Speed uncertainty and speed regulation in conflict detection and resolution in Air Traffic Control

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SPEED UNCERTAINTY AND SPEED REGULATION IN CONFLICT DETECTION AND RESOLUTION IN AIR TRAFFIC CONTROL

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Abstract

With the predicted increase of air traffic volume, new air traffic management models are under investigation in order to increase airspace capacity and keep low delays while maintaining transportation safety standards.

One of the tasks implied is to solve conflicts, i.e. maintain a sufficient separation between aircraft. Conflict resolution relies on conflict detection ; indeed predicting aircraft trajectories within a time window allows to detect the conflicts and apply avoidance measures. This approaches concerns both human control and models for automatic control resolution. The result of the conflict detection depends much on the uncertainty model, and especially on the level of uncertainty on aircraft trajectories. High uncertainty will lead to detect a high number of potential conflicts, and put a high workload on the monitoring and solving of conflicts, all the more than clusters of several conflicts are more likely to appear. On the other hand, too low uncertainty may ignore conflicts.

In this paper, we will expose statistics, obtained by air traffic simulation using real traffic data, regarding potential conflict detection, based on a speed uncertainty model, with different uncertainty levels. Then we will discuss the interest of a precise speed prediction and of the introduction of simple speed regulation maneuvers in the early stages of conflict resolution, in order to ease the global conflict resolution process.

Trajectory uncertainty

Conflict detection

The trajectory uncertainty can be modeled in different ways, even as regards its global function, depending on the way it will be used.

The trajectory can be considered in 3 dimensions, or 4 dimensions. In this study we will only consider 4D trajectories, as this study is in the field of the tactical air traffic control tasks, short-term conflict detection and resolution.

Air traffic control procedures take into account this uncertainty to a certain extent, by the definition of separation minimums. These distances (5 Nm or 8 Nm horizontally, and 1000 or 2000 feet vertically), are the minimum distance between aircraft to be respected. Aircraft being closer to each other than this distance (i.e., simultaneously below the minimums), are said to be in conflict, and that situation is to be avoided by the air traffic controllers. The controllers issue maneuvers that are to be performed by the aircraft crew to avoid the conflict.

Considering these important distances, a conflict situation is not of imminent danger but requires maneuvering within a few minutes. That is why, to a certain extent, trajectory uncertainty over a few minutes is taken into account in the separation minimums.

Moreover, the air traffic controllers are to ensure permanently a conflict-free situation and anticipate future conflicts, and thus trajectory uncertainty must be further considered.

Uncertainty model

Several different models of uncertainty can be considered :

- the position of a aircraft at a given time can be represented with a probability density function : $p(x, y, t, t)$; $0 \leq p(x, y, t, t) \leq 1$. This allows to estimate probability of conflicts between aircraft.
- the position of an aircraft can be represented by a region of space, outside of which it cannot be. The shape of the region can evolve with time. A conflict-free situation between two aircraft is a situation where any couple of points taken from the regions respects the separation minimum. This is a particular case of the probability modeling, where we consider the presence regions where $p \geq 0$.

The conflict detection can take place at regular times, for a given time range or a few minutes. At the detection time, the precise position of aircraft is known. Potential conflicts are detected in a time window. The delay between detections is much less than the time window (for instance, 1 minute and 5 minutes), which ensures that a conflict-free situation remains until the next detection.

Given the exact aircraft position at a given time, the trajectory uncertainty modeling is the way the regions representing the actual future aircraft position evolves from this point on.

Speed uncertainty model

Our model is based on the following assumptions :

- in the cruising stage, the altitude of an aircraft is stable,
- in the cruising stage, between waypoints, the heading is stable,
- in the cruising stage, the most uncertainty concerns the horizontal aircraft speed along the heading, due to the intrinsic uncertainty and the flight conditions,
- in climb and descend stages, the uncertainty concerns mostly the vertical speed : depending on the flight conditions, the aircraft load, and the flight preferences from the airliner and crew,
- speed uncertainties can be modeled by a relative uncertainty : actual speed may differ from the nominal value within a certain error percentage *e* : the bounds are *(1-e)v* and *(1+e)v*.

