A CASE STUDY IN AIR TRAFFIC MANAGEMENT AUTOMATION

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În această lucrare se prezintă un studiu de caz privind automatizarea controlului de trafic aerian. Utilizând o funcție obiectiv de tip TCR[4] modificată (prezentată în [1], [2]) și folosind o strategie de căutare euristică (algoritmi genetici) soluția propusă are avantajul integrării cu sistemul existent de controlul al traficului aerian. Spre deosebire de alte lucrări [3], [4], [5], am definit problema controlului de trafic așa cum este el aplicat în prezent și nu făcând presupuneri privind dezvoltări viitoare, cum ar fi TBO[5] sau PTC[6]. Astfel, rezultatele pot fi utilizate imediat în practică, fie pentru studiul soluțiilor de control automat pe traficul real, fie ca instrument de asistare a luării deciziilor de dirijare pentru controlorii de trafic. Principala contribuție a acestui articol este verificarea fezabilității unei soluții automate de control al traficului aerian bazata pe algoritmi euristici în cazuri dificile de control si compararea acesteia cu soluțiile controlorilor umani pentru aceeași problema.

This paper presents a case study in air traffic management automation. Using a TCR-like objective function (defined in [1] and [2]) and employing a heuristic search strategy (genetic algorithms) the proposed solution seamlessly integrates with the existing Air traffic management infrastructure and protocols. Unlike other works [3], [4], [5], we defined the problem of traffic control as it is currently applied and not making assumptions about future developments, such as TBO or PTC. Thus, the results can be used immediately in practice, either to study mechanization solutions for real traffic control problems, or as a tool to assist routing decisions for traffic controllers. The main contribution of this paper is the proof that automated air traffic control based on heuristic algorithms is feasible not only for normal traffic situations but also for very complex ones. Secondly, the paper directly compares human versus machine resolution of certain air traffic cases. No such comparisons have been found in the literature.

Keywords: air traffic control, genetic algorithms, TCR, conflict resolution

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[4] TCR = Total Costs and Risks
[5] TBO = Trajectory-Based Operations
[6] PTC = Precision Trajectory Control

1. Introduction

Maintaining the growth of the air transportation industry in Europe necessitates new solutions for two capacity problems: airports and Air Traffic Management (ATM). The airports capacity limitation has both intensive and extensive solutions and, if necessary, new infrastructure can be put in place. The ATM congestion is harder to overcome and, in order to ensure the safety and fluidity of air transport over the next thirty , the European Community launched the SESAR (Single European Sky ATM Research) programme with the main objective to develop a modernised air traffic management system for Europe.

Air traffic management automation as a way to increase capacity became a hot topic in the '90 and '00, but, although a number of solutions were proposed, none is in use today. A survey of the literature reveals two different approaches to the problem: conflict avoidance and conflict resolution. The first approach is usually a radical departure from today systems and, if implemented, will also help solve other problems, like CO_2 minimization etc. It typically involves solving the conflicts at the flight plan stage while simultaneously optimizing the trajectories for low fuel consumption, low carbon emission etc. For additional details on this line of research one may refer to [6], [7], [8], [4], [2], and [9].

Conflict resolution is a more modest approach, but it is, at least in theory, implementable in today ATM centers. It involves automatic conflict detection and resolution, typically concerning a predictive model based on kinematic or dynamic equations of the aircraft, flight plans as desired trajectories and a way to (re)initialize the model with the current traffic situation. This is also the approach used in this paper. Over the years, a number of algorithms were proposed and analyzed beginning with [10] – one of the first papers to use GA, [11] – a study of the complexity of conflict resolution problem, [12] – accelerated conflict detection and [13] – rules based approach.

This paper presents a case study for an implementation of a heuristic conflict resolution solver and contrasts it with human generated solutions.

2. The setup

We used the current system of routes taken and adapted from the July 2010 edition of the EUROCONTROL files. The sectorization used was that of the FIR Bucharest. We also used all the applicable rules and current control tactics of the human controllers, such that the pilots will not detect any difference from the classical traffic control. Routing solutions are interpreted by the human traffic controllers, and transmitted through the classical channel of communication by voice.

The used air traffic simulator is based on a simplified kinematic model of the aircraft. All the dynamic equations involving forces and moments are reduced to ordinary algebraic ones but the navigation equations are preserved in differential form and integrated in the simulator. The automatic control of the

aircraft is also modelled in the last four differential equations. The resulting equations are given in (1) – (10).

$$\overset{\circ}{TH} = g \cdot \tan\phi \, / \, (TAS \cdot \cos\gamma) \tag{1}$$

$$\overset{\circ}{m} = -E \cdot FF\left(mg, T, H, CAS, \overset{\circ}{CAS}, VS\right) \tag{2}$$

$$GS_{TN} = TAS\cos\gamma\sin\left(\pi/2 - TH\right) + WV\sin\left(3\pi/2 - WD\right) \tag{3}$$

$$GS_{TE} = TAS\cos\gamma\cos\left(\pi/2 - TH\right) + WV\cos\left(3\pi/2 - WD\right) \tag{4}$$

$$\overset{\circ}{LAT} = GS_{TN} \, / \, (R + H) \tag{5}$$

$$\overset{\circ}{LONG} = GS_{TE} \, / \, ((R + H)\cos LAT) \tag{6}$$

$$\overset{\circ}{H} = TAS\sin\gamma \, / \cos\alpha + VWV \tag{7}$$

$$\phi = k_\phi \max\left(\min\left(XTK, XTK_{SAT}\right), -XTK_{SAT}\right) - k_H\left(TC - TC_{TRG}\right) \tag{8}$$

$$\overset{\circ}{\theta} = k_H \max\left(\min\left(H_{SAT}, H - H_{TRG}\right), -H_{SAT}\right) - k_\theta\left(\theta - \alpha\right) \tag{9}$$

$$\overset{\circ}{CAS} = k_{CAS}\left(CAS_{TRG} - CAS\right) \tag{10}$$

The Total Costs and Risks (TCR) model is a trade-off between safety and cost effectiveness. The objective function adds up both all costs influenced by the trajectory, and all risks incurred by the navigation process. For this purpose, costs and risks have to be additive and equally scaled. The word "total" has more than one significance: a) the term gathers "all" predictable costs and risks; b) these are estimated for the "entire" duration of the flight (gate-to-gate); c) the function is computed for "all" the aircraft flying in a wider area (TBO area), to ensure the separations.

