AN OPTIMAL AIRCRAFT CONFLICT RESOLUTION SYSTEM BASED ON HYBRID MODELS

K. Bousson and **P. Paglione**
Department of Aerospace Sciences
University of Beira Interior
6200 Covilha, Portugal

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Abstract. Because of the continuous increase in aircraft activities nowadays, the air traffic density is getting higher and higher mainly in terminal areas (TMA). Therefore this may sometimes induce delays of departure and landing on airports, which are costive for airlines. One of the most critical implication of the high density of air traffic is the problem of collision avoidance between aircraft, also known as aircraft conflict resolution. The problem is posed in term of how to guide aircraft so as they do not collide with one another or that they meet some specified vertical and horizontal distance constraints between them. Meanwhile, since air traffic control done by air traffic controllers may be tedious and suboptimal, there is a need to build computer systems to help them solve conflicts as fast and optimal as possible.

Existing work on the subject focuses either on knowledge based systems using the experiential knowledge of air traffic controllers, or on flight mechanics models. The present paper deals with the combination of the symbolic knowledge of air traffic controllers and a simplified model of flight mechanics laws, in the sake of optimizing conflict resolution. The main processing part of the conflict resolution system so built is carried out by genetic algorithms.

1 Introduction

Air traffic control provides strategies and tactics to ensure flight safety in even dense traffic areas. It requires decisions involving human lives from one hand and enormous costs one the other. One of the central concerns of air traffic control is the problem of collision avoidance between aircraft, also known as aircraft conflict resolution (1,2,3,4). A conflict occurs when a given airspace is occupied by at least two aircraft, and is defined as the violation of any one of a set of separation criteria specified in air traffic manual of operations. Conflict resolution consists in developing procedures specifying flight path alterations for some of the aircraft involved in the conflict.

The complexity of collision avoidance stems from the fact that it is in fact a multiobjective optimization problem involving dynamic entities in a three-dimensional space. Each entity undergoes its proper set of constraints, and there are constraints involving all the overall set of aircraft. Indeed, as mentioned in (8):

1. Each aircraft must be separated by a given distance from each other at all the times.
2. Aircraft which are about to land must follow some predefined flight paths.
3. Each aircraft is subject to some speed limits according to its performance and air traffic control regulations.
4. Particular conditions regarding the flight level, maneuvers and speed alterations may be applied to some aircraft.

There may also be some temporal unforeseen constraints in addition to the aforementioned ones. Therefore, it is understandable that conflict resolution done by air traffic controllers may be tedious and suboptimal in dense traffic areas, mainly in the terminal areas (TMA). Hence, there is a need to build computer systems to help air traffic controllers solve conflicts as fast and optimal as possible.

Researchers and aviation engineers have worked, in collaboration with air traffic controllers, on conflict resolution in TMA. Existing work on the subject focuses either on knowledge based systems using the experiential knowledge of air traffic controllers, or on flight mechanics models. The present paper deals with the combination of the symbolic knowledge of air traffic controllers and a simplified model of flight mechanics laws, in the sake of optimizing conflict resolution. The main processing part of the conflict resolution system so built is carried out by genetic algorithms. The paper is organized as follows, section 2 describes the general analytical model supporting the proposed approach, section 3 deals with the practical model for simulating real-world situations. The paper ends with discussions and foreseen improvements to the proposed concepts.

2 Model Definition

The problem of conflict resolution consists in guaranteeing that aircraft do not collide with each other during flight. Hence, this is to ensure that the distance between each pair of aircraft is greater than a certain pre-specified minimum value $d_{\min}$. For practical considerations, when the collision avoidance has to be done in a TMA, the procedure is associated with a policy which makes the aircraft land.

Let consider a system of coordinates having the origin at the runway threshold with the z-axis as the local vertical, the x-axis in the north magnetic direction, and where the y-axis is such that the system R_{xyz} = (x,y,z) is a direct reference.

We assume the aircraft to be numbered according to the arrival sequence, that is, an aircraft receives the number i when there are already $(i-1)$ aircraft in the TMA when it arrives in. But when an aircraft has landed, the tagged number associated with any other aircraft is decremented by one. For instance, we assign an aircraft the number 3 if there are two aircraft in the TMA which arrived before it, but if one of the first two aircraft lands, the aircraft tagged number 3, will be tagged number 2.