Thus we can consider the following model. In the horizontal plane, the aircraft is represented by a segment whose extremities progress at the minimum speed and the maximum speed. Both extremities follow the flight plan, and at a waypoint the aircraft is represented by two (or several) segments. In the vertical plane, the aircraft is represented by a maximum and a minimum altitude deduced from the original altitude and the maximum and minimum vertical speed (or climb rate).

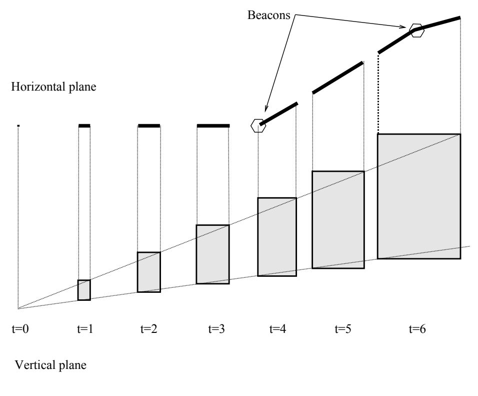

Figure 1. Uncertainty model

Relative errors for ground speed and vertical speed are distinct.

They may be different for individual planes (depending on the aircraft model, flight management system...), even if this is not used in our case simulations.

The evaluation of the influence of speed uncertainty has been conducted with CATS [1], a traffic simulation engine based on a discrete time slice execution model, using actual flight plan data. With our simple model, the simulation of one day traffic over Europe, with conflict detection, takes over 5,5 hours on a Pentium IV 3 GHz. Detailed durations are shown in tables 1 and 2. Computation costs vary only lightly (within 5%) according to the amplitude of the uncertainty.

An additional simulation was done without potential conflict detection. Actual conflict detection concerns only aircraft current position at a given time, with no trajectory forecast over a time window. This simulation, for which speed errors are marked N/A, provides the number of actual conflicts as a reference for comparisons. No predicting is done, and this explains that the computation costs are slightly lower.

Table 1. Simulation duration (s), France-wide

Ground speed error	Vertical speed error N/A	1	5	20
N/A	426			
1		1638	1641	1658
5		1657	1665	1687

Table 2. Simulation duration (s), Europe-wide

Ground speed error	Vertical speed error N/A	1	5	20
N/A	5735			
1		20302	20599	21462
5		20679	20938	21762

Tables 3 and 4 give the number of detected conflicts, both potential (with 1% and 5% error on ground speed, and 1%, 5% and 20% error on vertical speed) and actual. Table 5 and 6 give the relative error done on the conflict detection, relatively to the actual number of conflicts.

Table 3. Detected conflicts, France-wide

Ground speed error	Vertical speed error N/A	1	5	20
N/A	2696			
1		3604	3930	5218
5		5969	6426	8058

Table 4. Detected conflicts, Europe-wide

Ground speed error	Vertical speed error N/A	1	5	20
N/A	13445			
1		22493	26689	41219
5		34563	39209	55945

Table 5. Conflict overestimation, France-wide

Ground speed error	Vertical speed error 1	5	20
1	+34%	+46%	+94%
5	+121%	+138%	+199%

Table 6. Conflict overestimation, Europe-wide

Ground speed error	Vertical speed error 1	5	20
1	+67%	+99%	+207%
5	+157%	+192%	+316%

What explains that the overestimation is higher for Europe than for France only, seems to be that the flight phases involving climbing and descending are proportionally less represented in France. This is due to the flights that take off and/or land in Europe but are only in cruise phase while in France airspace.

The results show how conflict detection depends, to a large scale, on the amplitude of relative error used. Even a 1% error on speed leads to detect one-third more conflicts than needed; and with 20% vertical error and 5% horizontal errors, up to 200% and 300% more conflicts are detected. Reducing uncertainty in trajectory prediction is certainly promising to lower the traffic control workload.

Conflict solving

The conflict resolution consists in avoidance maneuvers applied by the concerned aircraft. These maneuvers can be heading angle changes (i.e. horizontal deviation), velocity changes, or vertical maneuvers, such as flight level changes for stable aircraft.

Various algorithmic approaches have been investigated in this context, using different categories of methods and different sets of maneuvers: optimization with genetic algorithms [2] [3], optimal control, multi-agent systems [4] [5], semidefinite programming [6], model with repulsive forces [7], mixed integer programming [8].

