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ADVANCES IN FORCE FIELD CONFLICT RESOLUTION ALGORITHMS

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ABSTRACT

Conflict detection and resolution (CD&R) systems are envisioned as an enabling technology for improving the efficiency, capacity, and safety of Air Traffic Management. The concept includes airborne equipment that monitors the traffic situation (conflict detection), informs pilots of potential airspace conflicts (conflict alerting), and suggests flight plan modifications to resolve the conflicts (conflict resolution.) This new, airborne surveillance and separation assurance function is made possible by Automatic Dependent Surveillance – Broadcast (ADS-B). One of the primary challenges for CD&R is the development of a conflict resolution algorithm that is both simple and robust. This paper contains results from recent tests of one such algorithm. The tests examined 1) the effects of delays in maneuver execution, 2) the problem of conflicts that occur near waypoints, and 3) the challenge of performing conflict resolution in the absence of intent information (i.e. knowledge of intended way point positions and arrival times). The first two studies confirmed the algorithm's robustness. The third study produced a surprising and exciting result – conflict resolution may be very successfully performed without knowledge of other aircrafts' intent information.

INTRODUCTION

Many of the nation's airspace users desire an increase in efficiency in the air traffic control system. Some feel that an increase in efficiency can be achieved by moving away from a centralized control paradigm towards a distributed control paradigm. In a distributed control paradigm, the cockpit crew would have more freedom in selecting and modifying their routes. This new paradigm is part of the Free Flight concept.

Increased autonomy of operations will require increases in cockpit information, pilot responsibility, and avionics capability. One of the key enabling capabilities will be the detection and resolution of airspace conflicts. Conflict detection and resolution (CD&R) systems will serve in a separation assurance role for the flight deck. This paper contains research results in the area of conflict resolution strategies.

Conflict detection and resolution functionality differs from TCAS in two ways. TCAS is a *collision avoidance system.* It is intended to prevent a collision of metal-to-metal when the primary means of separation assurance have failed. It is a "safety net." CD&R, on the other hand, is a *separation assurance system.* It is intended to be the primary means of separation assurance, not a safety net. Consequently, the look-ahead window of CD&R is farther than TCAS – minutes, rather than seconds. CD&R can be based on the intent (e.g., a flight plan) of the conflicting aircraft, rather than just the instantaneous velocity vectors. The resolution maneuvers for CD&R are intended to be more strategic in nature than TCAS Resolution Advisories.

There have been several strategies proposed for generating trajectories for conflict resolution. Jim Kuchar, in his survey of such strategies,[8] divides resolution approaches into the following three general categories: force fields, prescription, and optimization. Optimization techniques can be further subdivided into game theory, control theory, rule-based, and genetic algorithms. The CD&R research that uses ADS-B information has largely focused on the force field and rule-based approaches.

The research results contained in this paper build on previous work performed on a specific conflict resolution algorithm. The algorithm of interest was first proposed in 1994[1] and was further studied in 1998.[2] This strategy is based on the concept of potential fields. To illustrate the concept, Figure 1

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depicts several positively charged particles that have been released into a space containing fixed negative charges. The positive charges will tend to be drawn towards a fixed negative charge because of the mutual attraction of their opposite charges. At the same time, the positive particles tend to maintain distance between each other because of the mutual repulsion of their like charges. An analogy could be drawn to a free floating positive charge as an aircraft and a fixed negative charge as a destination. This analogy provides a crude model for developing conflict resolution algorithms.

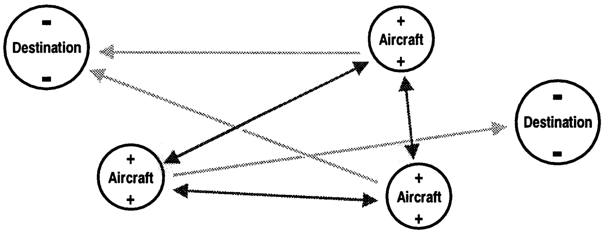


Figure 1. Potential Fields as a Conflict Resolution Strategy

Such an algorithm has been developed and tested for use as the foundation of a conflict detection and resolution system. Eby showed that this approach could successfully resolve conflicts in a centralized, ground-control situation.[1] Eby and Kelly adapted the algorithm to the airborne separation assurance situation.[2] The results of this prior work suggested that potential field algorithms are an extremely robust solution to the problem of CD&R. The results also show that these algorithms can be used in situations involving distributed computation and resolution. The advantage of a distributed approach is the decreased reliance on a central command authority. In simulation, separation can be maintained even with an unreasonable number of aircraft, in close proximity, with only partially reliable communications, and operating under tight constraints on maneuverability.

