading matching the heading instruction). The aircraft starts returning to its initial waypoint at a time of approximately 425 seconds.

We highlight that during simulation of the 67.5 degree approach case, a minimum separation distance of 1612.42m was achieved (the flight delay caused was 30 seconds). However, during the actual flight test, a minimum separation distance obtained was 2573.92m (the flight delay caused was 53 seconds). We highlight that the separation manager used a similar separation strategy in both the simulation and flight test. Hence, whilst both tests satisfy the desired separation distance of 1500m and used roughly a similar separation strategy, significantly different performance numbers were seen in the two cases.

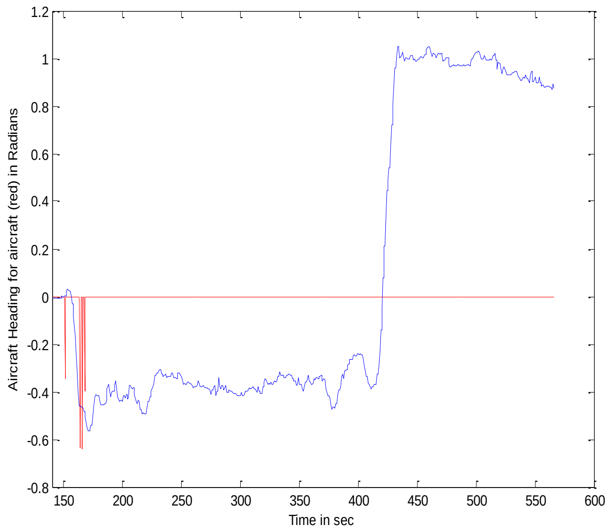

Figure 9: The real (red) aircraft heading commands are shown in read. The aircraft actual heading is shown in blue.

In summary, this initial flight test program illustrated the feasibility and provided preliminary validation of our new architecture for testing new automated separation management concepts. However, this initial test also highlights that simulation environments only provide a crude approximation of flight behavior during conflict and avoidance.

5 Conclusion

The demand for new automated separation management approaches will continue to grow as air traffic density increases over time. In this study, we have compared the impact of communication loss on several existing automated separation management approaches. Our studies showed that these algorithms exhibit significantly degraded performance when communication failure occurs. The main reason for degraded performance relates to assumptions about perfect communication. This paper also describes some initial flight tests for a new architecture which will assist in the development of new automated separation management concepts that are robust against communication failure.

Acknowledgement

This research is part of the Smart Skies Project and is supported, in part, by the Queensland State Government Smart State Funding Scheme.

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