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Co-operative Optimal Airborne Separation Assurance in Free Flight Airspace

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ABSTRACT

This paper proposes a new paradigm for airborne separation assurance of aircraft operating in *free flight* airspace. The paradigm is considered novel in that it provides a framework for explicit co-operation and cost sharing in conflict avoidance. The operational methods and algorithms that support the proposed separation assurance scheme are based on Distributed Artificial Intelligence (DAI). In this model, aircraft flying in *free flight* airspace are represented as autonomous intelligent entities (*agents*) embedded in a multi-agent system. Within this scheme, proximate aircraft form teams to establish a plan to maintain safe separation with an agreed set of conditions. The plan is developed from a dynamic programming algorithm in which the requirement for proximate aircraft to manoeuvre away from their defined *free flight* routes to avoid a conflict is minimised according to both safety and economic criteria.

I. INTRODUCTION

The goal of Air Traffic Management (ATM) according to the International Civil Aviation Organisation's (ICAO) committee on Future Air Navigation Systems (FANS) is:

"*To enable aircraft operators to meet their planned time of departure and arrival and adhere to their preferred flight profiles with minimum constraints without compromising agreed levels of safety*".

The key technologies required for the implementation of the ATM system are Communications, Navigation and Surveillance (CNS). Advances in these technologies and developments involving their integration into systems architectures provide the information framework for a global ATM.

One approach to realising the CNS/ATM objective for the *en-route* phase of aircraft operations is the concept of *free flight*, proposed by the United States Federal Aviation Authority. The *free flight* concept establishes a regime of Instrument Flight Rules (IFR) airspace where aircraft are allowed to fly user-preferred routes with the task of separation assurance delegated to the aircraft.

There is evidence [1] that *free flight* will bring significant cost savings to the airlines in addition to improving the efficiency and capacity of the current restricted airspace system.

Eurocontrol proposes to implement *free flight* operations in certain regions of airspace that will be promulgated by the airspace planning and management services on a daily basis according to the expected traffic demand [2]. The user-preferred route scheme will also be available for suitably equipped aircraft in managed airspace, where a ground-based control centre will be responsible for separation assurance.

The ability to fly operator-preferred routes is of questionable economic benefit if aircraft have to make frequent manoeuvres to avoid proximate traffic conflicts. This has motivated a number of recent studies on various aspects of conflict avoidance in *free flight*.

One of these studies describes a method based on hybrid control techniques and is reported in references [3], [4], and [5]. The method is a scheme to verify the safety of resolution manoeuvres in different conflict scenarios.

Another study proposes a probabilistic approach to conflict avoidance. In this work, presented in reference [6], a technique that employs an airborne alerting logic based on the probability of conflict is developed for encounters with one intruder.

Eurocontrol's FREER-1 (Free-Route Experimental Encounter Resolution-1) study [7] analyses the basic requirements for autonomous airborne separation assurance in *free flight* and introduces an interactive human-centred resolution scheme. A set of Extended Flight Rules (EFR) is defined to provide co-ordinated conflict resolution by assigning a priority to each aircraft involved in a conflict.

Optimal control theory is used in reference [8] to develop an algorithm for the resolution of conflicts involving two aircraft. This algorithm is based on the maximisation of the distance between two aircraft at the point of their closest approach. An advisory system based on this algorithm is introduced in the form of a set of manoeuvre charts that are to be used as "rules-of-the-air".

In reference [9] an economic model is presented to analyse cost-benefits in different resolution manoeuvres for far-term strategic conflicts.

Algorithms for resolving three-dimensional conflicts involving multiple aircraft are presented in reference [10]. These algorithms are based on trajectory optimisation methods and provide resolution actions that minimise a certain cost function.

When considering conflict scenarios in *free flight*, the approach proposed in this paper assumes that aircraft will be equipped with the airborne segment of the planned CNS system. In this system, accurate navigation information will be provided by the Global Navigation Satellite System (GNSS) and an information link with the proximate aircraft will be established through Automatic Dependent Surveillance-Broadcast (ADS-B) and Data Link Communications. By using these advanced CNS technologies, the requirement for look-ahead time in the conflict avoidance systems for *free flight* is estimated to be between 10 and 30 minutes [11]. This enhanced look-ahead time capability together with accurate trajectory prediction and the possibility of data exchanges between aircraft will permit co-operative conflict avoidance strategies that incorporate optimisation criteria that consider the interests of all the conflicting aircraft.

Regarding the assumptions outlined above, this paper makes two main contributions to Airborne Separation Assurance in *free flight* airspace:

(i) the definition of a formal framework that supports co-operative airborne separation assurance in *free flight* airspace.

(ii) the development of a dynamic programming algorithm to provide a weighted-cost sharing resolution to multiple aircraft conflicts.

