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An Advanced 3D Algorithm for Automatic Separation Assurance Systems

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***Abstract*— Hazardous collision situations among multiple aircraft could arise in future air transport system more often than today, since traffic density is predicted to hugely increase. An Automatic Conflict Resolution Algorithm is presented in this paper, which can provide automatic aircraft separation assurance for next generation air traffic control systems. Once a conflict arising with one or more aircraft has been detected, the proposed algorithm computes a safe flight trajectory to maintain separation with other traffic. The algorithm has been conceived for installation on-board autonomous aircraft because it performs required decision-making process for conflict detection and generates commands directly to the autopilot for conflict resolution. The algorithm is not rule-based but uses an efficient analytical solution to detect the conflicts, thus resulting suitable for real-time applications. Moreover, the proposed strategy for generating the conflict resolution maneuver minimizes the deviation from the original trajectory. In addition to algorithm description, some numerical simulations with challenging scenarios are presented in the paper, showing algorithm ability to solve a conflict situation in a self-organizing system including several aircraft equipped with the same proposed algorithm.**

Keywords-separation assurance; automated system; conflict detection; conflict resolution; real-time implementation

I. INTRODUCTION

Current air traffic control operations are based on conflict resolution rules and controller experience. Rule-based approaches might work when few aircraft are involved, but they may require a prohibitive number of rules to handle all the situations arising when several aircraft are involved. Conflicts involving more than two aircraft have been shown to occur in high-density traffic areas [1]. Furthermore, although today conflict situations rarely involve more than two aircraft at the same time, indirect conflicts are however possible, since the solution of a conflict involving one aircraft pair can generate a secondary conflict with neighboring vehicles. Moreover, multiple conflicts can arise in the future air traffic system, since air traffic density is predicted to hugely increase in the next years. According to EUROCONTROL data [2], in fact, it is estimated that the traffic levels in Europe in 2030 will be between 16.5 and 22.1 million IFR (Instrument Flight Rules) movements in the ESRA (EUROCONTROL Statistical Reference Area), which means 1.7-2.2 times the traffic in 2007.

Based on the above considerations, it is evident that designing a real-time Automatic Conflict Resolution Algorithm (ACRA) is hard task. ACRA should comply with some relevant requirements, namely: reliability (all conflicts shall be solved), efficiency (resolution strategies shall be computed in a reasonable time) and capacity (management of a large number of aircraft shall be performed). Moreover, ACRA must solve conflicts while making sure that the solution does not create new conflicts.

A comprehensive survey of conflict detection and resolution methods is provided in [3]. The conflict resolution among several aircraft is a highly combinatorial problem, whose solution can be found in a centralized or decentralized way [4]-[5]. By using centralized approach, solutions can be found that are both complete and globally optimized, but they are usually not deterministic and so computationally intensive to be not effective for real-time applications. In decentralized approach, each aircraft independently determines its individual resolution trajectory. This can be obtained by using different strategies, but in general a priority order is assigned to each conflicting aircraft and the conflict resolution problem is suitably simplified. Decentralized approach, therefore, leads to solutions that do not represent a global optimum for the whole conflict resolution problem. Furthermore, decentralized techniques are usually incomplete, i.e. they may fail to find a solution even though there is one. Anyway, the dramatic reduction of complexity makes the decentralized approach an excellent alternative to the centralized one.

This paper presents a decentralized approach where no priority is assigned to the conflicts. All aircraft are supposed to be equipped with the same algorithm (ACRA) and each aircraft involved in the conflict computes its own conflict-free trajectory. It is only assumed that each aircraft can detect the others within a certain range and send them its trajectory prediction. The proposed algorithm implements an analytical solution to detect the conflicts, so completely avoiding the explicit application of rules. Main advantage of the proposed algorithm is therefore the high efficiency, making the algorithm suitable for real-time implementation. Furthermore, another relevant feature of the algorithm is that

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it provides a system of N aircraft, all equipped with the same algorithm (ACRA), with self-organizing abilities.

It is worth noticing that, as it will be better emphasized in the following, the approach proposed in this paper assumes that each aircraft receives via data-link, from all the others surrounding it, their velocity vector. The proposed approach, therefore, is in line with the one usually adopted in the current ADS-B and TCAS II standards, where the cooperative hypothesis is assumed.