$$TCR_k = \sum_i C_{i,k} + \sum_j R_{j,k} = \sum_i C_{i,k} + \sum_j p_j D_{j,k} = \min \tag{11}$$

The costs and risks of a given solution for a single flight k (expressed in currency units, e.g. €), which depend on the proposed trajectory, are integrated over the entire flight. Damages are maximum costs in € of the possible damages arising from incidents or accidents caused by a bad choice of the trajectory. The probabilities for the undesired events to occur are functions of the separation from other trajectories, from the terrain (obstacles), from dangerous weather phenomena or from other operational hazards; the probabilities are computed over the entire flight as integral functions of the instantaneous hazard functions π_j [5], as follows:

$$p_j = 1 - e^{-\int \pi_j dt} \tag{12}$$

For TCR computation, steady state flight conditions are assumed, i.e. no accelerations – both linear and rotational acceleration are assumed to be zero.

Those assumptions hold for 99% of the flight time of a commercial airplane. Equilibrium incidence (α), throttle (δ_T) and fuel flow (FF) are computed as in [15], [1] and [5]. International Standard Atmosphere (ISA as described in ISO document 2533:1975) conditions are used for all environmental variables. This is needed manly because the published/indicated characteristics of the engines are available in ISA settings. For the current case study the effect of the wind was ignored, because the simulator used for training at ROMATSA ACC has no wind implementation and we want to directly compare automatic vs. human solutions.

The selected exercise is considered difficult and the reason for choosing it was to test the capability of automatic conflict resolution algorithm. One metric which can be used to asses ATM exercises difficulty is based on conflict density i.e. the number of potential distinct bilateral conflicts per hour. Another metric is based on density of probability of occurrence of one potential distinct bilateral conflict and it is measured h^{-1}. Our case study is at 16 conflicts per hour difficulty and based on interviewing eight experienced air traffic controllers, such a situation occurs once in about five years.

All aircraft were considered capable of RNAV and RVSM. Vertical separation is 1000 ft[7] up to FL410[8] and 2,000 ft above (RVSM). Horizontal separation was considered the 5 NM[9] applicable in the airspace of Bucharest FIR in 2010, a separation necessary to avoid the wake vortex effects.

The density of the traffic is normal for a busy day for Bucharest FIR at the rush hour. The density of traffic is measured in number of movements (flights) per 10k nmi[2] per hour and is a random variable with hourly / weekday / seasonal variations and with multiannual trend of growth. For Bucharest FIR the growth rate is at 5% p.a. and the traffic density averages at around 7.31 in 2010. However, instant values for certain sectors usually go as high as 50-60 during rush hour and as low as 2-5 over night.

The conflict resolution solver was tuned using the routing preferences presented in Table 1. The priority is only "soft enforced", the solver preferring lower index rules over higher ones but inversions are possible. Table 1 was inferred from interviews with human controllers in order to make solutions equivalent. Comparing the obtained solutions, we found that, confronted with difficult situations, human controllers tend to use climb and descent, while the automatic solver (controlled by the preference given in Table 1) rarely uses level changes. In normal circumstances, human controllers prefer not to change flight level [16], but in this case, with a high complexity of traffic (a large number of conflicts in a short interval) they change behaviour, probably as a way to reduce complexity.

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[7] ft = feet; 1 ft = 0.3048 m - Imperial unit are used in aviation as a norm
[8] FL410 = 41,000 ft = 12.497 m
[9] NM = Nautical Miles; 1 NM = 1.852 m

Table 1

Routing preferences

Priority	Actions	values, observations
1	no intervention	If there is no conflict involving this aircraft in the current or next sector then there are no changes to the flight plan.
2	direct	**PROCEED DIRECT TO \<waypoint\>** This action is a shortcut, speeding up the evolution of the aircraft through the sector.
3	vectorization	**TURN LEFT/RIGHT 5/10/15 DEGREES FOR SPACING** this type of routing creates a slight delay, and must be followed within 2 to 10 minutes of an other order to return to the next waypoint **RESUME YOUR NAVIGATION TO \<waypoint\>** No heading changes with more than 15°.
4	parallel offset	**PROCEED ON PARALLEL OFFSET LEFT/RIGHT 2/3/4/5/6 MILES DUE TO TRAFFIC** ; Resuming flight plan require a return command
5	change in flight level	**CLIMB AND MAINTAIN FL... / DESCEND AND MAINTAIN FL... DUE TO TRAFFIC** The new FL will be preserved (no resume to flight plan FL); vertical speeds are +1000fpm[10] for climb and -2000fpm for descent.
6	Holding pattern	**HOLD AT \<waypoint\> FOR 3/4/5/6/8/10 MINUTES DUE TO TRAFFIC** Standard holding pattern at indicated point. Flight plan will resume after completion of one or two waiting patterns.

The methods used to solve the case study presented in this paper are general, i.e. work with any pattern of traffic, at virtually any density of conflicts. The demonstration of their performance in the following chapters stands for a 16 conflicts per hour density which is one order of magnitude larger than the average traffic. Also generalization is made possible by considering the whole range of ATC actions allowed by ICAO documents and in current use.