The proposed framework supports the methodology for a multiple aircraft, strategic airborne separation assurance system in which aircraft share the costs involved in the conflict resolution. This methodology is based on the theory of multi-agent systems in Distributed Artificial Intelligence (DAI) [12], [13], [14], [15]. A set of proximate aircraft operating in *free flight* airspace is cast as the multi-agent system. These aircraft are modelled as intelligent agents having *Joint Responsibility* [15] to establish a defined *Joint Goal* [15] of separation assurance. This *Joint Goal* is achieved through a *Joint Solution* or common conflict resolution plan. Upon detection of a predicted conflict by one or more aircraft, a team of the conflicting aircraft is formed with the purpose of resolving the conflict.

A set of *conventions* [15] establishes the foundation for a communication protocol that allows the co-operation and negotiation of resolution plans [16], [17], [18].

A dynamic programming algorithm enables the agent aircraft conflict scenario to compute resolution actions consisting of a set of airspeed controls for each aircraft involved in the conflict. These plans are implemented by the team members according to the framework presented above. The proposed conflict avoidance algorithm is based on the concept of motion planning in robotics [19], [20], [21].

All the techniques described in this paper would be implemented as a facility to enhanced the pilot situation awareness and aid the human decision making process. However, these ideas could form the basis of fully autonomous aircraft operations in the future.

II. OPERATIONAL METHODOLOGY

A. Multi-Agent System Model

The operational methodology for the proposed airborne separation assurance system for aircraft in *free flight* airspace is based on the theory of multi-agent-systems within the broader scope of Distributed Artificial Intelligence (DAI) [15].

Proximate aircraft flying in *free flight* are modelled as autonomous and intelligent entities (*agents*) that constitute a multi-agent system. They fly according to their self-interests (user-preferred routes) but are willing to co-operate to avoid conflicts. Conflicting aircraft associate in *teams* to co-operate in separation assurance. Team members adopt the avoidance of the predicted conflict as a *Joint Goal* [15] and commit to the execution of a conflict avoidance plan (*Joint Solution* [15]).

A set of rules called *conventions* known to the agents regulates the team formation process according to the model of *Joint Responsibility* [15] and establishes the foundation for a co-operation protocol.

The attributes of the aircraft forming a separation assurance team are:

- the aircraft share minimum separation conflict avoidance as the common goal G.

- each aircraft in the team has a defined priority for its *free flight* operations, which is communicated to the other aircraft in the team.
- all aircraft in the team are aware of the *free flight* priorities of the other team members.

B. A Protocol for co-operative conflict avoidance.

Let A represent a group or *set* of proximate aircraft flying in *free flight* airspace. Each aircraft in this set is monitoring the tracks and communications of the other aircraft in the set to determine the possibility of the violation of separation minima. When an aircraft $a_0 \in A$ detects a possible violation of separation minima involving itself and one or more other aircraft in A, the aircraft a_0 defines the subset $A_C \subset A$. The subset A_C consists of the aircraft in A that are on courses that are predicted to conflict with the single aircraft a_0. The aircraft a_0 that is detecting the conflicts, broadcasts a message to the aircraft in the set A_C. The purpose of this message is to form a team of aircraft A_T that will co-operate to establish a common resolution plan. In this team a_0 assumes the role of *team organiser.* Each aircraft belonging to the subset A_C considers its defined set of *conventions* to assess the request from a_0. When the assessment is complete, each aircraft replies to a_0 indicating whether it will join the team or continue with its current intentions. Thus a team A_T also included in the set A is organised by a_0. It follows that the membership of A_T consists of a_0 and the members of A_C that are willing to co-operate in the resolution of the conflict.

Once the team has been formed, a_0 designs a common resolution plan P and transmits this plan to the other team members. The plan P consists of a set of actions that each aircraft in A_T must execute to maintain safe separation. This plan provides a strategy to solve the predicted conflicts in a co-ordinated manner while taking account of the costs of the resolution for all the members of the team A_T.

JOINT RESPONSIBILITY CONVENTIONS FOR a_i

REASONS FOR NOT JOINING A TEAM:
- EMERGENCY
- LOW FUEL

REASONS FOR RE-ASSESSING TEAM MEMBERSHIP:
- JOINT GOAL G IS MET (CONFLICT HAS BEEN AVOIDED)
- JOINT GOAL G WILL NEVER BE MET (P WILL NOT AVOID CONFLICT)
- JOINT GOAL G IS IRRELEVANT IN CASES OF:
  - EMERGENCY
  - EQUIPMENT FAILURE
- AVOIDANCE ACTION CANNOT BE EXECUTED
- AVOIDANCE ACTION HAS NOT BEEN EXECUTED PROPERLY

ACTIONS:

A1: IF JOINT GOAL G IS MET OR
JOINT GOAL G WILL NEVER BE MET OR
MOTIVATION FOR JOINT GOAL G IS NO LONGER PRESENT
THEN DROP COMMITMENT TO G AND P (QUIT TEAM) AND
INFORM FELLOW TEAM MEMBERS OF NEW INTENTIONS

A2: IF AVOIDANCE ACTION CANNOT BE EXECUTED OR
AVOIDANCE ACTION HAS NOT BEEN EXECUTED PROPERLY
THEN DROP COMMITMENT TO P

A3: IF DROP COMMITMENT TO P AND CAN PERFORM CONFLICT AVOIDANCE ACTION
WITHOUT INTERFERRING WITH P (FELLOW TEAM MEMBERS INTENTIONS)
THEN DEVELOP AND INFORM FELLOW TEAM MEMBERS OF NEW INTENTIONS

A4: IF DROP COMMITMENT TO P AND CANNOT PERFORM CONFLICT AVOIDANCE ACTION
WITHOUT INTERFERRING WITH P (FELLOW TEAM MEMBERS INTENTIONS)
THEN DROP COMMITMENT TO G AND INFORM FELLOW TEAM MEMBERS OF NEW INTENTIONS

Figure 1: High-level conventions for Joint Responsibility.