The paper describes the proposed algorithm and reports the results of some numerical simulations with challenging scenarios. Realistic aircraft models (with proper dynamic limitations) are used, so avoiding the assumption of simplifying hypotheses typically adopted in the conceptual design phase of conflict resolution algorithms.

It is worthwhile noticing, nevertheless, that the proposed self-organizing conflict resolution ability of N aircraft, through cooperative interaction among N individual algorithms, still needs to be formally proven. Furthermore, the relationship between the proposed individual algorithm and the stability of a system including several aircraft shall be also investigated in detail. Anyway, even if simulation results presented in this paper do not represent a complete assessment of the proposed approach, they preliminarily show the effectiveness of the algorithm.

II. SYSTEM ARCHITECTURE

In order to focus the application framework of the proposed algorithm, a possible functional architecture for an Automatic Separation Assurance and Collision Avoidance System (ASACAS) is here described. The system core is a decision-making algorithm which receives velocity and position vectors of own aircraft ($\vec{P}_A, \vec{V}_A$) and velocity, position and intent vectors of all surrounding aircraft $\left(\vec{P}_{Bi}, \vec{V}_{Bi}, \vec{I}_{Bi}\right)_{i=1..N}$. The outputs of the decision-making algorithm are the reference signals to the autopilot, in terms of demanded velocity module (V_A^d), flight path angle (γ_A^d) and track angle (χ_A^d).

The Decision-Making algorithm executes two functions: Separation Assurance (SA) and Collision Avoidance (CA). They are allocated on two different logical levels, since CA is considered as an emergency function that is activated only when an emergency event is raised. The emergency event can be raised in presence of non-cooperative aircraft (non-equipped with ASACAS) or in case of data-link loss. As an additional input, CA module also receives information about the class of surrounding aircraft (C_{Bi}), estimated by an onboard sensor fusion algorithm and used to perform an appropriate avoidance maneuver. An example of such sensor fusion algorithm can be found in [6]. In normal operations, the SA module assures safe separation among aircraft, so the CA module is not activated.

III. AUTOMATIC CONFLICT RESOLUTION ALGORITHM

A. *Assumptions*

The development of the Automatic Conflict Resolution Algorithm here proposed is based on some hypotheses: 1) each aircraft A/C$_i$ is in conflict with M_i of the remaining $N-1$ aircraft ($M_i \leq N - 1$); 2) all aircraft are initially moving with constant velocity vectors; 3) all aircraft are equipped with the proposed ACRA algorithm; 4) each aircraft can solve its conflicts by means of an instantaneous single step change in its velocity vector; 5) each aircraft solves its conflicts by computing a conflict-free trajectory for itself and communicating via data-link its intentions to all surrounding aircraft, so a simultaneous independent conflict resolution approach is applied, without considering any pre-programmed sequence.

The algorithm has been designed in order to: a) solve all conflicts arising among A/C$_i$ and M_i aircraft (primary conflicts); b) not induce new conflicts with the remaining ($N - M_i - 1$) aircraft (secondary conflicts); c) minimize the deviation of A/C$_i$ from its original trajectory.

Based on the above described assumptions, each aircraft always considers all surrounding aircraft moving with constant velocity vectors and solves its conflicts instantaneously, even if one conflict at a time and not all M_i at the same time. Even though only one aircraft at a time performs its conflict resolution maneuver, the proposed conflict resolution strategy has to be considered cooperative, since all aircraft intentions are supposed to be known by the maneuvering aircraft each time. This system of N aircraft is self-organizing, because conflict resolution is achieved through actions taken by individual elements of the system, rather than by a centralized control strategy.

It is worth noticing that the assumption about instantaneous change of A/C$_i$ velocity vector is of course unrealistic. Actually, the proposed approach foresees that, during the planned maneuver, A/C$_i$ broadcasts its final commanded velocity vector $\vec{V}_{Bi}^d$ to the surrounding aircraft, which will consider this final velocity for their conflict detection and resolution strategies, even though current velocity vector of the maneuvering aircraft is still $\vec{V}_{Bi} \neq \vec{V}_{Bi}^d$. Simulation results have shown that this assumption is definitely acceptable in typical conflict resolution problems.

Conflict detection and resolution are here addressed in a 3D framework. The aircraft that is currently solving its conflict is modeled as a point object with a 3-Degrees Of Freedom (DOF) kinematics, whereas the other conflicting aircraft is modeled as a moving sphere with radius R (safety bubble).