RESEARCH OVERVIEW

This paper discusses the performance of the potential field algorithm as it relates to three topics – intent uncertainty, conflicts near trajectory change points (TCPs), and maneuver delays. In performing development and testing related to these three topics, the authors' primary purpose has been to stress the algorithm. Can the algorithm continue to perform well in unusually high densities and in difficult encounter geometries? The results have been very promising. In the future, Monte Carlo simulations using realistic traffic densities and typical encounters will be useful for estimating nuisance alarm rates and the expected benefits of a CD&R system. However, this current research has focused on identifying potential failure situations, particularly under the conditions described in the following three subsections:

Maneuver Delays

First, the authors asked the questions, "What is the effect of the pilot scan interval?" and "What is the effect of a delay in the execution of the resolution maneuver?" These effects are illustrated in Figure 2. Previous studies assumed the instantaneous response of the pilot to the recommended resolution. The authors considered the fact that pilots may not always immediately respond to conflict alerts and there may be additional delays involved in the selection and execution of a conflict resolution maneuver.

Conflicts Near TCPs

Previous conflict resolution studies considered scenarios in which the aircraft's intended trajectory was linear in the vicinity of the conflict as shown in Figure 3a. The algorithm performed remarkably well in these situations. However, there is the very real possibility that a conflict will occur near waypoints of one or more of the aircraft involved in the conflict, as shown in Figure 3b. The authors asked the question, "How can conflicts occurring in close proximity to TCPs be resolved using force field-based resolution protocols?"

Intent Uncertainty

Previous research had assumed the availability of intent information in the form of trajectory change points (TCPs) in the ADS-B messages. Figure 4 lists some of the information available in ADS-B broadcasts. During the early stages of ADS-B equipage, many aircraft will not have the capability to broadcast intent. Some aircraft (e.g., low-end general aviation aircraft, balloons, gliders) may never broadcast intent. The authors asked, "Can the candidate algorithm be used when the intent information of the other aircraft is unknown?" In this case, the system must perform conflict resolution based solely on the other aircraft's state information. "Is this information sufficient for performing conflict resolution?"

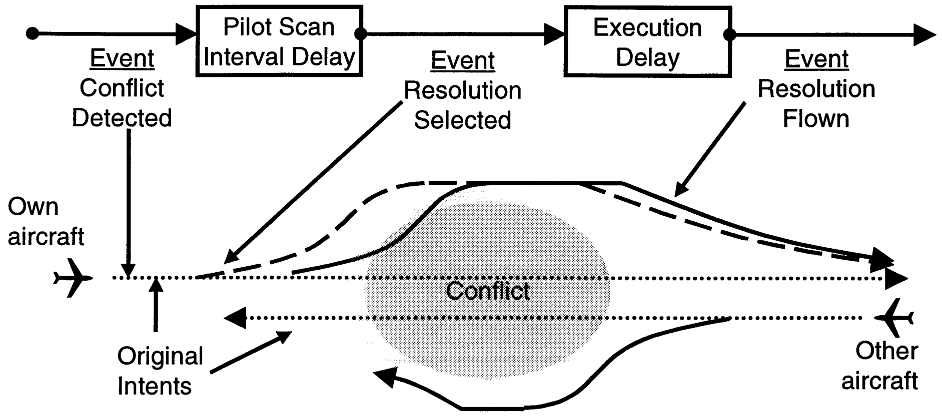
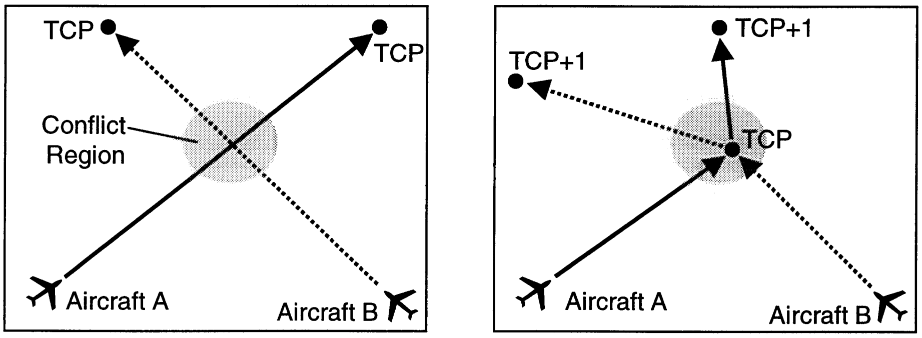