When the members of the team formed by a_0 have received the plan P designed by a_0, they assess the plan against their conventions and their current situation. Each aircraft in the team A_T communicates its imminent intentions to the team organiser a_0. If a team member a_i decides to drop its commitment to the execution of the plan P, it is assumed it does so because it is unable to execute the actions assign to it in the plan P devised by the team organiser a_0. This may occur for the following reasons:

(i) The team organiser a_0 has incomplete knowledge of a_i's current situation and suggests a plan that a_i cannot execute because it has suffered an emergency and/or an equipment failure.

(ii) The aircraft a_i is aware of another resolution action that is more effective to its own situation and that it can apply to itself to maintain safe separation from the other aircraft in A_T. This resolution action can only be made if it does not interfere with the actions that the plan P assigns to the other team members.

In the case of (i) the team organiser re-plans with a new team that excludes a_i and considers it as an intruder that becomes a constrain in the new plan.

In the case of (ii) either the original plan is executed by the remaining team members or a significantly more efficient plan is devised by the organiser.

Figure 1 illustrates the structure of the set of conventions that can be implemented by the individual aircraft agent a_i.

It is considered that the airborne communication, navigation and surveillance technologies being developed for the future ATM system will be capable of supporting the airborne separation assurance scheme outlined above.

III. PLANNING ALGORITHM

This section presents a dynamic programming algorithm that enables a team organiser to design co-operative strategic resolution plans for two-dimensional conflicts involving multiple aircraft. These plans consist of a set of feasible speed control actions for each of the team members and provide weighted-cost sharing solutions suitable to be implemented according to the operational methodology described above.

A team organiser a_0 uses its knowledge of its current flight plan and the proximate aircraft's intentions to predict possible conflicts. The aircraft a_0 forms a team A_T and designs a common conflict avoidance plan. As the designer of this plan, a_0 acts as a *central planner* [19] and searches for the speed control actions to enable the members of the team A_T to track cost effective conflict-free trajectories along their intended paths.

For simplicity, it is supposed that there are neither navigation nor conflict prediction errors. The conflicts considered involve aircraft in *free flight* airspace flying along straight-line tracks at their optimal cruise speed.

The use of speed control actions as a strategic conflict resolution technique in *free flight* is justified by the fact that conflicts can be solved considering cost savings without changing the aircraft's preferred paths. Speed control conflict resolution can be implemented in a cost-effective manner and considering passengers' comfort if the conflict is detected at least 10 minutes prior to the time of closest approach [9].

Moreover, since the aircraft's intended paths remain unchanged, this technique presents the additional advantage of a low probability of creation of new conflicts with the proximate aircraft as a result of the execution of the resolution actions.

A. Mathematical foundation

The conflict avoidance planning algorithm presented in this paper is based on concepts from game theory [22], optimal control [25], motion planning in robotics [19], [20], [21] and dynamic programming [22], [23], [24].

Conflict avoidance is modelled as a multi-stage decision making process consisting of k stages and involving n decision-makers. A scalar-valued stage-additive functional

$$L^i = \sum_{s=1}^{k} l_s^i \qquad (1)$$

is defined for each team member. The functional L^i is called the *loss functional* of the i^{th} decision-maker and l_s^i represents an accumulative cost.

Loss functionals are defined to guide the decision-makers in the search for a sequence of actions that provides optimal conflict avoidance. Therefore, loss functionals encompass both safety and economic costs.

Safety costs are introduced by considering the times to the points of closest approach for the aircraft involved in predicted conflicts [26].

The economic costs that loss functionals take into account are those that accumulate with time, such as flight time, fuel consumption, etc.

The mathematical framework for conflict avoidance presented in this paper introduces a hybrid architecture in which discrete-time analysis (decision making) is combined with continuous dynamics (implementation of the decisions). This hybrid architecture together with a discretisation of the state and decision spaces produces feasible actions that can be implemented by the Flight Management System.

B. Multi-objective optimisation

Designing a separation assurance plan consists of searching for a sequence of decisions (speed control actions) for each decision-maker (team member) that enables it to track a conflict-free trajectory while optimising its loss functional.

Since co-operative conflict is the goal, the issue becomes a *multi-objective minimisation* [28] of the loss functionals, which is subject to the constraints associated with aircraft dynamics and separation minima. The aircraft dynamic models used by the algorithm are based on the Eurocontrol's Base of Aircraft Data (BADA) [27].