3. The case study

The case study is illustrated in Figs. 1-5, which is a chronological representation of flights according to flight plans, without the traffic control intervention. It consists of 143 flights over a period of three hours. Traffic builds up naturally and all relevant conflicts are concentrated over a 30min period. We highlighted a number of representative conflicts in Table 2. Only bilateral conflicts were considered, i.e. a potential multilateral conflict is broken into elementary bilateral conflicts for the purpose of clarity. The algorithm on the classic (human) air traffic control is by its nature multilateral and not bilateral. In the attempt to emulate that, the authors did not split the multilateral conflicts into bilateral conflicts except for their description in Table 2 (a table with a variable number of columns would have taken too much width). The algorithm used in this

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[10] fpm = feet per minute; 1 fpm = 0.00508 m/s

paper iterates until a conflict-free solution is found, without breaking up the multilateral conflicts (such as that in Fig. 9) into bilateral ones.

Table 2

No	Time	Flight 1	Segment 1	Flight 2	Segment 2	Conflict Type (vertical/ horizontal)
1	10:58:41	CAI622	ERVAL-LAMIT	AUI801	LAMIT-EROBA	0 ft/4.88 NM
2	11:00:38	THY1768	ERVAL-LAMIT	YUMTU	VEKOD-LAMIT	0 ft/0.36 NM
3	11:19:25	AIC1	GAVRI-NEPOT	BER2237	EPUKI-NEPOT	0 ft/0.00 NM
4	11:19:33	CFG521	UBITA-NERDI	THY550	NEPOT-NERDI	0 ft/3.14 NM
5	11:19:50	CFG521	UBITA-NERDI	AZA480	EROBA-NERDI	0 ft/4.19 NM
6	11:20:07	SMJ841	ENIMA-NERDI	CCA939	EPUKI-NERDI	0 ft/0.64 NM
7	11:20:10	THY550	NEPOT-NERDI	AZA480	EROBA-NERDI	0 ft/0.60 NM
8	11:29:31	AUI521	MOBRA-BAKOV	AZA480	MOBRA-BAKOV	0 ft/0.00 NM

Conflict no. 1 is a convergence at the same level (FL310) and has a low degree of complexity. It can be seen in Fig. 1 (simulation time 10:58:41).

Conflict no. 2 is also a converging on the same level (FL370), but, in this case, both flights arrive at the point of conflict at about the same time. Visual description of the conflict is given in Fig. 2 (simulation time 11:01:00). One complicating factor in this conflict is the difference in the ground speed of the two aircraft (447 kts[11] for THY1768 vs. 332 kts for YUMTU).

Conflict 3 is a convergence in waypoint NEPOT at the same level (FL360) with large difference in speed between the two aircrafts. The conflict is obvious in Fig. 3 (simulation time 11:19:00).

Conflicts 4 and 5 form a single trilateral problem, a convergence in NERDI on the same flight level (FL330). The conflict is illustrated in Fig. 4 (simulation time 11:19:45) and Fig. 5 (simulation time 11:20:00). To complicate things, two other flights converge at the same time in NERDI from opposite direction on FL320 and FL340 respectively.

Conflict 6 is a catch up on the same route at FL330, due to the difference in speed.

Conflict 7 is a convergence on a common entry route at the same waypoint. Aircraft have different speeds, causing a catch up conflict.

Overall, the density of conflicts per unit of time is quantitatively high, leaving a low margin of manoeuver for the controller.
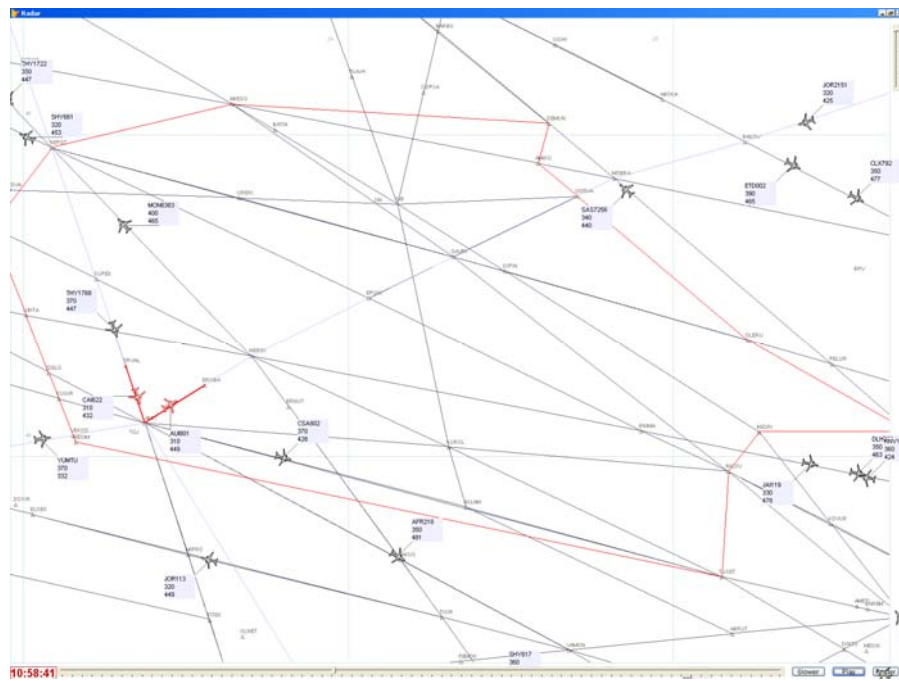
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[11] Kts=knots, 1kts=1NM/h