Figure 2. Delays in Selection and Execution of Conflict Resolution



(a) (b)

Figure 3. (a) Conflicts Occur on Linear Portions of Flight Paths
(b) Conflicts Occur Near Trajectory Change Points (TCPs)

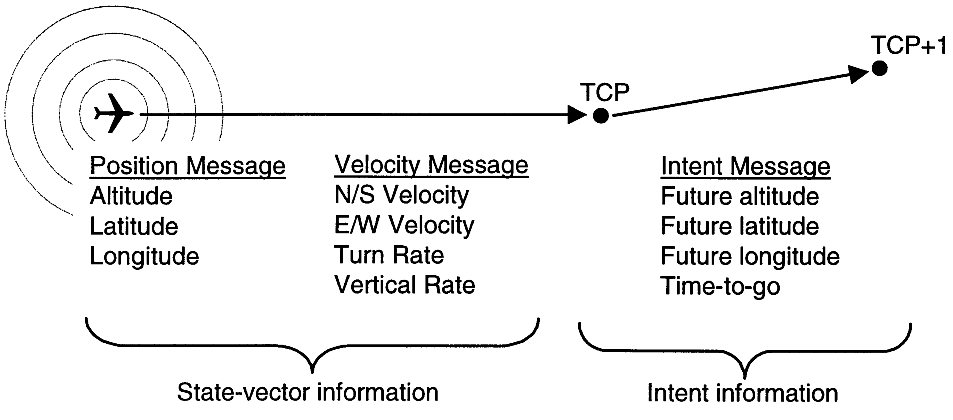


Figure 4. ADS-B messages include both state-vector and intent information.

TESTING METHODOLOGY

For the purposes of further testing the self-organizing algorithms, a simple random conflict generator was created. It produced fifty very challenging random conflict scenarios. Each scenario involved eight aircraft traveling at randomly determined speeds ranging between 60 and 600 mph in a randomly assigned direction. The midpoint of each aircraft's original trajectory was then translated such that it fell on a randomly determined point inside a circle of three miles radius. The result was a set of difficult, eight-way conflict configurations involving aircraft of widely varying speed capabilities approaching each other from various angles to produce a particularly complex, random, conflict scenario. Figure 5 illustrates a typical conflict scenario.

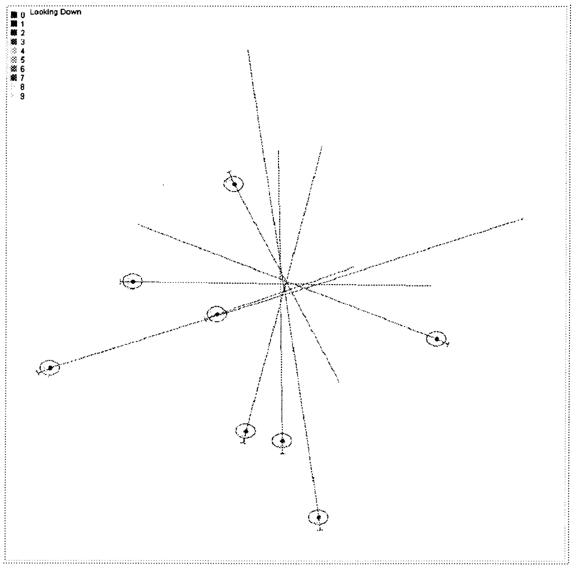


Figure 5. A Randomly Generated Conflict Scenario

The overall success with which the 50 scenarios in each test are resolved may be represented by plotting the closest approach for each aircraft pairing as a function of the percentage of flight completed, as shown in Figure 6. For the purposes of plotting effective separation, all miss distances are shown as horizontal separations. To do so, the altitude has been scaled by a factor of 200 such that 1000 feet of vertical separation is equivalent to 5 miles of horizontal separation. For each of the 50 eight-aircraft scenarios, there are 28 aircraft pairings. Therefore, each simulation run provides 1400 data points.

