A decentralized approach for Air Traffic Congestion

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Abstract: Congestion in the air traffic network is a problem with an increasing relevance for airlines costs as well as airspace safety. One of the major factors is the limited operative capacity of the air network. In this work an agent based approach to the real time air traffic control is proposed. The air network is considered partitioned in different sectors. Each sector has its own decision agent devoted to the air traffic control involved in. In each of these sectors, in order to guarantee the respect of both delay and capacity constraints, a real time scheduling of the flights is obtained by an iterative procedure based on a specific graph model. Different levels of cooperation between sectors are tested to better resolve the congestion problem.

Key-Words: - Air Traffic Control, Scheduling, Routing, Air Traffic Flow management

1 Introduction

Congestion problems are becoming increasingly acute in many European and American airports and air sectors. To protect Air Traffic Control (ATC) from overload a planning activity called Air Traffic Flow Management (ATFM) tries to anticipate and prevent overload and limit resulting delays. When the traffic expects to exceed the airport arrival and departure capacities or the airsector capacity a delay in the flight arrival (so called-congestion) occurs. The casuistry to be considered in this field is very extensive. In general, most references to be found in the literature written some years ago refer to the simplest models, those which do not take into account airsector. This is so because this work was first studied in USA, where only the problems of congestion in airports basically occur The management of the evolution of the air traffic management (ATM) systems involves a careful evaluation of alternative scenarios, from a various perspectives involving technical, operational, economic, and environmental issues. Additional cost caused by delays are substantial. So, the air traffic in Europe and the USA has experimented an spectacular growth during the last years (more than 50 per cent in the last 10 years according to recent estimations) and a 50 per cent traffic increase is expected by 2018.

While in the USA congestion problems are restricted to the airports, since there are no big problems in the airsector, in Europe the overcrowding of airsector is more important and in certain cases close to collapse. This congestion comes from the difficulty of coordinating air traffic control in each country. In order to solve these problems and avoid a worsening situation, a European organization has been set up to manage air traffic control in Europe (European Central Flow Management Unit, CFMU) which depends of EUROCONTROL.

The paper is organized as follows. In Section 2 reader can find the detailed description of the different approaches known in literature to solve congestion problem. The model is described in
Section 3 and 4, some experimental results are reported in Section 5.

2 Different approaches
The increasing demand of air traffic in the last years had to a heavier use of Air Traffic networks, it is constituted of airports, airways and sectors. While Air Traffic networks have been used more and more every year, their capacities have not grown accordingly. The main effect is the congestion of the Air Traffic network. Different approaches are proposed to minimize this undesirable crucial aspect. (see [1],[2],[3],[4],[5],[6],[7]).

2.1 Ground Holding policies
The ground-holding problem (GHP) consists of determining the amount of delay to be imposed on the ground on each flight, in order to minimize the over cost of delays (in the ground and in the air) in the network. A Ground Holding (GH) policy imposes on selected aircraft a ground-holding prior to their departures, so that congestion during peak periods of time may be smoothed away. The usefulness of these policies stems from the following facts. First, air delays are much costlier than ground delays. Second, the capacity of an airport is affected by weather conditions. Third, if pilots were free to depart at will the situation could get completely out of control (i.e. too many flights in a certain part of the air traffic network) and the air traffic controllers would not be able to provide any instructions, with serious safety risks. Cost and safety are sufficient to justify the study of methods for managing air traffic in unstable weather conditions.

2.2 Free flight policies
Many airlines in the USA been complaining about the GH policies, and have been pushing toward the concept of "free flight". They are asking the FAA to provide them only with an arrival time slot, leaving them freedom of selecting, for each flight, its departure time, route and speed, as long as they are able to arrive at the assigned time slot. More rigorously, free flight is a safe and efficient flight operating capability under instrument flight rule in which the operators have the freedom to select their path their speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight.