Fig. 1 Conflict CAI622 - AUI801 in its most acute phase after AUI801 passing through the point of convergence
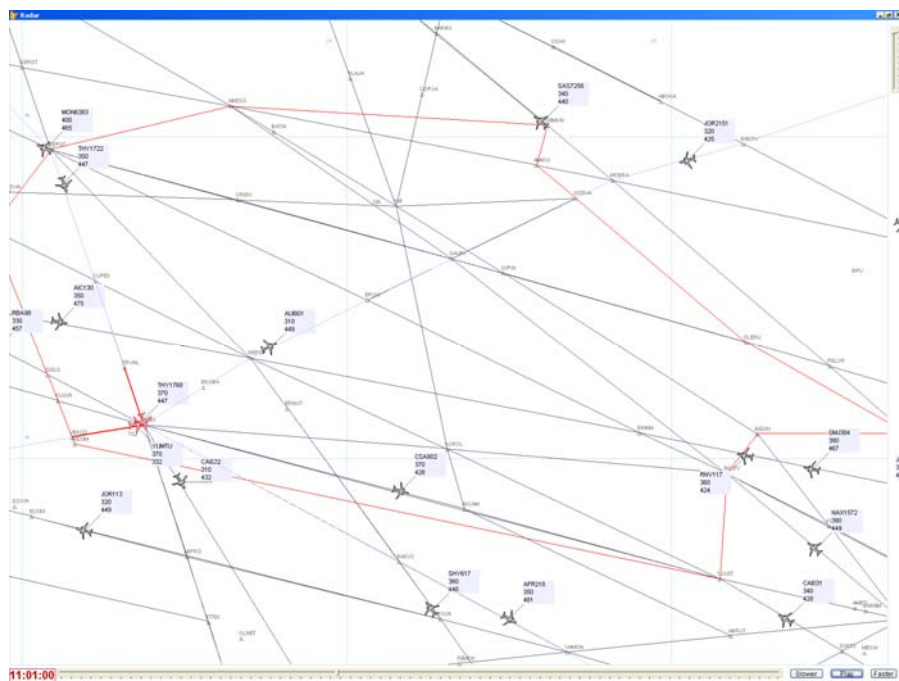

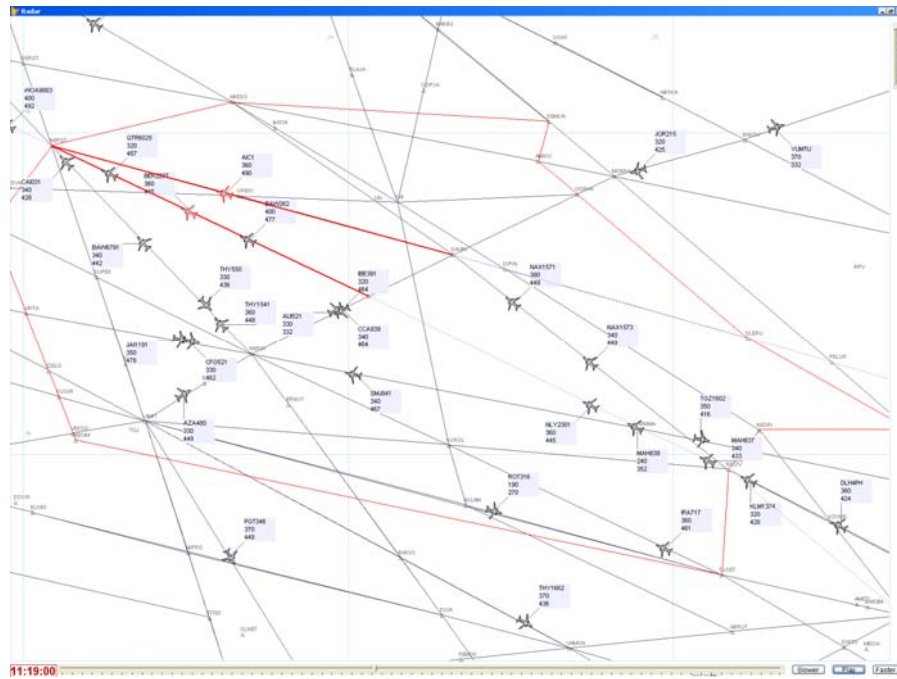Fig. 2 – Possible air collision between THY1768 and YUMTU

Fig. 3 – Evolution of conflict BER2237 - AIC1 is aggravated by the difference in speed between the two aircraft (Boeing 747-400 has a higher TAS)
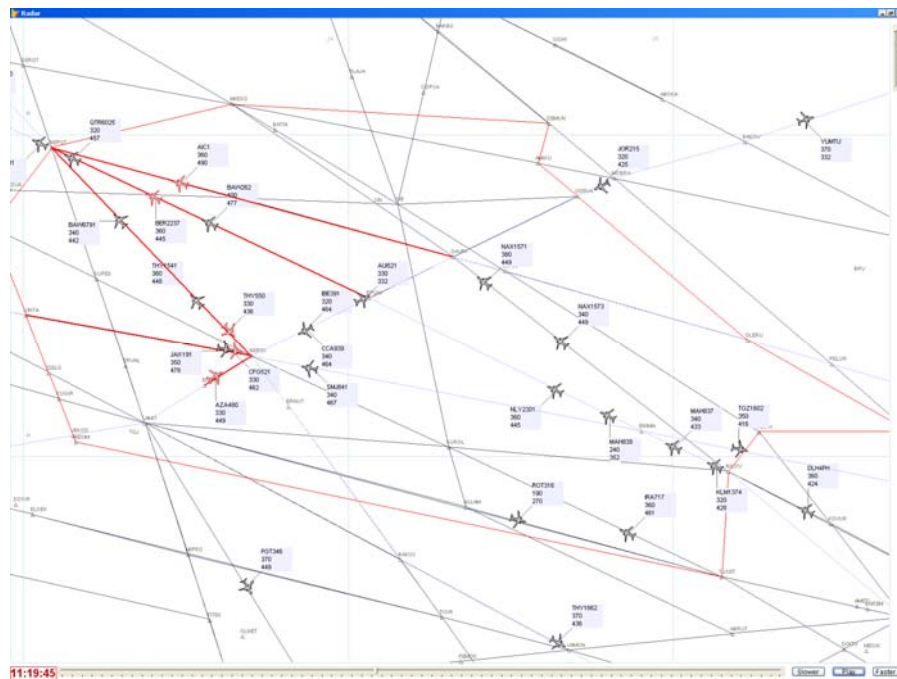