The results shown in Figure 6 illustrate the case that no resolution strategy is applied. It shows the closest approach of each aircraft pairing in the absence of any conflict resolution for fifty, random eight-aircraft conflict scenarios. It shows that, without resolution, all fifty conflict scenarios involve the eight aircraft coming at least within six miles of each other at approximately the same time.

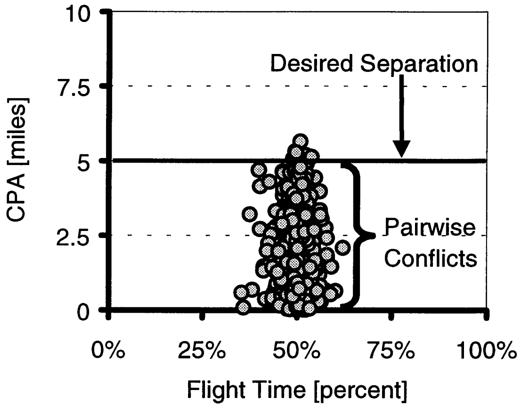


Figure 6. Random Scenario without Conflict Resolution Algorithms

Several observations about these tests can be made.

- The 60 to 600 mph range for nominal aircraft airspeeds is not realistic for common airspace. This range was selected to make the problem more difficult, however.
- While a slower obstacle aircraft permits more time to resolve head-on conflicts, their ability to maneuver is limited relative to faster aircraft. In addition, a slow moving obstacle aircraft reduces the time available for conflict resolution during passing conflicts.
- While the impression may be that each test scenario consists of a single eight-way conflict, that is not how they are solved by the distributed algorithms. Each obstacle aircraft generates an independent correction to a subject aircraft's route. The effect is the same as if the individual conflicts were spaced at larger temporal and spatial distances. However, the close proximity of the pairwise conflicts leads to more frequent and more complex interactions between the aircraft.
- These are extremely difficult conflict scenarios. It is assumed that any technique which cannot robustly resolve difficult, albeit rare, conflicts involving multiple interacting aircraft is unsuitable for free flight CD&R regardless of how successful it might prove at solving common two- or three-way conflicts.

MANEUVER DELAY

In the previous study of potential field algorithms,[2] there was no implementation of a "pilot." Rather, the conflict resolution maneuvers of each aircraft were calculated and executed on a 12-second cycle. In this current work, the simulations included a "pilot," which was modeled with the following features:

- The pilot "observed" the conflict resolution computer at a "consideration interval," which was a parameter of the test. For example, a 30-second consideration interval corresponds to a real-life scenario in which the pilot scans, analyzes, and acts upon his traffic display twice a minute.
- The pilot "executed" the conflict resolution after an "implementation delay," which was also a parameter of the tests. The implementation delay models the time that a real pilot might spend analyzing and implementing a resolution presented to him by a CD&R system.

Initial Results

Six simulation sets were run with varying values for the consideration interval and implementation delay parameters, as shown in Table 1.

Table 1. Maneuver Delay Test Parameters.

	Consideration Interval [sec]	Implementation Delay [sec]
#1	15	0
#2	30	0
#3	30	15
#4	45	0
#5	45	15
#6	45	30
	The following parameters were also used:	
	ADS-B Transmission Rate:	*12 seconds*
	ADS-B Range	*120 miles*
	Probability of Tx/Rx:	*98%*
	Max Aircraft Acceleration:	*0.1 G*
	Max Climb/Descent Rate:	*1000 fpm*

Due to space considerations, only the results for tests #1 and #6 are shown in this paper. Figure 7 suggests that even for a 15-second consideration delay, the desired separation is achieved. As would be expected, Figure 8 reveals that degradation occurred when the delays were increased. The results of all six tests showed that the degradation was limited to relatively few aircraft pairings and roughly proportional to the intervals and delays imposed.