The decision-making algorithm concerning ASACAS module, both for the SA functionality and the CA one, can be formulated as a two-stage process. In the first stage, *Conflict Detection*, a potential conflict between two aircraft is detected, determining if, after a certain amount of time, their future positions could experience a separation loss (i.e. own vehicle trajectory enters the safety bubble of the surrounding aircraft). If so, the second stage, *Conflict*

Resolution, is activated and the trajectory of own vehicle is suitably re-planned to resolve the conflict.

Depending on the considered functionality; SA or CA, two different safety bubbles are defined. In the CA functionality, the considered safety bubble has a radius $R_{CA} = 500\ ft$, based on FAA incident criteria [7]. In the SA functionality, the safety bubble (also referred as "protected zone") represents a non-intrusion zone, around a given aircraft, greater than the safety bubble defined for CA and it is not necessarily motivated by collision avoidance reasons. Several studies, indeed, proved that trailing vortices originating from aircraft wing tips create rolling moments, which could potentially overpower the roll control of a following aircraft [8]. In [9] authors estimate shape and sizes of suitable protected zones in order to avoid such a phenomenon. Based on the work carried out in [9] and assuming that aircraft state information is provided by GPS-based ADS-B [10], a suitable protected zone should cover a spherical volume centered in own aircraft and a cylindrical volume behind the vehicle, in order to take into account the vortex region. Nevertheless, in order to simplify the analytical formulation of the problem, in this paper a conservative estimation of such a protected zone has been used. The safety bubble for SA has been considered as spherical with radius $R_{SA}=2\ nmi$, in order to include the above described sphere+cylinder protected zone considered in [9].

B. *Conflict Detection*

Conflict detection is a kinematic problem where two aircraft are moving, which is equivalent to consider a problem where A/C$_A$ moves with respect to a fixed A/C$_B$ with relative velocity vector $\vec{V}_{AB} = \vec{V}_A - \vec{V}_B$. If $\vec{r}$ indicates the relative position vector of A/C$_B$ with respect to A/C$_A$, the minimum distance $\vec{d}_{AB}$ experienced between the two aircraft after an infinite time horizon can be calculated as:

$$\vec{d}_{AB} = \frac{\vec{r} \cdot \vec{V}_{AB}}{\left\| \vec{V}_{AB} \right\|^2} \vec{V}_{AB} - \vec{r}. \qquad (1)$$

In [11] it has been proven a general theorem stating that a point object A and a sphere B with radius R, which are moving in a 3D environment with constant velocities, are headed for a collision if and only if the following conditions are satisfied:

$$\left\| \vec{d}_{AB} \right\| \le R \quad and \quad \dot{r} < 0. \qquad (2)$$

Based on the considered assumption that all aircraft are initially moving with constant velocity vectors and on the cited theorem, conditions (2) represent the conflict detection criterion for any pair of aircraft here considered. Of course, depending on which functionality is currently performed, SA or CA, the radius R to be considered in (2) will be R_{SA} or R_{CA}.

C. *Conflict Resolution*

In [11] it has been derived the conflict function $f_{B_i}(\chi,\gamma,V)$ of own vehicle (A/C$_A$) with respect to a generic intruder aircraft B_i, such that:

$$f_{B_i}(\chi,\gamma,V) < 0 \;\Leftrightarrow\; \left\| \vec{d}_{AB_i} \right\| > R \;\Leftrightarrow\; \textit{No Collision}$$

$$f_{B_i}(\chi,\gamma,V) > 0 \;\Leftrightarrow\; \left\| \vec{d}_{AB_i} \right\| < R \;\Leftrightarrow\; \textit{Collision}$$

$$f_{B_i}(\chi,\gamma,V) = 0 \;\Leftrightarrow\; \left\| \vec{d}_{AB_i} \right\| = R \;\Leftrightarrow\; \textit{Tangential solution}$$

If (χ_A,γ_A,V_A) is the current velocity vector of aircraft A/C$_A$, which is solving its conflicts, and $\gamma \in [\gamma_{A\min}, \gamma_{A\max}]$ and $V \in [V_{A\min}, V_{A\max}]$ are its envelope limitations, a general formulation for the conflict resolution problem is:

$$\min_{\chi,\gamma,V} \quad |\chi-\chi_A| + \alpha|\gamma-\gamma_A| + \beta|V-V_A|$$
$$s.t. \begin{cases} f_{B_1}(\chi,\gamma,V) \le 0 \\ f_{B_2}(\chi,\gamma,V) \le 0 \\ \ldots\ldots \\ f_{B_N}(\chi,\gamma,V) \le 0 \\ \gamma \in [\gamma_{A\min},\gamma_{A\max}], \quad V \in [V_{A\min},V_{A\max}] \end{cases} \qquad (3)$$

In (3), α and β are proper weights: α has been introduced to separate vertical from horizontal maneuver, while β is used to separate velocity from directional control.