Fig. 4 – The convergence of three aircraft (CFG521, AZA480 and THY550) produces a medium complexity conflict over NERDI
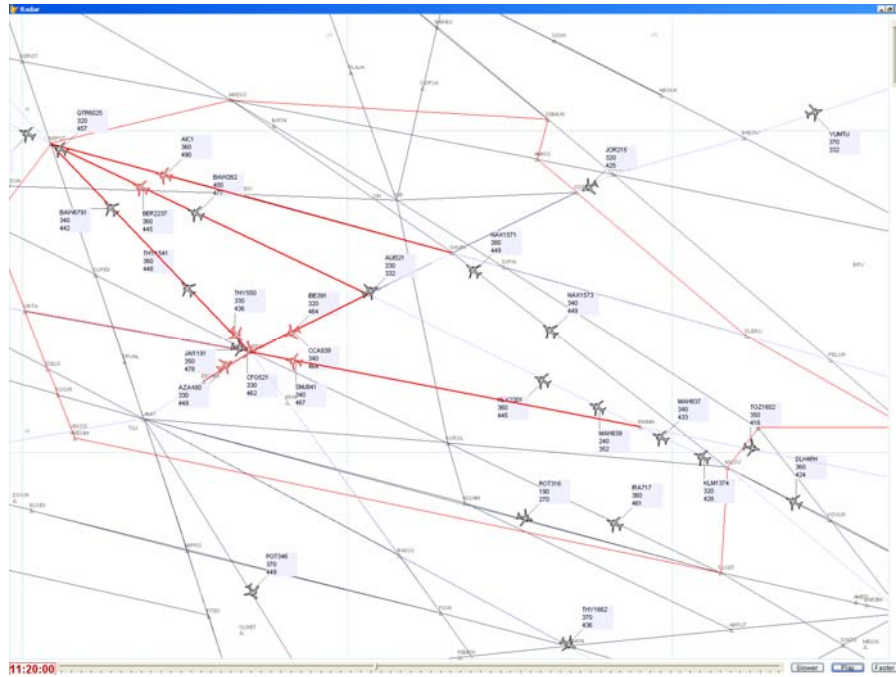
Fig. 5 Level change for any of three flights in convergence at FL330 over NERDI is prevented by inbound traffic (SMJ841 at FL340 and IBE391 at FL320 and IBE391)

4. The automated Air traffic management solution

Numerical simulation was used extensively to put forward and analyze an automated solution. The simulator was used for two distinct purposes:

First, the whole simulation is run in order to get "actual" data – we will call that real-time as, in an eventual implementation, this is the actual situation and not a numerical simulation.

Second, at any given time, an "accelerated-time" simulation is run on a finite time horizon (we try various intervals from 5 to 30 min) in order to predict conflicts ahead. In the present implementation, this is done as an advanced-time simulation that is reset only when needed (when new commands are given), those greatly reducing the computational effort. A conflict detection algorithm is run on that simulation and elementary conflicts are isolated. They form the basis for chromosome representation.

A hybrid GA approach [17] [18], is used, with routing preference implemented as symbols and parameters (among which command time is the most important) implemented as continuous (floating point) values. In order to preserve the coherence of the representation, the genetic operators (crossover and mutation) only act at individual aircraft level.

The computational effort is quite big as every chromosome evaluation requires a full real-time simulation run. Distributed computation architecture was used in order to reduce computation time.

Fitness index was implemented as a modified TCR optimization problem with routing tactics explicitly weighted in.

A solution computed by this algorithm is presented in Fig. 6-12 and the commands required are summarized in Table 3.