To obtain solutions that minimise the losses in an equitable manner for all the team members, the *weighting-objectives method* [28] is applied. Therefore, the problem is changed to a scalar minimisation of a global functional of the form:

$$L = \sum_{i=1}^{n} w_i \cdot L^i = \sum_{i=1}^{n} w_i \cdot \left(\sum_{s=1}^{k} l_s^i \right) \qquad (2)$$

where the scalars $w_i \geq 0$ are the weighting coefficients. Optimal strategies obtained by minimising equation (2) are *Pareto non-dominated solutions* [28] of the multi-objective optimisation problem. Therefore the global solutions are optimal in the sense that the value of any individual loss functional cannot be reduced without increasing the value at least one of the other individual loss functionals.

The default values for the weighting coefficients in the planning algorithm are $w_i = (1/n)$ for each of the n members of the team. These values can be changed to represent the relative importance of the loss functionals according to the aircraft priorities.

The development of analytical continuous-time solutions to the problem of the minimisation of equation (2) would require detailed analysis of the specific models and geometry of the conflicts. However, the introduction of a multistage decision-making process and the discretisation of the decision and state spaces make the application of *dynamic programming* possible for the resolution of the problem [22], [23], [24]. Dynamic programming provides the means for the numerical computation of solutions for a certain discretisation of both the decision and state spaces. Therefore, a planning algorithm based on dynamic programming can be adapted to other discretisations.

In the algorithm presented in this paper, dynamic programming is used to find sequences of speed control actions (decisions) for all the aircraft in the team. These control actions are designed to enable all the aircraft in the team to avoid the predicted conflicts while at the same time minimising the global loss functional, equation (2). This loss functional provides a trade-off between the self-interests of each aircraft and a cost sharing between team members and assures safe separation.

Dynamic programming is carried out in a forward stepping manner applying the Theorem of Optimality for discrete and deterministic multi-stage decision processes [22]. Hence, optimal sequences of decisions are found through an iterative minimisation process:

$$L_{s+1}^{*}(x_{s+1}) = min \left[L_s^{*} + \sum_{i=1}^{n} w_i \cdot l_s^i \right] \qquad (3)$$

where L^{*}_{s} is a minimum of the global loss computed from equation (2) up to stage *s*. Equation (3) is minimised at every stage until the conflict is avoided.

Constraints associated with separation minima and the aircraft dynamics must be satisfied at each stage and during the intervals of transition between stages.

IV. COMPUTED EXAMPLE

An example of the application of the operational methodology and the planning algorithm presented in this paper is shown below. A scenario is considered where three aircraft A1, A2 and A3 are flying along straight tracks at the same altitude in *free flight* airspace and at their selected speeds. They are assumed to be equipped with GNSS, ADS-B, Data Link inter-aircraft communications. In addition each aircraft is equipped with the co-operative separation assurance system presented above. A range of 120 nm for ADS-B and Data Link communications is assumed [7]. A conflict alert is declared if a separation of less than 5 nautical miles between any two aircraft is detected along the aircraft's intended trajectories.

The initial configuration is displayed in Figure 2. Figure 3 shows the evolution of the distances between the aircraft if their current speeds are maintained. Three predicted violations of the separation minima are displayed.

At the initial configuration aircraft A1 predicts three violations of separation minima shown in Figure 3.

A1 initiates the formation of a team with A2 and A3 to avoid the conflict co-operatively. A1 can communicate with A2 and A3, but A2 and A3 cannot communicate with each other.

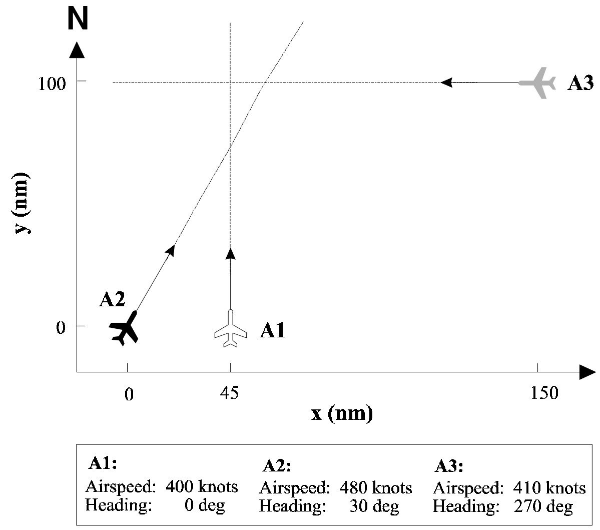

Figure 2. Initial configuration for three aircraft conflict.

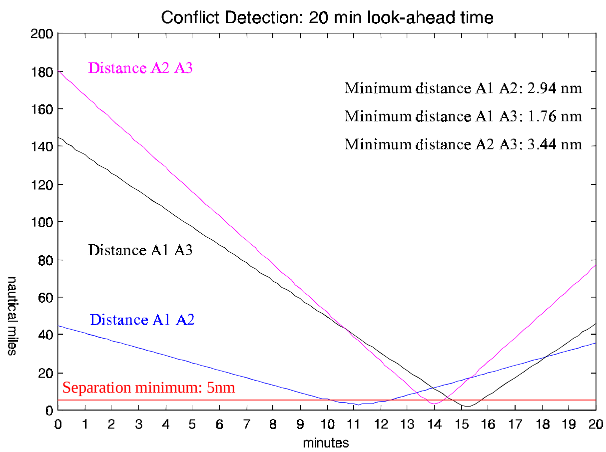

Figure 3: Prediction of possible conflicts by A1 at initial configuration.