The conflict resolution problem (3) for the SA functionality is here approached in two ways:

- *Velocity Control Strategy*, where $\chi=\chi_A$ and $\gamma=\gamma_A$ are kept constant in $f_{B_i}(\chi,\gamma,V)$;
- *3D-Directional Control Strategy*, where velocity module $V=V_A$ is kept constant in $f_{B_i}(\chi,\gamma,V)$.

1) *Velocity Control Strategy*

The idea of using velocity control as a mean to reduce controller workload is not new [12]-[13]. The novelty of the method proposed in this paper is in the analytical nature of the conflict function $f_{B_i}(\chi,\gamma,V)$ [11], which leads to a closed-form solution valid under the assumed hypotheses.

If $\chi=\chi_A$ and $\gamma=\gamma_A$ are kept constant in the conflict function, assuming as unknown V, problem (3) can be simplified as:

$$\min_{V} \quad |V-V_A|$$
$$s.t. \begin{cases} f_{B_1}(\chi_A,\gamma_A,V) \le 0 \\ f_{B_2}(\chi_A,\gamma_A,V) \le 0 \\ \ldots\ldots \\ f_{B_N}(\chi_A,\gamma_A,V) \le 0 \\ V \in [V_{A\min},V_{A\max}] \end{cases} \qquad (4)$$

Condition $f_{B_i}(\chi_A,\gamma_A,V) > 0$ provides intervals of V such that a collision with aircraft A/C$_{Bi}$ is certain to happen. These intervals are forbidden sets $F_{Bi}^{\chi_A,\gamma_A} = \{V \mid f_{Bi}(\chi_A,\gamma_A,V) > 0\}$. Starting from the general expression of $f_{B_i}(\chi,\gamma,V)$ derived in [11] and assuming χ_A and γ_A as constant, the condition $f_{B_i}(\chi_A,\gamma_A,V) > 0$ becomes:

$$d_i V^2 + 2g_i V + h_i < 0 \qquad (5)$$

where

$$d_i \equiv \|\vec{r}_i\|^2 - R^2 - (\vec{r}_i \cdot \hat{V}_A)^2$$
$$g_i \equiv (\vec{r}_i \cdot \vec{V}_{Bi})(\vec{r}_i \cdot \hat{V}_A) - (\|\vec{r}_i\|^2 - R^2)(\vec{V}_{Bi} \cdot \hat{V}_A)$$
$$h_i \equiv (\|\vec{r}_i\|^2 - R^2) V_{Bi}^2 - (\vec{r}_i \cdot \vec{V}_{Bi})^2$$

Inequality (5) can be analytically solved in order to individuate the forbidden sets $F_{Bi}^{\chi_A,\gamma_A}$ of A/C$_A$ velocity. They can be either connected or disconnected. In Fig. 1 example, $F_{B1}^{\chi_A,\gamma_A}$ and $F_{B3}^{\chi_A,\gamma_A}$ are connected, whereas $F_{B2}^{\chi_A,\gamma_A}$ and $F_{B4}^{\chi_A,\gamma_A}$ are disconnected. In this example, A/C$_{B1}$ and A/C$_{B2}$ are in conflict with A/C$_A$ (primary conflicts), since A/C$_A$ current velocity is $V_A \in F_{B1}^{\chi_A,\gamma_A} \cap F_{B2}^{\chi_A,\gamma_A}$. A/C$_{B3}$ and A/C$_{B4}$ are not in conflict with A/C$_A$. Velocity Control Strategy searches for a solution V_A^d such that primary conflicts with A/C$_{B1}$ and A/C$_{B2}$ are solved, no secondary conflicts with A/C$_{B3}$ and A/C$_{B4}$ arise and $|V_A - V_A^d|$ is minimized.