Table 3

Numerically obtained solution

| No	Time	Flight 1	Routing solution 1	Flight 2	Routing solution 2	Observation
1	10:57:06	CAI622	-	AUI801	PARALLEL OFFSET 5 NM LEFT FOR 3 MINUTES	/ at segment LAMIT-EROBA
2	10:59:39	THY1768	PROCEED DIRECT TO BAKUS	YUMTU	-	Command started over ERVAL
3	11:15:10	AIC1	TURN LEFT 15 DEGREES FOR 7 MINUTES	BER2237	-	RESUME TO EVRIG
4	11:16:08 / 11:13:15	CFG521	TURN RIGHT 15 DEGREES FOR 8 MINUTES / RESUME TO ENIMA	THY550	PARALLEL OFFSET 5 NM LEFT FOR 8 MINUTES	Command started over UBITA
5	11:19:31	CFG521	-	AZA480	TURN RIGHT 15 DEGREES FOR 7 MINUTES	/ RESUME TO ODEVA
6	11:14:00	SMJ841	TURN RIGHT 15 DEGREES FOR 9 MINUTES / RESUME TO UBITA	CCA939	-	Command started over ENIMA
7	11:20:10	THY550	-	AZA480	-	conflict already solved
8	11:29:31	AUI521	-	AZA480	-	conflict already solved
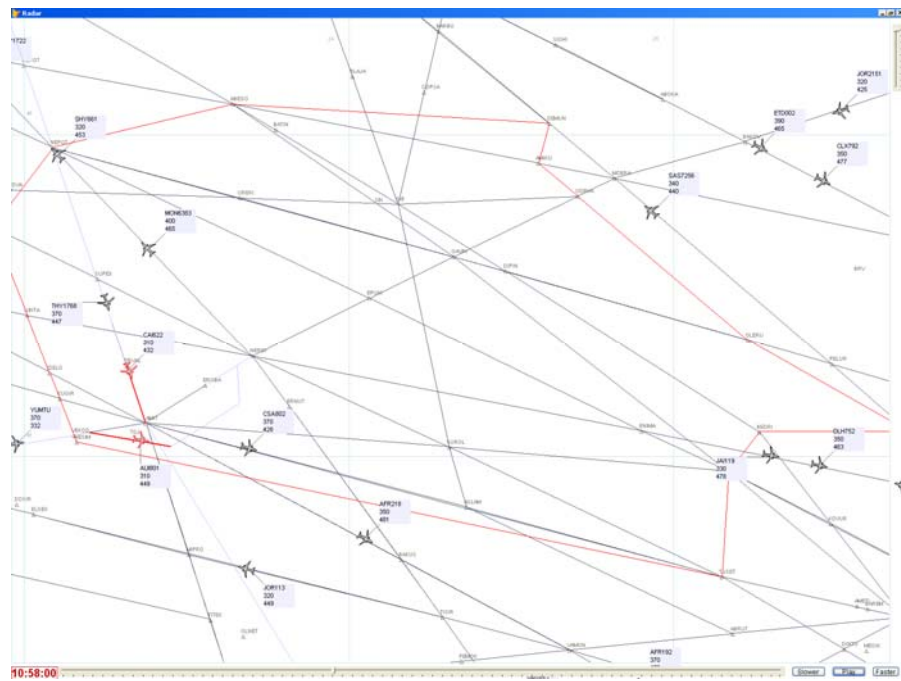
Fig. 6 Avoiding conflict through parallel offset of AUI801 is sufficient
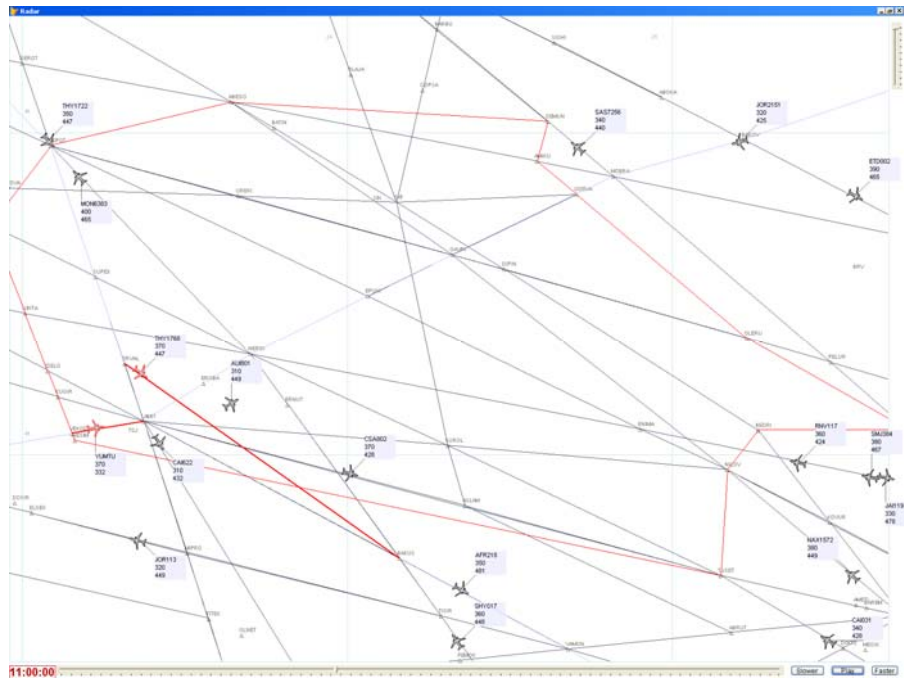

Fig. 7 Automatic resolution of THY1768 - YUMTU conflict by THY1768 vectorization
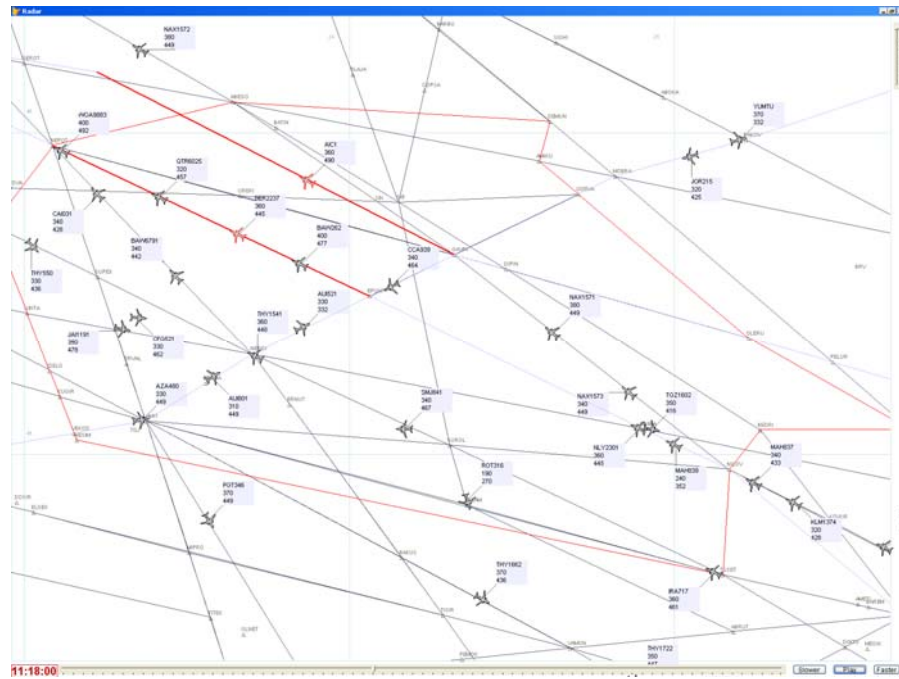directly to the next waypoint