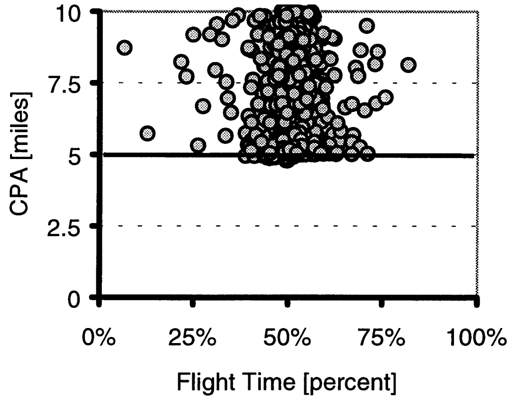


Figure 7. Results for Maneuver Delay Test #1

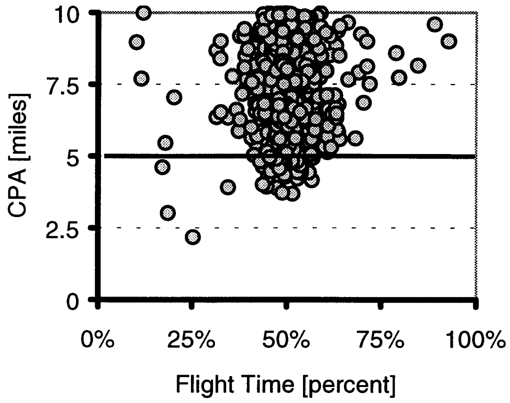


Figure 8. Results for Maneuver Delay Test #6

Compensating for Implementation Delay

It is possible for the CD&R system to compensate for anticipated delays in implementing a conflict resolution maneuver. This is achieved by calculating the resolutions based on future projections, rather than the current configuration. If a 15-second delay in implementation is expected, the CD&R system may project the situation 15 seconds into the future in calculating appropriate resolutions.

Simulations #1-#6 of Table 1 were repeated, with the algorithm altered to anticipate a 15-second delay in implementing the resolution maneuver. The results suggested that compensating for expected implementation delay does yield modest improvement in the separation achieved. Also, there is little harm in over-estimating the pilot delay – the net effect is merely that the pilots resolve the conflict somewhat more aggressively than is required.

CONFLICTS NEAR TCPS

Not all conflicts occur as aircraft are traveling between waypoints. In the ADS-B messages, the waypoints can be broadcast as Trajectory Change Points (TCPs). An open research question has been, "How will the potential field algorithm perform for conflicts near TCPs?" When such conflicts occur, it is necessary for the affected aircraft to adjust either the position or the time-of-arrival for the waypoint.

Algorithm Extension

In this work, the authors adjusted the position of the waypoints in a manner analogous to the adjustments previously used[2] to avoid traffic conflicts that occur on segments between waypoints. That is, calculate the point of greatest conflict-hazard. At that point, determine the smallest deltas in X, Y, and Z position that resolve the conflict. Adjust the TCP's position by these deltas and a scaling factor based on two distances – the distance between the conflict and the TCP; the distance between the aircraft and the TCP.

This is an extension of the basic force field algorithm, which compensates for conflicts near TCPs. As was true of the basic conflict avoidance maneuvering, the process of adjusting TCPs to avoid conflicts is error driven – when no conflicts are detected, there are no adjustments. Changes in the TCP positions are both gradual and appropriate to the magnitude of predicted intrusion and the temporal proximity of the conflict.

Results

Figure 9 illustrates the functioning of the enhanced algorithm for the case a conflict near a TCP. The conflict is predicted to occur roughly 200 seconds and 10 miles ahead. Similar experiments were run with eight converging aircraft, all with TCPs occurring in the conflict zone. The results confirmed that conflicts could be successfully resolved even when those conflicts occur near planned TCPs. Figure 10 is an example of an eight-aircraft scenario with near-conflict TCPs.