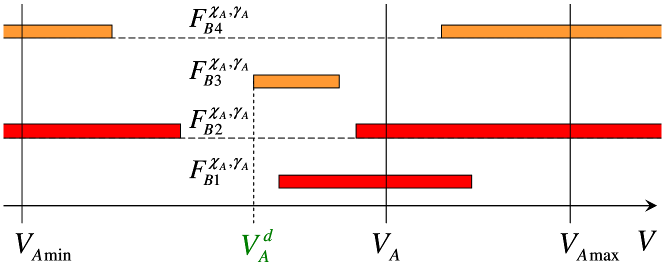


Figure 1. Example of forbidden sets for Velocity Control Strategy

If all forbidden sets are connected, there is a good chance to find a closed-form solution for the conflict resolution problem (3). If C is the set of indexes i of A/C$_{Bi}$ in conflict with A/C$_A$ and indicating with $V_{Ai}^-, V_{Ai}^+ \in \Re$ the two solutions (if they exist) of equation $d_i V^2 + 2g_i V + h_i = 0$, after having computed $V_A^- = \min_{i \in C}(V_{Ai}^-)$ and $V_A^+ = \max_{i \in C}(V_{Ai}^+)$, four cases can be considered, as illustrated in Fig. 2.

Case (a) refers to a situation where the current velocity of A/C$_A$ (V_A) is inside the global forbidden set $[V_A^-, V_A^+]$ and is closer to its upper bound V_A^+: in this case, the A/C$_A$ velocity value that solves the primary conflicts, while minimizing the A/C$_A$ velocity variation, is of course $V_A^d = V_A^+$. Case (b) refers to a situation similar to the one of case (a), with the only difference that here the current velocity of A/C$_A$ is closer to the lower bound V_A^-. Case (c), then, refers to a situation where the lower bound of the global forbidden set is lower than the lower bound of A/C$_A$ velocity envelope; therefore, the only way to solve the primary conflicts is to choose $V_A^d = V_A^+$ (it is worth noticing that, in this case, it is not always possible to minimize the A/C$_A$ velocity variation). Case (d), finally, refers to a situation similar to the one of case (c), with the only difference that here the upper bound of the global forbidden set is greater than the upper bound of A/C$_A$ velocity envelope. It is worth noticing, furthermore, that a situation where the global forbidden set includes the whole allowed velocity envelope of A/C$_A$ would lead, of course, to the impossibility to solve the primary conflicts by using the velocity control strategy.

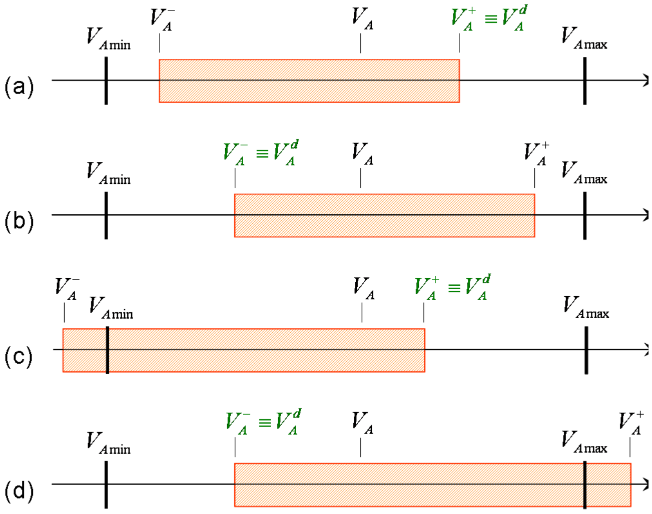


Figure 2. Closed-form solution in Velocity Control Strategy

If V_A^d is such that no conflicts with remaining aircraft (secondary conflicts) arise, it is the desired solution. Otherwise an iterative search for the solution, restricted to interval $[V_{A\min}, V_A^-[\cup]V_A^+, V_{A\max}]$ is started.