Fig. 8 BER2237 take over by AIC1 (with substantial higher speed) is solved by a parallel offset manoeuvre by AIC1
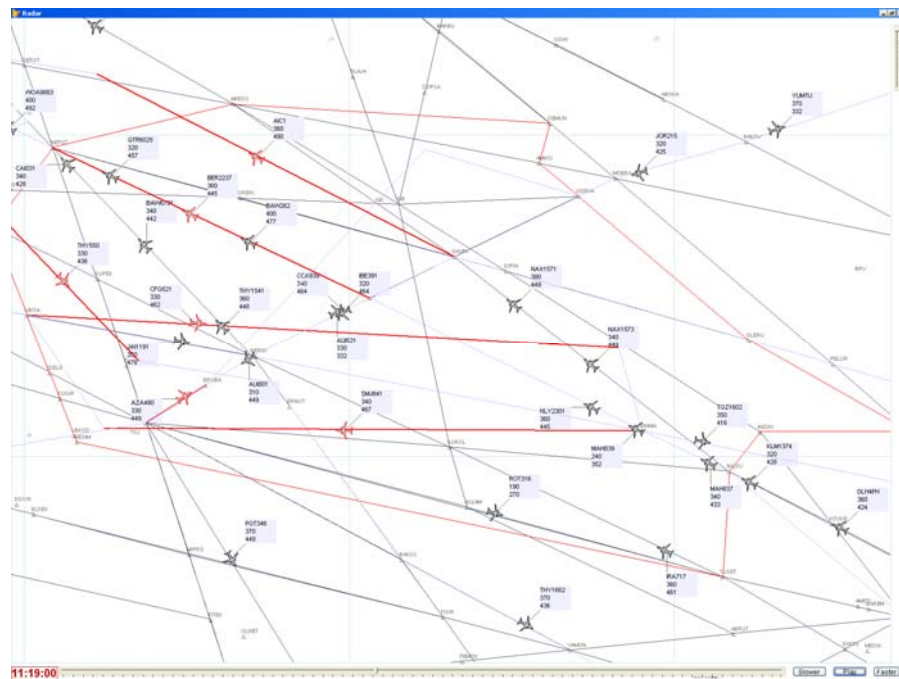

Fig. 9 Multiple conflicts over NERDI are solved by conducting several manoeuvers: a parallel offset of THY550, a 15° right vectorization of CFG512 and a 15° left vectorization of AZA480
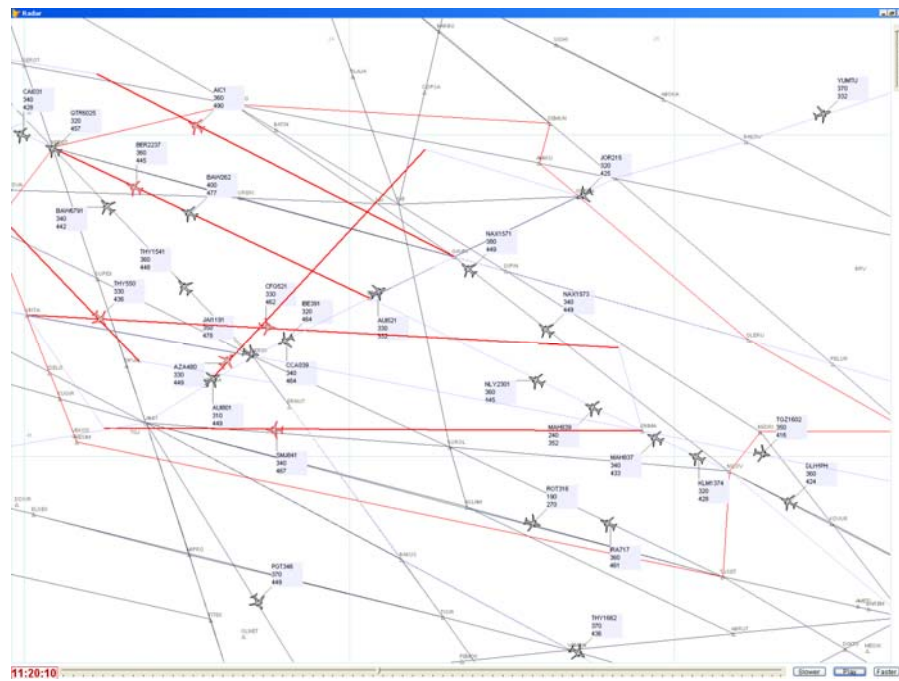
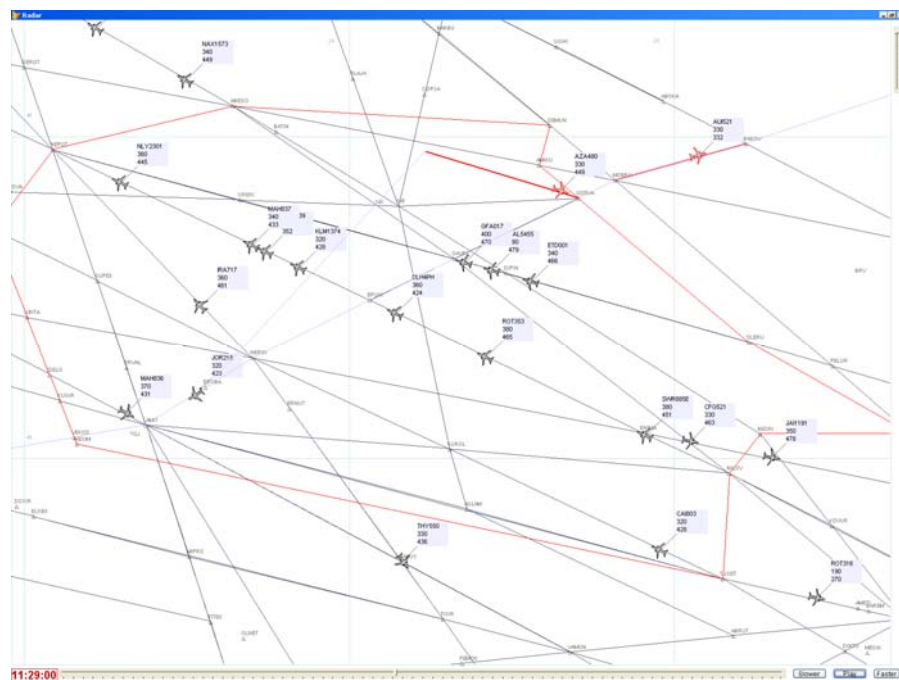Fig. 10 Evolution of the triple conflict over NERDI and overcome of AIC1 by BER2237