Let $M_i = \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}$ and $M_j = \begin{pmatrix} x_j \\ y_j \\ z_j \end{pmatrix}$ be the geometrical points representing any two aircraft, tagged i and j respectively, in the R_{xyz} coordinate system. Then the fundamental constraint underlying the collision avoidance is:

$$d(M_i, M_j) \geq d_{\min} \tag{1}$$

where $D_{ij} = d(M_i, M_j)$ is the euclidean distance:

$$D_{ij} = \left[(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2\right]^{1/2}$$

There is another geometrical constraint which is that the aircraft should remain in the TMA. Let D be the domain defined by the TMA, then each aircraft i, represented as the geometrical point M_i, should be such that:

$$M_i \in D \tag{2}$$

For each aircraft i, let $V_i = \begin{pmatrix} v_{xi} \\ v_{yi} \\ v_{zi} \end{pmatrix}$ be its speed. Without loss of generality, we are going to assume that the wind effect if negligible. Hence, the projection of the speed vector on the x-y plane yields the ground-speed vector and this ground-speed vector makes an angle Ψ with respect to the x-axis. Angle Ψ is by definition the *heading* of the aircraft. The coordinate of the speed vector relatively to the z-axis is the aircraft rate of descent which may help determine the flight level of the aircraft over time. Furthermore, since the relation between the speed vector and the position is:

$$\begin{cases} \dot{x_i} & = v_{xi} \\ \dot{y_i} & = v_{yi} \\ \dot{z_i} & = v_{zi} \end{cases} \tag{3}$$

the information about the speed vector is enough to know the heading, the ground speed, and the position of the aircraft over time. Actually, the speed vector may be used as a control variable to guide the aircraft because of the causal influence it induces on the heading and the position. Hence, the problem of collision avoidance may be transformed into a control problem.

Since the aircraft have to land, the criterion of the control problem is that the sum of the distances between the aircraft and the runway threshold should be minimized. But, first arrived aircraft in the TMA should land first, we thus adopt the FIFO (first in first out) policy to guide the aircraft to the runway. Therefore, if n_t is the number of aircraft in the TMA at time-instant t and O the runway threshold, the criterion to minimize at t is:

$$J_t = \sum_{i=1}^{n_t} \alpha_i \cdot [d(O, M_i)]^2 \tag{4}$$

The coefficient α_i is a weight which aims at forcing the aircraft i to land before any other aircraft j if $j \geq i$. Hence, for $j \geq i$ we should have $\alpha_j \leq \alpha_i$.

Thus the optimization model for collision avoidance in the TMA is composed of constraints (1) and (2), the differential system (3) and the criterion (4).

3 Model Simulation with genetic algorithms

The simulation of the above mentioned model consists in solving an optimization problem. This is to find out the optimal speed vector such that the criterion (Eq. 4) is minimized. Meanwhile, the optimization procedure is guided by using the expert knowledge of the controllers. For example the change in the speed of an aircraft should not exceed 20 m/s within one minute, or a former aircraft in the TMA should have its flight level decreased when it happens to separate it vertically with regard to a latter aircraft at the same flight level. Some constraints about the bounds of the aircraft speeds according to their categories can also be taken into account. Once the optimal speed vector is determined by means of the optimization problem, projections and the integration of (Eq. 3) lead to compute the appropriate heading, ground-speed or flight level which are to be provided to the pilots as outlined in the previous section. This section first presents the concept of genetic algorithms which has been used for finding the pragmatic solution of the optimization problem, then we show how the optimization model has been dealt with for practical use.

3.1 Genetic algorithms versus classical optimization techniques

Genetic algorithms (6,7) are adaptive algorithms to find solutions to, for instance, multiobjective optimization problems such as the one provided by equations (1- 4) above, by using a process similar to natural selection. They provide rather quickly near optimal solutions which can be made as close to the exact solution as required given sufficient amount of time. Therefore, they appear to be interesting for many applications where highly reliable solutions are required within short delays. This is the case of the subject considered here: The aircraft conflict resolution.

Classical gradient-based optimization techniques need to compute function derivatives repeatedly and this may be time consuming. In the case of non-differentiable function optimization such techniques cannot be tuned easily to give acceptable results. Another problem is that if the criterion function is multimodal, these techniques can lead to a local minimum which may be non-global. An important feature of genetic algorithms is their massively parallel search technique which allows to avoid the possibility to get trapped by a local minimum while another important feature is that only repeated evaluations of the criterion function (the *fitness function*) are necessary.