2) 3D-Directional Control Strategy

If velocity module V=V_A is kept constant in $f_{B_i}(\chi,\gamma,V)$, assuming as unknown χ and γ, problem (3) can be simplified as:

$$\min_{\chi,\gamma} \quad |\chi - \chi_A| + \alpha|\gamma - \gamma_A|$$
$$s.t. \begin{cases} f_{B_1}(\chi,\gamma,V_A) \le 0 \\ f_{B_2}(\chi,\gamma,V_A) \le 0 \\ \quad \ldots\ldots \\ f_{B_N}(\chi,\gamma,V_A) \le 0 \\ \gamma \in [\gamma_{A\min}, \gamma_{A\max}] \end{cases} \qquad (6)$$

Once again, it is possible to define, for each aircraft A/C$_{Bi}$, forbidden sets as $F_{Bi}^{V_A} = \{(\chi,\gamma) \mid f_{Bi}(\chi,\gamma,V_A) > 0\}$, which can be connected or disconnected. An example of forbidden sets emerging from the application of this strategy is indicated in Fig. 3, where χ_A and γ_A represent current A/C$_A$ track and slope angles, respectively. Since point (χ_A, γ_A) is within forbidden sets $F_{B1}^{V_A}$, $F_{B2}^{V_A}$ and $F_{B3}^{V_A}$, A/C$_A$ is simultaneously in conflict with A/C$_{B1}$, A/C$_{B2}$ and A/C$_{B3}$. In this case, (χ_A^d, γ_A^d) represents the solution of the considered conflict situation that minimizes deviation from the original trajectory. This solution can be computed by an iterative search algorithm.

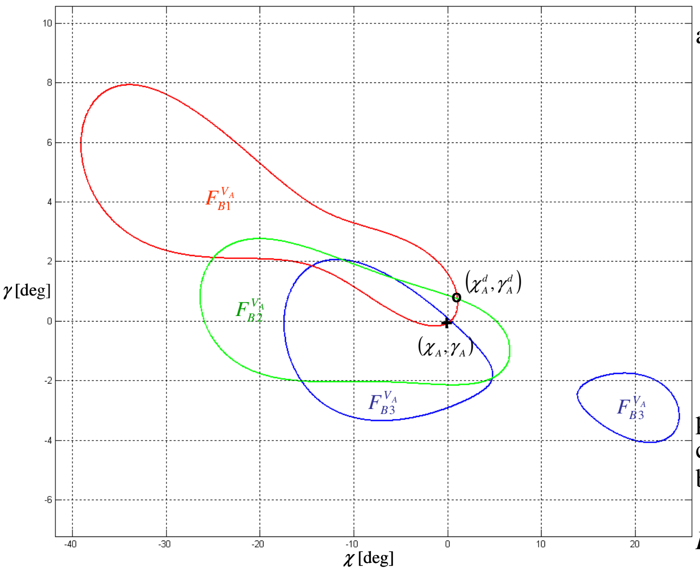


Figure 3. Forbidden sets applying 3D-Directional Control Strategy

The Automatic Resolution Algorithm here proposed implements proper decision-making logic in order to combine the use of Velocity Control Strategy and 3D-Directional Control Strategy. First ACRA tries to apply the Velocity Control Strategy, where forbidden sets are analytically computed, so allowing reduced computational effort. If this strategy does not solve the conflict, ACRA applies the 3D-Directional Control Strategy, less efficient from the computational point of view due to the use of iterative process.

For what concerns the CA function, finally, it is activated only when event *emergency* happens, as described before. A suitable algorithm to be applied in this case has been presented by the authors in [6] and [11].

IV. NUMERICAL VALIDATION AND PERFORMANCES

Preliminary simulation results presented hereafter show the effectiveness of the proposed approach, even though they do not represent a formal proof that it works in any situation. They mainly aim evaluating potential performances of the proposed algorithm.

A. Scenario Definition

Scenarios used for numerical validation here described foresee N aircraft starting, with the same initial velocity, from the border of a circle having radius r_0 and converging towards a central point. It is a very challenging situation, since all aircraft are conflicting each other with reduced free airspace. A sensitivity analysis with respect to N and r_0 has been performed, considering the following cases:

- N = 4, 8, 12, 16, 20, 24, 28, 32;
- r_0 [nmi] = 25, 50, 75, 100.

Scenarios always consider safety bubble radius R_{SA} = 2 nmi, 3DOF kinematic aircraft model, 1 Hz data-link update rate and Boeing 747 performance model for envelope limitations, maximum load factor, roll rate and roll angle.

The parameters here considered for performance analysis are:

- n_C: number of occurred collisions;
- τ_T: average time interval required by the system of N conflicting aircraft to reach the steady state (all trajectories are free of conflicts);
- $\left|\Delta\chi_i^d\right|$: mean value of track angle change during a conflict resolution maneuver;
- D_i: average deviation from the nominal trajectory.