Different solutions to this conflict scenario can be obtained depending on:

a) whether A2 and A3 join the team
b) the economic criteria considered in the loss functionals.

Three possible solutions are presented below.

Solution 1: Team solution. Separation assurance with minimum manoeuvring costs.

If both A2 and A3 are willing to co-operate in the conflict avoidance and therefore join the team, A1 applies its planning algorithm to search for a global solution to the conflicts that minimises a given loss functional. This solution consists of speed control actions for the three aircraft involved in the conflict.

The global loss functional minimised by A1 encompasses safety as well as economic criteria for the three aircraft involved in the conflicts. The economic criteria considered in this case are the time of operation at non-optimal speed and the additional costs due to accelerations and decelerations. Therefore, the solution assures separation with the minimum number of manoeuvres and at the same keeps optimal speeds for as long as possible. Deviation from the 4D intended trajectory has not been considered as an economic cost in this case.

The three weighting factors in the global loss functional are set to the same value to distribute equitably the costs among the three aircraft involved in the conflicts.

The results of this case are shown in Figures 4 and 5 and in Table 1.

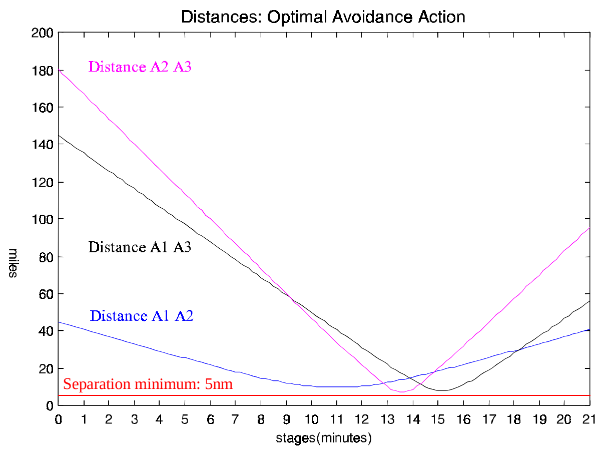

Figure 4: Distances for conflict avoidance action (case 1).

Conflict avoidance: Solution 1

Minimum distance A1 A2: 9.6 nm
Minimum distance A1 A3: 7.7 nm
Minimum distance A2 A3: 7.1 nm

t_{4D}-t_{avoid}*:
A1: 1.0 min
A2: 0 min
A3: -0.98 min

*Delay from the optimal 4D time at the point of the trajectory in which the conflicts are considered as avoided.

Table 1: Conflict avoidance solution 1

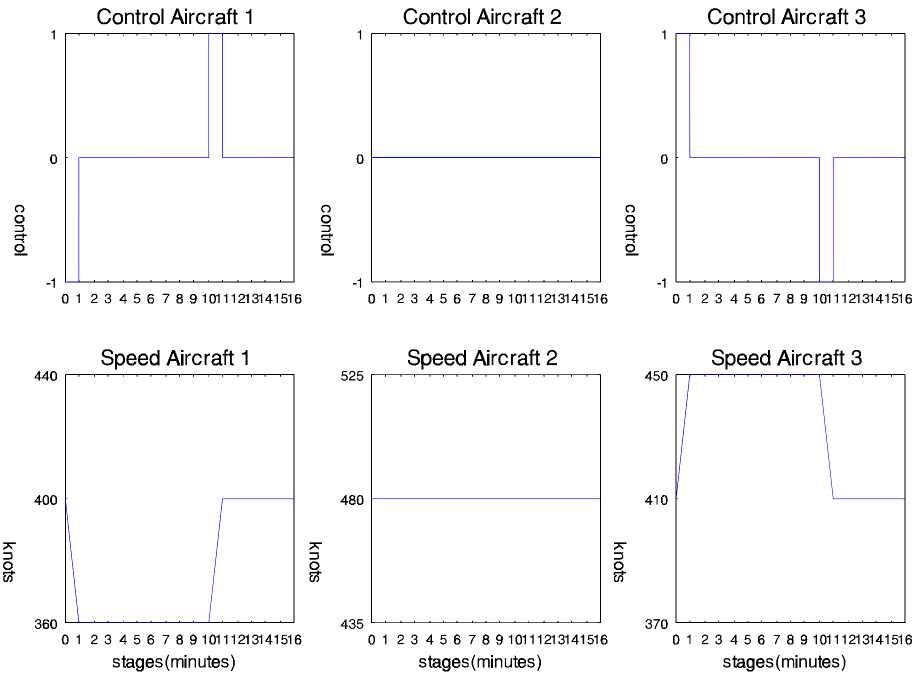

Figure 4: Conflict avoidance speed control actions (Solution 1).