Genetic algorithms treat artificial individuals (*chromosomes*) which relate potential solutions to strings of bits, thus the current set of solutions constitutes the *current population*. The evolution of the population proceeds by means of three main operators: *crossover, reproduction* and *mutation*. The crossover operator randomly selects two individuals (with some probability) among the fittest of the current population and exchanges tail substrings of random length. The reproduction operator considers the fittest individuals (with some probability) and replicates them into the next generation. The mutation operator selects individuals (with a small probability) and randomly changes some of their bits. Individual (solution) evaluations are realized by the *adaptation function*. The basic genetic algorithm is as follows:

```
initialize population;
evaluate population;
while convergence not achieved
    perform population fitness;
    perform reproduction;
    perform crossover and mutation;
    evaluate population;
end-while
```

We adopt the approach by Fonseca and Fleming (5) for dealing with our optimization problem.

3.2 Practical simulation model and results

The system composed of relations (1), (2), (3) and (4) defines the conflict resolution model to be solved. However for practical cases, we need to integrate (eq. 3) by time sampling as done qualitatively by air traffic controllers. Indeed, an air traffic controller does not watch its control screen continuously, but regularly: it checks up the situation of the traffic from time to time, and between two consecutive checkups, he assumes that the speed of each aircraft does not change too much; in other words, the controller assumes the speed to be practically constant between two checkups eventhough he updates it at each checkup. By tacking this into account, we integrate the differential system (3) by assuming that v_{xi}, v_{yi} and v_{zi} have constant values (but of course all the three components may be different) within each sampling period, and these constant values are updated as the control values for the following sampling period.

We simulated the flight of four aircraft, with a time sampling period equal to $T_s = 10$ *seconds*. The TMA is described as the cylindrical domain D centered at the runway threshold and having 15 Nautical miles as radius and 19500 feet as height. The minimum distance between each pair of aircraft is set to $d_{min} = 1000\ m$. Constraints on the heading and the accelerations of the aircraft have also been taken into account. The overall application model considered for the simulation is as follows, where $i = 1, 2, 3, 4$, and $j < i$:

$$d(M_i, M_j) \geq d_{\min} \tag{5}$$

$$M_i \in D \tag{6}$$

$$\begin{cases} x_i(t) = x_i(t-1) + v_{xi}.T_s \\ y_i(t) = y_i(t-1) + v_{yi}.T_s \\ z_i(t) = z_i(t-1) + v_{zi}.T_s \\ t \text{ is the discrete time} \end{cases} \tag{7}$$

$$\text{Minimize } J_t = \sum_{i=1}^{n_t} \alpha_i . [d(O, M_i)]^2 \tag{8}$$

$$(\forall t)\ \alpha_i = \frac{n_t - i + 1}{n_t} \tag{9}$$

The results of the simulation are illustrated in figures 1 - 4. Fig.1 and 2 depict the horizontal and vertical trajectories respectively. Fig. 3 is concerned with the aircraft interdistances where d_{ij} is the distance between aircraft i and j, all these distances converge to the minimum distance specified $d_{min} = 1000\ m$. In fig. 4 is illustrated the heading of each aircraft.

4 Conclusion

The research described in this paper has resulted in two achievements:

- The construction of a simple optimization model for aircraft conflict resolution in terminal areas, this model is coupled with a knowledge-base containing the expert knowledge of air traffic controllers. The problem of conflict resolution is transformed into an aircraft speed control problem since the position and the heading of each aircraft can be known and controlled through its speed. The model is really simple and is well-suited to real-time processing.
- The simulation of air traffic control based on the above mentioned model. The optimization problem is carried out by genetic algorithms.

Future research concerns the improvements of the present system to deal with randomly generated entries of aircraft in the TMA, the synchronization between landing and departure, and the extension to the case of TMA with multiple runways.