Maneuvers

CATS includes two distinct conflict solving modules, that solve detected conflicts by applying conflict avoidance maneuvers. These maneuvers, issued by air traffic controllers, are modeled in CATS as follows.

At last three types of maneuvers can be considered :

- horizontal deviation maneuvers, i.e. heading change by a given angle. We here consider a finite set of discrete angle value : 10°, 20° or 30° to the right or to the left. At t_0, the heading is changed by the given angle, and at t_1 the maneuvers ends and it heads towards the destination (see figure 2);
- vertical maneuvers depend on the flight phase (see figure 3). For instance, a stable aircraft descends to the lower flight level at t_0 and starts to climb back at t_1;
- speed regulation maneuvers could be modeled quite the same way, with two times, t_0 and t_1, for the beginning and end of the maneuver, and the amplitude of the maneuvers, being an increase or decrease by a given fraction of the standard air speed.

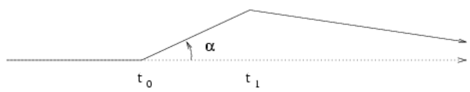

Figure 2. Horizontal maneuver

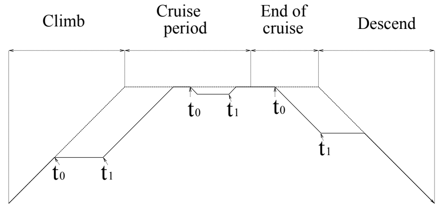

Figure 3. Vertical maneuvers

Discretized angle values for the heading angle change and the speed regulation are realistic as regards both the execution of the maneuvers by the pilots and the visualization by the other aircraft pilots and the controllers.

Thus the maneuvers can be described by 2 or 3 variables : t_0 and t_1, plus the amplitude of the maneuver for horizontal deviation and speed regulation maneuvers. In the current implementation, the current maneuvers must be either horizontal or vertical, and no combination of both. An aircraft cannot start a maneuver during another, nor change its current maneuver (except by shortening or extending the maneuvers, by reconsidering the ending moment t_1 of the maneuver at the next detection/optimization iteration).

Solving conflicts

The conflict solvers aim at providing optimal (as regards flight length or duration) conflict-free trajectories.

The conflict solvers in CATS are :

- a solver based on genetic algorithms [1]. The solving process is applied individually to every conflict cluster. A cluster is a set of conflicting aircraft, the transitive closure of the conflict relationship. Indeed, all aircraft within a cluster interfere with each other. In this particular implementation of genetic algorithms, an individual or a chromosome represents the set of maneuvers applied to every aircraft in the cluster (can be a maneuver of any type, or no maneuver).
- a distributed sequential solver, which consists of tree-search optimization, and relies on a scheduling of aircraft. The global scheduling is based on neighborhood heuristic priorities and a token allocation algorithm. [10] [11]. The optimal trajectory is computed for each aircraft, taking into account previously computed trajectories.

Either of these modules can be used for conflict solving. The former performs non-deterministic global optimization ; the latter performs deterministic non-global optimization. Indeed, the resolution of conflicts between *n* aircraft is highly combinational and cannot be optimally solved using classical mathematical optimization techniques.

Objectives

The speed regulation maneuvers are currently being implemented for both conflict solvers. The objective is double. First, they can be used at the same level as lateral deviation maneuvers and vertical deviation maneuvers. The range of available maneuvers being broader, more efficient maneuvers can be applied, as regards the global resolution efficiency.

Second, these maneuvers can be used in an early resolution stage, which we will now discuss.

The potential interest in speed maneuvers is that they have a small impact on the flight conditions, as compared to lateral deviation maneuvers, and especially vertical maneuvers. Those are potentially more disturbing for the aircraft crew, passengers, and for the controllers themselves. Indeed speed maneuvers do not change the 3D trajectory and so modify only lightly the global view of the traffic.

What's more, speed regulation (within the limits of the aircraft performance envelope) is easy to implement. It is of course highly efficient to solve overtaking conflicts, and is widely used for en-route in-trail aircraft, especially in the American ATM system. Moreover, its execution could be delegated to the FMS.

A long-term approach of such a regulation system for short-term conflict management could include Data-Link, FMS and a sector-centralized partial solver with enhanced capabilities.