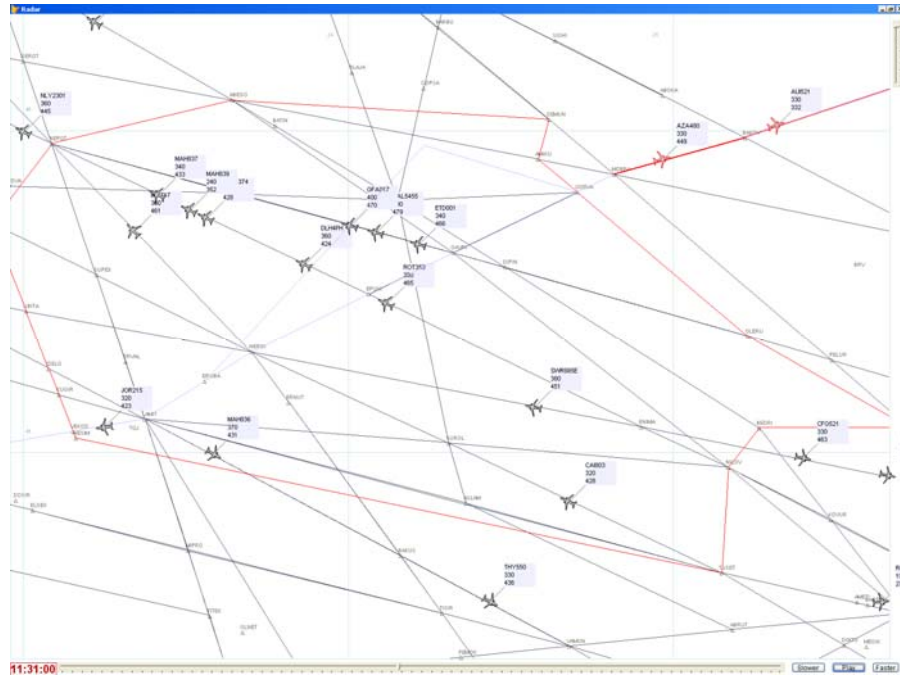Fig. 11 Return to desired flight path for AZA480

Fig. 12 AZA480 no longer chatch up with AUI521 owing mainly to delay due to prior vectorization

Solving the eight separation conflicts in the case study necessitated a number of 7 routing orders based on data from the time interval 10:57:06 to 11:14: 00 presented in Table 3: a direct to command, four 15° vectorizations and two parallel offset commands. By comparison, the solution proposed by human controllers consisted of six vectorizations and two level changes.

The first conflict CAI622/AUI801 occurs at 10:58:41 and is a loss minimum at 4.88 NM. It is solved by a parallel offset of AUI801 5 NM left for 3 minutes, over EROBA-LAMIT segment.

The second conflict THY1768/YUMTU occurs at 11:00:38 and is severe. A direct to BAKUS command for THY1768 at 10:59:39 at the vertical of waypoint ERVAL is sufficient to solve this conflict. Routing command time is the actual time at which its execution must start; therefore we have to provide time for the transmission and confirmation, the operation should be initiated 1-2 minutes earlier.

Conflict AIC1/BER2237 occurs at 11:19:25. Convergence is followed by a common segment, where AIC1catch BER2237. The vectorization of AIC1 at 11:15:10 with 15° for 7 minutes solves this conflict. AIC1 is the faster aircraft (B744), and it is left behind BER2237 (B738), apparently a poor choice. However, after a relatively short common segment, the flight routes split and no other separation conflict occurs.

The triple CFG521/THY550/AZA480 conflict is a convergence that occurs over NERDI at 11:19:33 and solving it requires three routing commands:

at 11:13:15 THY550 receives a parallel offset left 5NM for 8 minutes; at 11:16:08 CFG521 is vectorized 15° right for 8 minutes and AZA480 turns right at 11:19:31 with 15° for 7 minutes. SMG841/CCA939 conflict at 11:20:07 is solved by vectorization to the right by 15° for 9 minutes. Vectorizations by 15° can be replaced in some cases by 5° or 10°, but early conflict predictions are required. Greater horizon prediction must be used in the accelerated simulator in order to calculate and display the anticipation time for these variants.

5. Conclusions

The solver has shown reluctance to change flight level. It should be noted that the exercise was specifically designed to provide trouble-level changes, which must be initiated very early in human generated solution through early coordination with neighboring areas. Preference for offset parallel algorithm may be influenced by the search logic or by providing a penalty of that solution. All modern aircraft have an FMS with parallel offset capability. Manoeuver to place such an aircraft on a parallel offset is quite simple and has the advantage of not removing the aircraft from under the authority of FMS, as it happens in a vectorization. From the psychological point of view, the pilots are somewhat relaxed with a parallel offset, primarily because it maintains the FMS in the loop and secondly because of the feeling that nearly all of the flight is the same. In a vectorization, with each minute that passes, the flight is increasingly perceived as on a non optimum path. If an older aircraft is not capable of an assisted parallel offset implementation of the solutions, it is complicated for both pilot and ground controller. He must ask for the continuous reporting of the heading, then give two successive vectoring segments to obtain the offset, and, at the end, a direct preferably at a waypoint later on the path.

However, changing the flight level may be at least as problematic. That changes the predictions for neighboring sectors and requires the implementation of multi-level maneuvers, with intercrossing of opposite traffic. Overloaded aircraft sometimes have difficulties to climb, or if they do climb, it will take time and occupy flight levels for longer. Temporary descent commands are disliked by pilots because the increase in fuel consumption due to flying in denser air.

Although the solution presented in Table 2 and Fig. 7-12 is not the best that can be found (being a sub-optimal solution as it is usually the case with GA like algorithms), this method opens the way for research leading to intelligent routing solutions in real time, fully applicable to the current ATM system and also to the future plans for traffic control automation, in accordance with SESAR and NextGen directions.

The main contribution of this paper is the proof air traffic control that based on automated on heuristic algorithms is feasible not only for normal traffic situations but also for very complex ones. Secondly, the paper directly compares human versus machine resolution of certain air traffic cases. No such comparisons have been found in the literature.

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