Further studies have been carried out involving more parameters concerning ACRA performances characterization. They are here omitted for the sake of brevity.

B. Simulation Results

First is here considered an example of scenario simulation involving N=24 aircraft starting from r_0 = 25 nmi. Simulation results in this case (see Fig. 4) show that all conflicts are solved, since $s_i(t) \equiv \min_{j \neq i} \left\| \vec{r}_{ij}(t) \right\| > R_{SA}, \quad \forall i = 1,\dots,N$. To better understand how the proposed ACRA works, the time history of aircraft A/C$_5$ track, slope and velocity module are shown in Fig. 5. It is possible to notice that during the first 5 s the control action is directional (track and slope simultaneously) and after that the velocity control action is adopted.

Once illustrated by means of the exemplary scenario the way ACRA works, the results obtained from the simulation of the various scenarios indicated in the previous section are now addressed. In particular, the simulation of the various scenarios with different values of N and r_0 resulted in only two cases of collision (i.e. minimum distance between two aircraft lower than 2 nmi). These two cases occurred in the scenarios

- N=28, r_0 = 50 nmi (minimum distance resulted in 1,7 nmi);
- N=32, r_0 = 50 nmi (minimum distance resulted in 1,3 nmi).

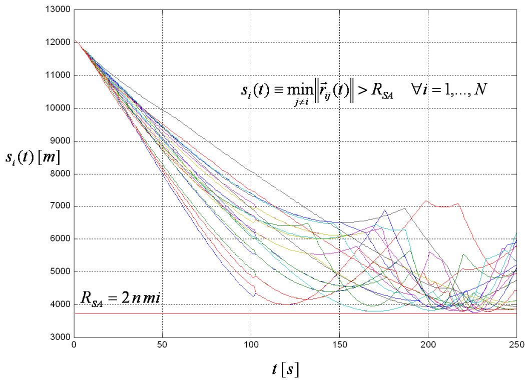


Figure 4. Simulation results with N=24 and r_0 = 25 nmi

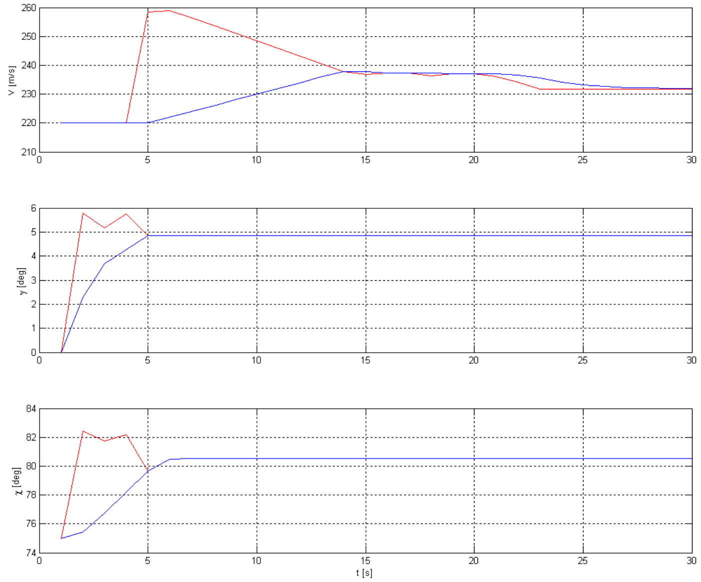
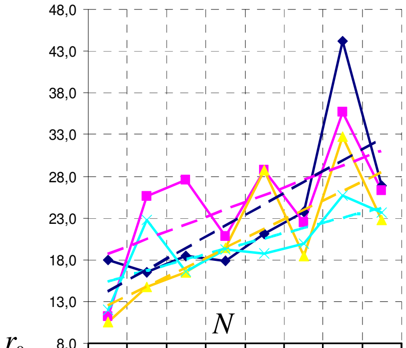


Figure 5. Time history of A/C$_5$ track (χ), slope (γ) and velocity module (V): actual (blue) and demanded (red)

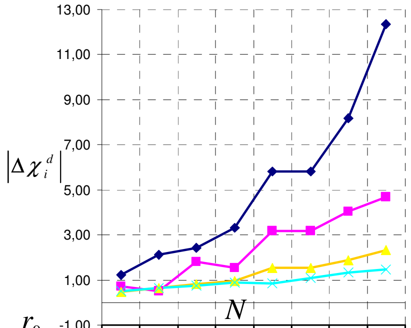
Nevertheless it is worthwhile noticing that 28 or more aircraft all converging towards a same point is a very unlikely event and, also in this very uncommon situation, only one pair of aircraft has been involved in a collision and with a penetration of only 0.3÷0.7 nmi inside a safety bubble with radius R_{SA} = 2 nmi.