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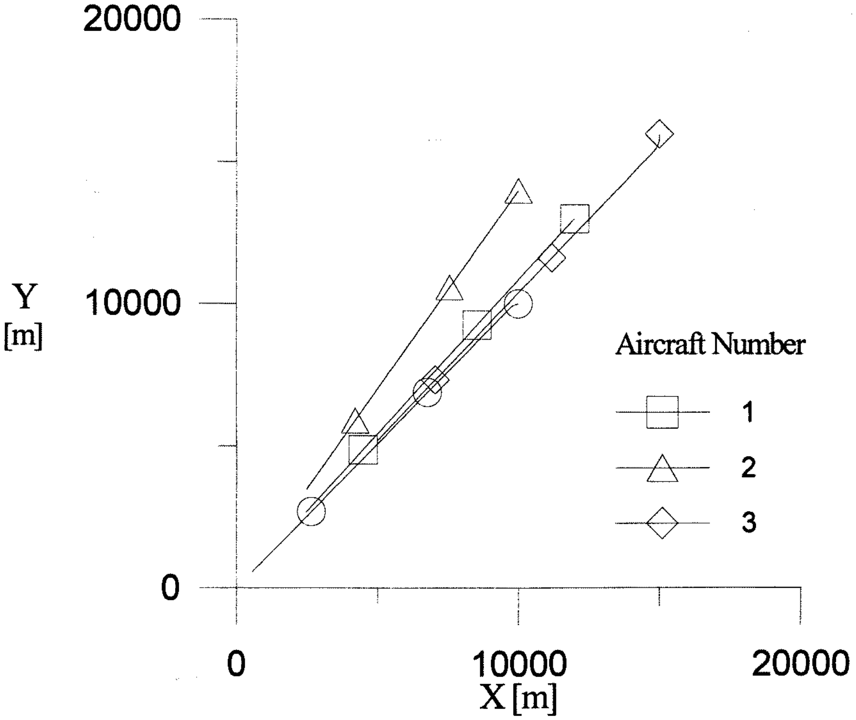