Solution 2: Team solution. Minimisation of 4D losses.

Taking again the scenario described for Solution 1, consider a situation where A1 is required to compute a global loss functional which takes account of the team members performing separation assurance actions that are causing them to deviate from their individual optimal 4D trajectories.

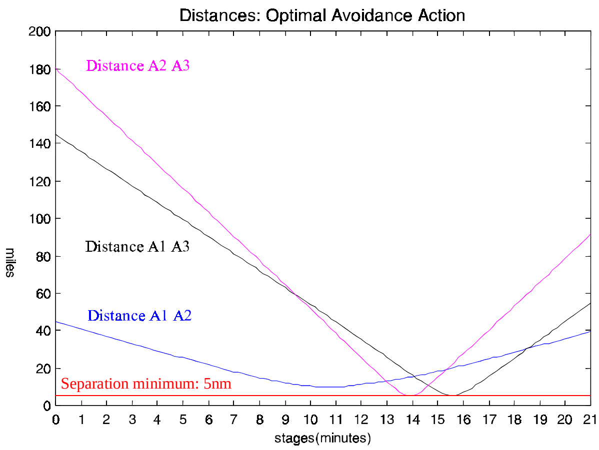

Figure 6: Distances for conflict avoidance action (Solution 2).

The minimisation of this new global loss functional, carried out by A1, provides all three aircraft with a new set of speed control actions guarantees co-ordinated separation assurance. Providing the same value is assigned to the three weighting factors in the global loss functional, this new set of control actions minimises both the deviations from the optimal intended 4D trajectories and the economic criteria considered in Solution 1.

This team solution distributes the costs equitably between the three members.

The results of this case are shown in Figures 6 and 7 and in Table 2.

Conflict avoidance: Solution 2
Minimum distance A1 A2: 9.85 nm
Minimum distance A1 A3: 5.37 nm
Minimum distance A2 A3: 5.1 nm
t_{4D}-t_{avoid}***:**
A1: 1.05 min
A2: 0.09 min
A3: -0.39 min
*Delay from the optimal 4D time at the point of the trajectory in which the conflicts are considered as avoided.

Table 2: Conflict avoidance solution 2

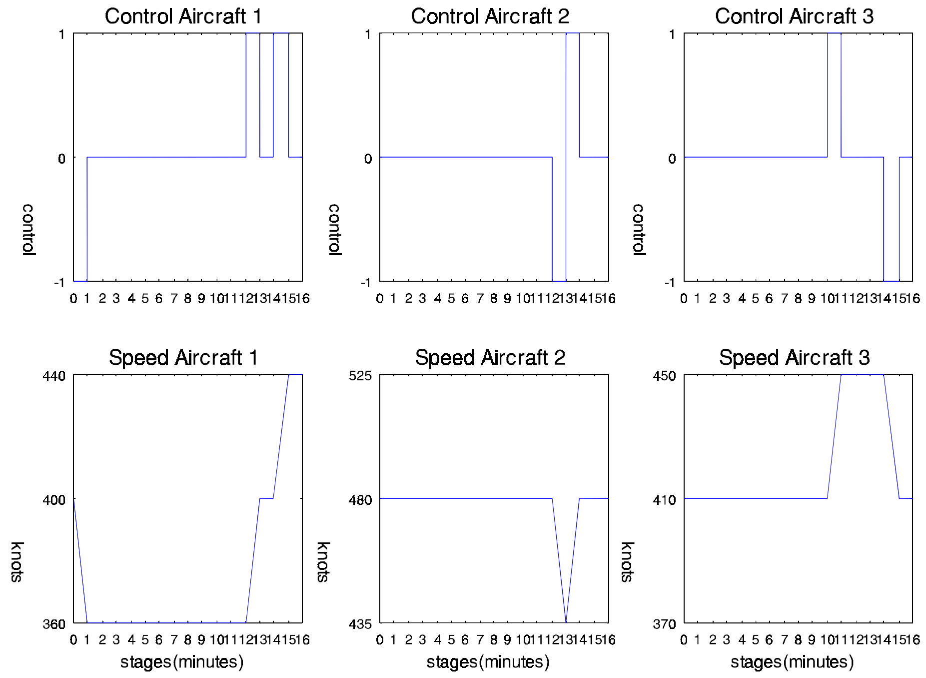

Figure 7: Conflict avoidance speed control actions (Solution 2).

Solution 3: No team solution (A3 does not join the team).

The case is now considered where the scenario of Solution 2 is modified with A3 not willing to co-operate in the conflict resolution plan. It is assumed that A3 intends to maintain its current trajectory. Thus the team in this case is reduced to the two aircraft A1 and A2. The solution presented here provides an avoidance plan for A1 and A2 that accounts for the optimisation criteria considered in Solution 2. The aircraft A1 minimises a new global loss functional where the weighting factors are adjusted such that A1 and A2 share the all the costs involved in the resolution leaving A3 to continue on its intended trajectory.