Average transient τ_T of the whole system of N aircraft is shown in Fig. 6: the linear regression (dotted lines) represents the trend of the measured points. As expected, it is an increasing function of N and a decreasing function of the initial range. The demanded track angle changes are shown in Fig. 7, while the aircraft average deviation from their nominal trajectory is represented in Fig. 8. Considering the low values of these quantities, it is possible to derive that ACRA tends to reduce as possible the deviation of the manoeuvering aircraft from its nominal trajectory.



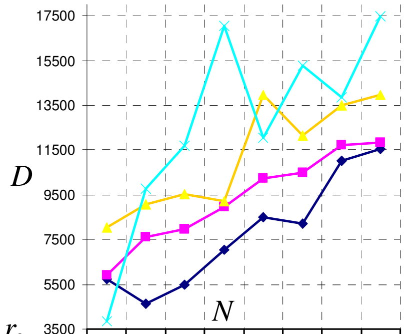
r_0	4	8	12	16	20	24	28	32
25 n mi	18,0	16,5	18,5	17,9	21,1	23,8	44,2	26,8
50 n mi	11,3	25,6	27,6	20,8	28,7	22,5	35,7	26,3
75 n mi	10,5	14,8	16,5	19,4	28,8	18,5	32,8	22,7
100 n mi	12,0	22,8	16,6	19,3	18,8	19,9	25,8	23,6

Figure 6. Average transient τ_T required by the system of N conflicting aircraft to reach the non-conflicting state



r_0	4	8	12	16	20	24	28	32
25 n mi	1,22	2,10	2,43	3,30	5,81	5,83	8,16	12,33
50 n mi	0,71	0,50	1,81	1,55	3,16	3,17	4,04	4,67
75 n mi	0,47	0,63	0,82	0,94	1,54	1,52	1,89	2,33
100 n mi	0,50	0,65	0,75	0,87	0,86	1,08	1,34	1,47

Figure 7. Mean absolute value of the demanded track change [deg]



r_0	4	8	12	16	20	24	28	32
25 n mi	5726	4618	5490	7047	8489	8200	11018	11539
50 n mi	5903	7625	7958	8976	10253	10470	11727	11831
75 n mi	8050	9078	9543	9205	13946	12147	13488	13972
100 n mi	3837	9793	11677	17043	12029	15259	13867	17457

Figure 8. Average deviation from the nominal trajectory [m]

V. CONCLUSIONS

In this paper the problem of solving conflicts arising among several aircraft has been addressed and an Automated Conflict Resolution Algorithm (ACRA) has been proposed. ACRA has been conceived as an automatic onboard system that generates commands directly to the autopilot. The proposed system only needs to know position and velocity of surrounding aircraft and properly combines two control strategies: Velocity Control Strategy and 3D-Directional Control Strategy. The algorithm is not rule-based but adopts an efficient analytical approach, thus resulting suitable for real-time applications. In addition, the proposed strategy can achieve required safety levels while minimizing deviation from the original aircraft trajectory.

Even if the self-organizing conflict resolution capability of *N* aircraft – with a cooperative interaction through *N* separate algorithms – is still far from being fully and formally proven, the method seems to be very promising. Simulation results presented in this paper do not represent a complete verification of the proposed approach, but they highlight its potential performance.

As further research, some simplifying hypotheses need to be removed. For instance, linear only trajectories have to be replaced with open polygons having a finite number of segments. Future possible improvement of the ACRA algorithm could be the consideration of separation maneuvers compliant with the rules of the air. Another open issue to be investigated is the optimal conflict-free recovery of the nominal trajectory, after a conflict resolution maneuver. Moreover, further studies should be carried out in order to design conflict detection and resolution algorithms with respect to protected zones defined by more complex geometries, constituted by a sphere and a cylinder (enveloping aircraft vortex region) or by a spheroid, since a single big sphere enveloping all aircraft vortex region seems to be too conservative.

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