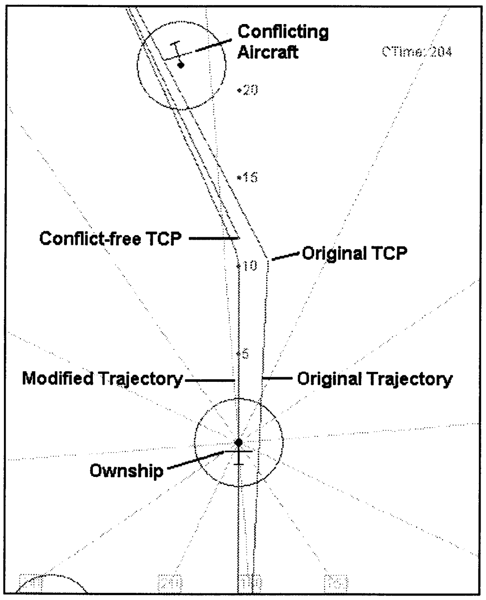
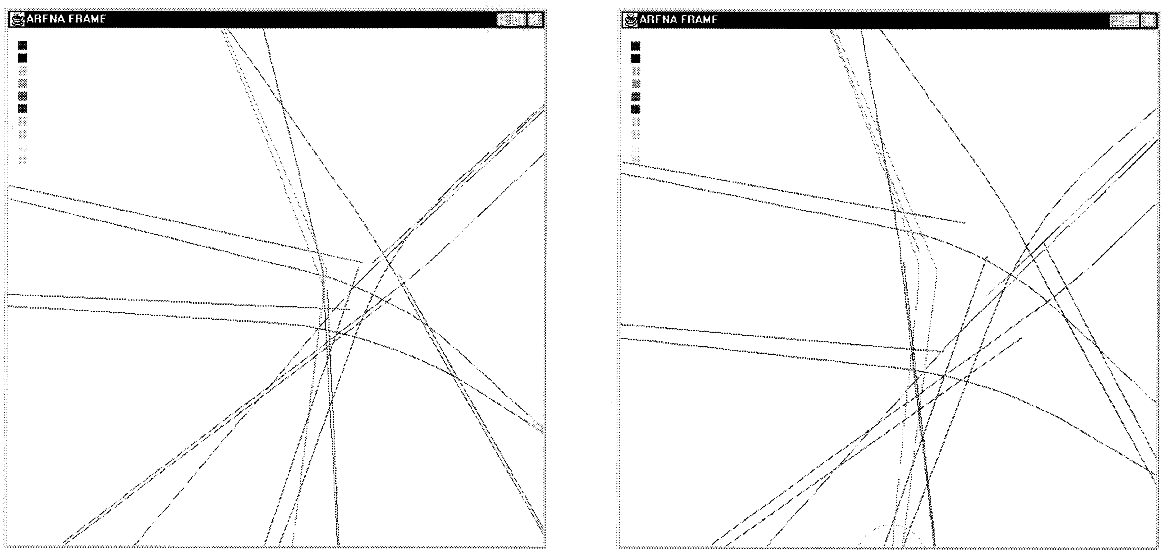


Figure 9. Moving a TCP to Avoid a Conflict



Before Conflict Resolution

After Conflict Resolution

Figure 10. Eight-Aircraft Conflicts near TCPs

INTENT UNCERTAINTY

One of the primary goals of this current research was to confirm the utility of the potential field algorithms when the other aircraft's intent is not known. The other aircraft may not be broadcasting TCPs. In this case, the conflict resolution must be performed based solely on "state vector" information available in ADS-B – current position and velocity.

Initial Studies

These studies of state-vector only (SVO) resolutions were conducted using the same operating conditions as the Maneuver Delay study described in a previous section. Eighteen tests were developed by varying three parameters: look-ahead window, pilot scan interval, and number of aircraft.

An example of an eight-aircraft scenario is shown in Figure 11, in which the look-ahead window was 300 seconds and the scan interval was 15 seconds. Overall, the resolutions were not as good as achieved using intent information. The average separation was modestly lower for most runs and the number of aircraft pairings which violated spacing criteria by two miles or more was much larger. However, all conflicts involving two aircraft and nearly all four aircraft conflicts were resolved to closest approaches of 4 miles or greater.

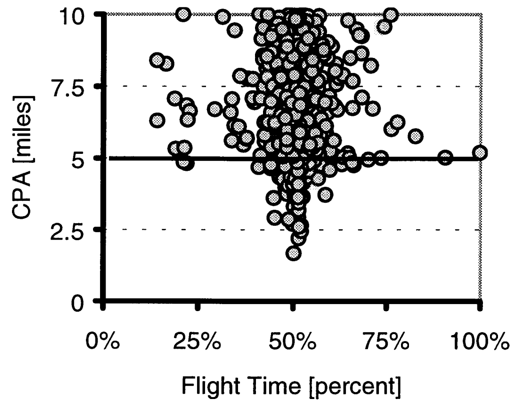


Figure 11. Separation Without Intent information.