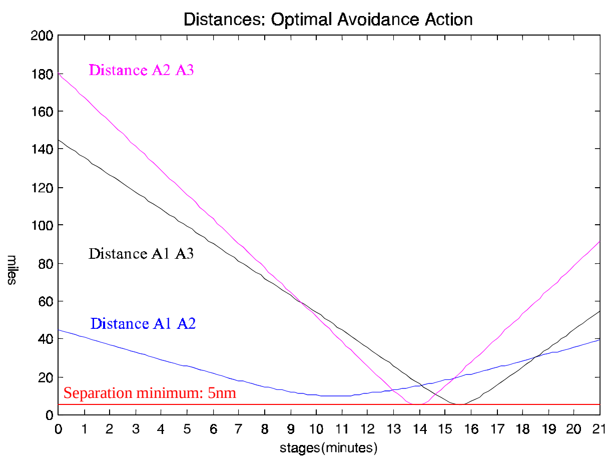

Figure 8: Distances for conflict avoidance action (Solution 3).

The results of this case are shown in Figures 8 and 9 and in Table 3.

Conflict avoidance: Case 3

Minimum distance A1 A2: 11.05 nm
Minimum distance A1 A3: 8.43 nm
Minimum distance A2 A3: 6.85 nm

t_{4D}-t_{avoid}*:
A1: -1.55 min
A2: 0.80 min
A3: 0 min

*Delay from the optimal 4D time at the point of the trajectory in which the conflicts are considered as avoided.

Table 3: Conflict avoidance solution 3

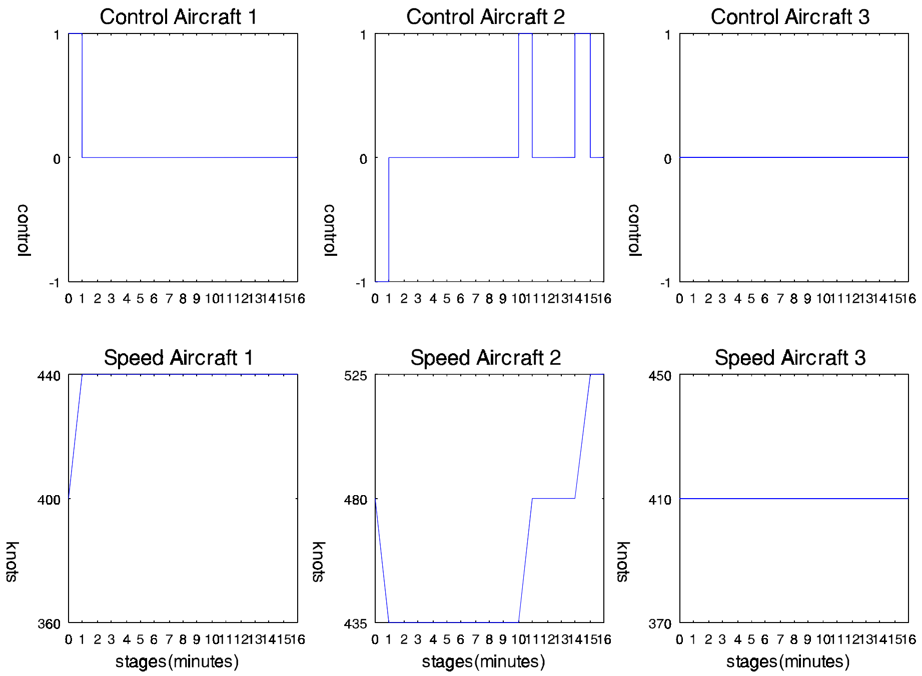

Figure 9: Conflict avoidance speed control actions (Solution 3).

V. CONCLUSIONS

A new framework based on Distributed Artificial Intelligence has been proposed to implement autonomous airborne separation assurance in *free flight* airspace. This framework supports co-operation and costs optimisation in airborne strategic conflict avoidance. Within the framework, conflicting aircraft form teams to co-operatively resolve conflicts. An operational protocol for team formation has been presented. The detailed definition of this protocol will depend on the future technical requirements of inter-aircraft data communication systems (ADS-B and Data Links).

A dynamic programming algorithm has been developed for airborne centralised conflict avoidance planning. The algorithm provides avoidance strategies that minimise a global loss functional that considers safety as well as economic costs.

The conflict avoidance manoeuvres considered in the current version of the algorithm are speed control actions. Therefore, the existence of a global optimal avoidance strategy is not guaranteed and depends on the loss functional that is being minimised. However, solutions can be found in more complex cases by increasing the weigh assigned to the safety costs within the individual loss functionals.

Future versions of the planning algorithm will provide solutions for three-dimensional conflicts and will allow for co-operative resolution that includes both horizontal and vertical manoeuvres.

VI. REFERENCES

[1] D. L. Allen, A. Haraldsdottir, R. W. Lawler, K. Pirotte, R. W. Schwab, “The Economic Evaluation of CNS/ATM Transition”, *CNS/ATM Projects*, Boeing Commercial Airplane Group, April 1998.

[2] European Organisation for the Safety of Air Navigation (Eurocontrol), “Operational Concept Document (OCD)”, Edition 1.1, 4 January 1999.