- The FMS and the downlink could allow precise estimation of the trajectories in the short term. Many potential conflicts that would need careful watch could be labeled early as no-conflict situation in a display for the air traffic controller, freeing attention for the rest of the traffic.
- A partial solver could propose to try and solve some conflict situations by speed regulation maneuvers, and delegate the execution to the aircraft crew and eventually the FMS by the uplink, under control by the air traffic controller.

At the preliminary stages of this study, we have to:

- study further the impact of the uncertainty amplitude;
- estimate the uncertainty models used by ATC and compare with realistic FMS error

models, including normal flight operation and weather conditions;

- estimate the efficiency of speed regulation maneuvers as a first layer of conflict avoidance measures;
- explicit the requirements for FMS to perform speed regulations according to the needed precision.

Especially, when a speed regulation solver is implemented, we need to test the efficiency of a solving system based on speed regulation only, satisfying the following constraints:

- the regulation amplitude must be within the bounds of the performance envelope;
- the regulation amplitude must be higher that the uncertainty amplitude, else the maneuver cannot ensure a conflict-free situation.

Conclusion

By evaluating the influence of speed uncertainty in conflict detection and the efficiency of a solver system based on speed regulation, this study aims at:

- alleviating the workload related to watching potential conflicts, using reasonable levels of uncertainty to identify non-conflict situations;
- alleviating the workload related to solving conflicts by proposing speed regulation maneuvers when they are relevant.

This study is still in a very early stage, yet tools are currently under design to conduct the first experimentations.

References

[1] Alliot Jean-Marc, Nicolas Durand, J. Bosc, L. Maugis, 1997, Cats: a complete air traffic simulator, Irvine, 16th AIAA/IEEE Digital Avionics Systems Conference.

[2] Alliot, Jean-Marc, Hervé Gruber, Marc Schoenauer, 1993, Using genetic algorithms for solving ATC conflicts, 9th IEEE Conference on Artificial Intelligence Application.

[3] Durand, Nicolas, 1996, Optimisation de trajectoires pour la résolution de conflits en-route, PhD dissertation, Toulouse, INPT.

[4] Tomlin, Claire, George Pappas, Shankar Sastry, 1996, Conflict resolution for Air Traffic Management: a case study in multi-agent hybrid systems, University of California at Berkeley.

[5] Goodchild, Colin, Miguel A. Vilaplana, Stefano Elefante, 2000, Cooperative optimal airborne separation assurance in Free-Flight airspace, Napoli, 3rd Usa/Europe ATM Seminar.

[6] Frazzoli, Emilio, Zhi-Hong Mao, JH Oh, Feron Eric, 1999, Resolution of conflicts involving many aircraft via semidefinite programming, MIT.

[7] Zeghal Karim, 1998, A review of different approaches based on force fields for airborne conflict resolution, Boston, AIAA Guidance, Navigation, and Control Conference.

[8] Pallottino, Lucia, Eric Feron, Antonio Bicchi, March 2002, Conflict resolution problems for air traffic management systems solved with mixed integer programming, IEEE Transactions on Intelligent Transportation Systems, vol 3, pp 3-11.

[9] Kosecka, Jana, Claire Tomlin, George Pappas, Shankar Sastry, 1997, Generation of conflict resolution maneuvers for Air Traffic Management, International Conference on Robotics and Intelligent Systems.

[10] Granger, Geraud, Nicolas Durand, Jean-Marc Alliot, 2001, Token allocation strategy for Free-Flight conflict solving, Seattle, IJCAI.

[11] Archambault, Nicolas, Nicolas Durand, 2004, Scheduling heuristics for on board sequential air conflict solving, Salt Lake City, 23rd IEEE Digital Avionics Systems Conference.

Biography

Nicolas Archambault, graduated from Ecole polytechnique and Telecom Paris (France), is now a second year PhD student in computer science in the Global Optimization Laboratory, under the direction of Jean-Marc Alliot (CENA) and Vu Duong (Eurocontrol Experimental Centre). He is currently working on methods for air conflict detection and resolution. The Global Optimization Laboratory is a joint laboratory of the Air Navigation Research Centre (CENA, Centre d'Etudes de la Navigation Aerienne) and the Civil Aviation School (ENAC, Ecole Nationale de l'Aviation Civile) in Toulouse, France.