Fig. 1: Horizontal Trajectories

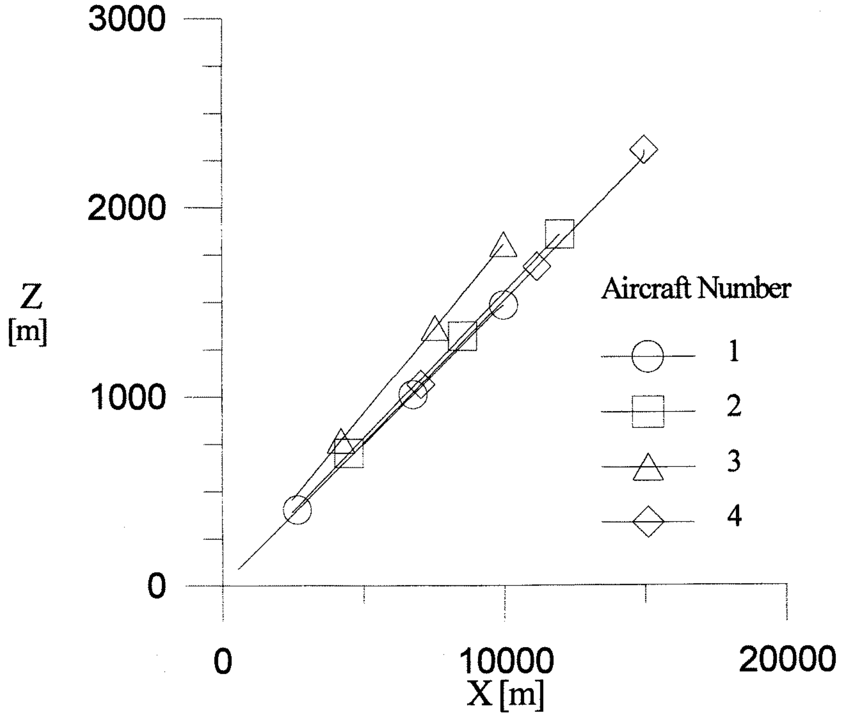

Fig. 2: Vertical Trajectories

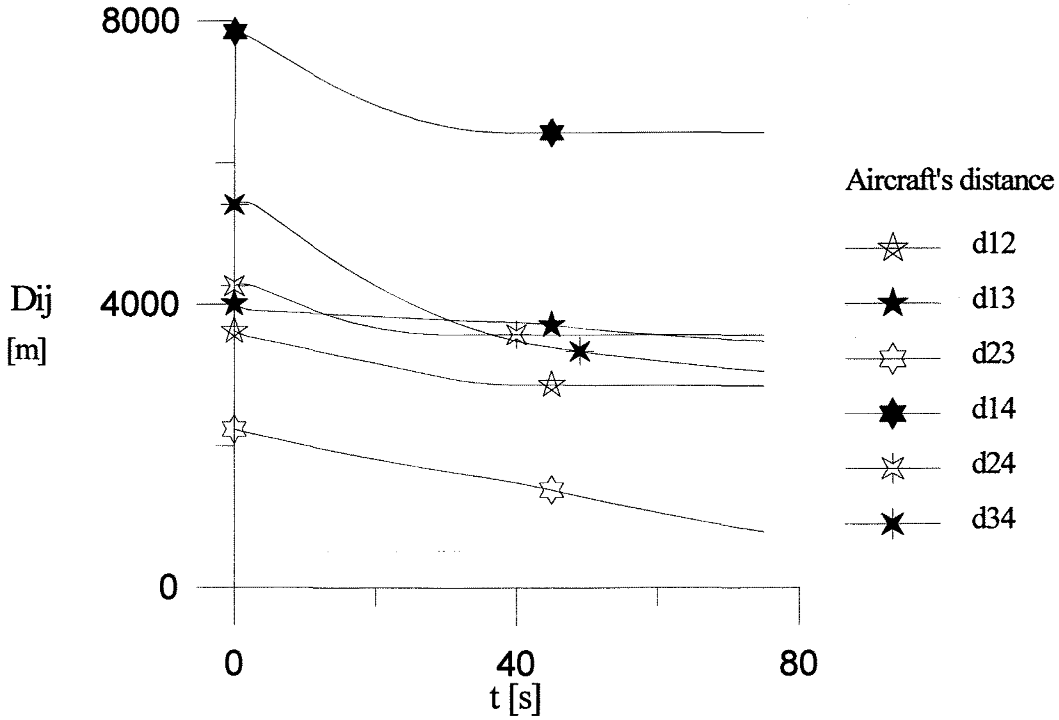

Fig. 3: Aircraft's Mutual Distances

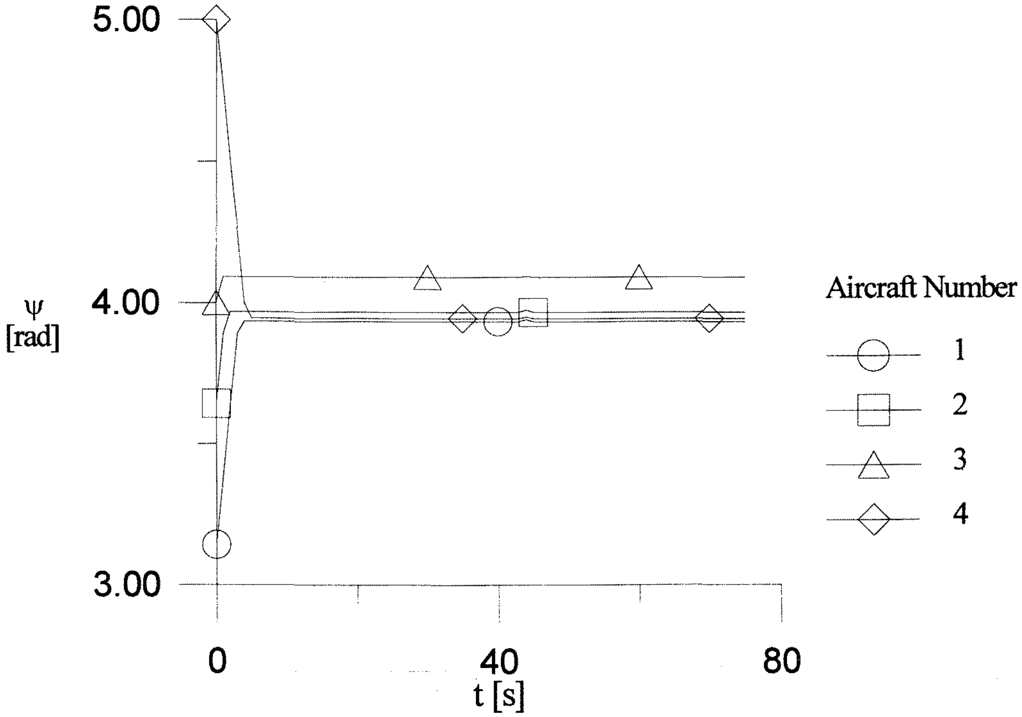

Fig. 4: Aircraft's Headings