[3] C. Tomlin, G. J. Pappas, S. Sastry, “Conflict resolution for Air Traffic Management: A study in Multiagent Hybrid Systems”, *IEEE Transactions on Automatic Control*, vol. 43, No. 4, April 1998.

[4] J. Kosecka, C. Tomlin, G. J. Pappas, S. Sastry, ”Generation of Conflict Resolution Maneuvers”, *Technical Report, from IEEE International Conference on Intelligent Robots and Systems*, pp 1598-1603, 1997.

[5] C. Tomlin, G. J. Pappas, S. Sastry, ”Noncooperative Conflict Resolution”, *Proceedings of the 36th Conference on Decision and Control*, San Diego, California USA, December 1997.

[6] L. C. Yang, J. K. Kuchar, ”Prototype Conflict Alerting System for Free Flight”, *Journal of Guidance, Control, and Dynamics*, Vol 20, No 4, July-August 1997.

[7] V. N. Duong, E. Hoffman, J. -P. Nicolaon, “Initial Results of Investigation into Autonomous Aircraft Concept (FREER-1)” , *paper from 1st USA/Europe ATM R&D Seminar*, Saclay, June 1997.

[8] J. Krozel, T. Mueller, G. Hunter "Free Flight Conflict Detection and Resolution Analysis", *AIAA Guidance, Navigation and Control Conference*, San Diego, California USA, July 1996.

[9] J. Krozel, M. Peters "Strategic conflict Detection and Resolution for Free Flight", *Proceedings of the 36th Conference on Decision and Control*, San Diego, California USA, December 1997.

[10] P.K. Menon, G. D. Sweriduk, "Optimal Strategies for Free-Flight Air Traffic Conflict Resolution", *Journal of Guidance, Control, and Dynamics*, Vol 22, No 2, March-April 1999.

[11] A. Warren, "A methodology and initial results specifying the requirements for Free Flight transitions", *paper from 1st USA/Europe ATM R&D Seminar*, Saclay, June 1997.

[12] R. Mandiau, S. Piechowiak, "Conflict Solving Into the Multi-Agent Distributed Planning", *Universite de Valenciennes,* 1998.

[13] M. Woodlridge, "The Logical Modelling of Computational Multi-Agent Systems", *PhD thesis, UMIST, Manchester,* October 1992.

[14] M. P. Singh, A. S. Rao, M. P. Georgeff, "Formal Methods in DAI: Logic-Based Representation and Reasoning", *in Multi-agent Systems: A Modern Approach to Distributed Artificial Intelligence*, Gerhard Weiss (ed), MIT Press, 1999, chapter 8, pp 331, 376.

[15] N. Jennings, *Cooperation in Industrial Multi-Agent Systems*, World Scientific Publishing Co. Pte. Ltd., Singapore, 1994.

[16] R. Davis, R. G. Smith, "Negotiation as a metaphor for Distributed Problem Solving", *Artificial Intelligence,* Vol. 20, pp 63-109, 1983.

[17] J. P. Wangermann, R. F. Stengel, "Distributed Optimization and Principled Negotiation for Advanced Air Traffic Management", *Proceedings of the 1996 IEEE International Symposium on Intelligent Control,* Dearborn, MI USA, September 1996.

[18] J. P. Wangermann, R. F. Stengel, "Optimization and Coordination of Multiagent Systems Using Principled Negotiation", *Journal of Guidance, Control and Dynamics,* Vol. 22, No. 1, January-February 1999.

[19] S. M. LaValle, S. A. Hutchinson, "Optimal Motion Planning for Multiple Robots Having Independent Goals", *IEEE Transactions on Robotics and Automation,* Vol. 14, No. 6, December 1998.

[20] S. M. LaValle, "A Game-Theoretic Framework for Robot Motion Planning", *PhD thesis, University of Illinois at Urbana-Champaign,* 1995.

[21] M. Mediavilla, J. C. Fraile, J. R. Peran, G. I. Dodds, "Optimization of Collision Free Trajectories in Multi-Robot Systems", *Proceedings of the 1998 IEEE International Conference on Robotics & Automation* Leuven, Belgium, May 1998.

[22] A. Kauffmann, *Graphs, Dynamic Programming, and Finite Games*, Academic Press Inc., New York 1967

[23] R. Bellman, *Dynamic Programming*, Princeton University Press, Princeton, New Jersey, 1957.

[24] B.Gluss, *An Elementary Introduction to Dynamic Programming. A state equation approach,* Allyn and Bacon Inc., Boston 1972.

[25] F. L. Lewis, V. L. Syrmos, *Optimal Control, 2nd edition,* John Wiley & Sons, Inc., New York, 1995.

[26] N. L. Fulton, "Airspace design: towards a rigurous specification of conflict complexity based on computational geometry", *The Aeronautical Journal,* February 1999.

[27] P. Baulleret, "User Manual for the Base of Aircraft Data (BADA) – Revision 3.1", *EEC Note No 25/98,* Eurocontrol, November 1998.

[28] A. Osyczka, *Multicriterion optimization in engineerin with FORTRAN programs*, Ellis Horwood series in engineering science. England 1984.

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