Path Bumping

One of the more noticeable effects of the SVO resolutions was an effect the authors termed "path bumping." Path bumping describes the observation that aircraft would repeatedly maneuver to resolve conflicts and then turn back into those conflicts. This occurred because the error signal was based on projections of their state vectors rather than on their intended trajectories. As soon as the aircraft deviated from their original trajectories to solve a future conflict, the 'error signal' became zero such that their was no 'potential field' force keeping them from returning to their original, conflicted path.

Not surprisingly, path bumping was most severe when the scan interval was large. In this case, the error signal resembles a binary signal rather than a signal that varied with the severity of the conflict to be resolved.

Secondary Implementation

In order to counter the path bumping effect, a simple "predictive Airborne Separation Assurance System" (pASAS)[11] function was implemented. So long as the path directly to the next waypoint is predicted to have a conflict, the aircraft would attempt to maintain current speed and heading rather than attempting to reach the blocked goal. In practice, this simple modification provided two valuable benefits and introduced two (usually minor) problems. The benefits can be seen by comparing Figure 12 with Figure 11.

While the resolutions were improved, there were two problems observed. Because the conflict is resolved as soon as the projected paths no longer conflict, the proactive pilot is penalized with the larger (or only) deviation. Secondly, an aircraft's course could diverge a great deal from the course to the ultimate goal even though conflict-free courses more closely approaching the goal are available.

Clearly, a more complete predictive ASAS capability is required and is the goal of future research for the authors. These preliminary results confirm the conclusion of others[11] that the intent information is not necessary for free flight operations.

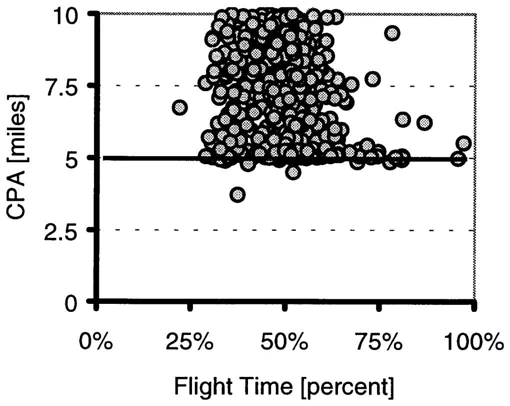


Figure 12. Separation Using Simplistic pASAS.

CONCLUSION AND FUTURE WORK

The authors considered three factors that may affect the performance of a conflict resolution algorithm – maneuver delays, conflicts near trajectory change points (TCPs), and intent uncertainty. Very demanding simulations demonstrated that the force field-based algorithms perform well in the face of small and moderate consideration intervals and implementation delays. The achieved separation degrades gracefully as these delays increase. Regarding conflicts near TCPs, we have shown that such conflicts may be successfully resolved by adjusting the temporal and spatial position of the TCP using the same algorithms which resolve trajectory conflicts.

The results of experiments in conflict resolution without intent information are more surprising and exciting. The authors demonstrated that the force field algorithm may be used to resolve complex, random, multi-aircraft conflicts without the use of intent information. Free flight separation assurance may be reliably accomplished by simply projecting the current velocity of each aircraft forward over a brief period of time and applying force-field algorithm derived corrections to any conflicts detected. One implication of this finding is that a "fall-back" mode – not employing intent information – exists to handle conflicts which were not successfully resolved at longer ranges due to incorrect intent information or other failures. Perhaps more significantly, the finding implies that substantial free-flight operations should be possible even for low-end aircraft lacking advanced navigation and flight management computers.

In this and previous work, the robustness and suitability of specific force-field-based algorithms for conflict resolution have been amply demonstrated. Going forward, additional research opportunities exist in testing under realistic (as opposed to particularly difficult, but artificial) traffic scenarios, analytical search of possible failure modes, and analysis of appropriate conflict alerting and resolutions thresholds.

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