2.3 Autonomous Agents approach
Autonomous agents (AA) are becoming increasingly popular in different fields related to computer applications, although often disguised by different concepts. In manufacturing, telecommunications, medicine and public administration different entities such as intermediate providers, departments, wards or even final users may have sufficient freedom to organize their own activity within a general framework, without depending on external influences ([7],[8]). In all these cases, the concept is that a project or a process should be regarded as the result of the interaction of several different subjects, rather than of a single centralized decision maker. Each individual acts in order to pursue his/her/its own objectives, which may be sometimes expressed by means of a mathematical objective function. Generally speaking, for the individuals to carry out their tasks in a feasible and profitable way for the overall system, they will have to cooperate and negotiate to some extent. Cooperation means that two individuals may realize that taking a common action may turn out to be convenient for both of them. Negotiation refers to the fact that one individual may accept losing something in exchange for something else. With respect to centralized decision making, autonomous agents typically offer such advantages as management simplicity, flexibility, modularity, ease of monitoring and more. Transportation is a natural setting in which the autonomous agents' concept may yield considerable payoffs. In the organization of the transportation system, it is natural to identify the agents with the elements having a certain amount of behavioral autonomy, be it a vector, a station, a booking centre, a single passenger or a vehicle. In the implementation of the autonomous agents concept there are at least two trades-offs which must be carefully addressed. A trade-off is between the amount and the detail of the information available to the agent and the quality of its decisions. An adaptive, multiagent approach is an ideal fit to this naturally distributed problem where the complex interaction among the aircraft, airports and traffic controllers renders a predetermined centralized solution severely suboptimal at the first deviation from the expected plan. Though a truly distributed and adaptive solution (e.g., free flight where aircraft can choose almost any path) offers the most potential in terms of optimizing flow, it also provides the most radical departure from the current system. As agent methods are a natural tool to help automate existing air traffic systems, there
has been significant research into other agent solutions as well.
In the context of the Air Traffic Control (ATC), one of the challenge facing the decision makers is to increase the air traffic capacity while providing safety improvements. The flight route assignment problem, aiming at global flight plan optimization, has already become a key issue owing to the growth of air traffic.
Recent research has produced stochastic optimization models for adjusting traffic flows in response to predicted congestion in the an route airspace. These models simultaneously consider a set of options for each flight that includes both the possibility of ground delay and reroutes.

In this paper we explore a multiagent algorithm to reduce congestion through local actions, considering collaborative actions. We present an optimization conflict resolution procedure, in which flights interact through a simple coordination protocol. In particular, it allows to smooth traffic peaks and reduce the criticality of the short term conflict resolution activity, as well as to avoid low capacity areas and waiting times in holding patterns. The problem consists of finding a routing for the planned flights assigning planes to feasible slots in such a way that (i) the capacity constraints are satisfied (ii) the delay is minimized.

In order to guarantee the safety, the maximum number of movements in a sector is bounded in each slot.
This number is called capacity of the facility in the slot. The coordination mechanisms among different aircraft are derived on the ground of a set of different models. The complexity of the basic decision models will be analyzed; such basic models are useful to point out effective management procedures, but many facets of real environments are not suitably represented. A real-time slot allocation procedure based on simple coordination mechanisms among sectors is proposed.
In our model we have considered two different types of Autonomous Agents, the sector control agent (CSA) and aircraft agent (AA) [1]. The sector control agents can take the decision on the air traffic flow in the sector, and the aircraft agents give only their necessary information for the decision of the sector controller.

3 The network model
Some assumptions allow us to set the structure of the airspace network following the main idea of remodelling the original network. Airspace is made of routes that cross each other. The network starts off with a number of initial nodes, corresponding to beacons, and a set of fixed links corresponding to the probable used links. This can be realized simply by deducing the used links from a given air traffic situation, where all flight plans are given, and preferred routes are already known. In the graph corresponding to the initial network, potential conflicts can be seen as the overload of some nodes, identified as potential conflict area. Also the airports are represented like nodes with their capacity, but in these nodes it is possible apply the ground holding policy. Let us first fix some hypothesis which will help us to build our model: 1. aircraft are in constant motion; 2. a number of aircraft may be placed in the same air segment, and conflicts are resolved using appropriate method, i.e. there is no capacity imposed on links; 3. the different flight levels are collapsed in a single one. In the following \( G=(V,E) \) denotes the graph representing the airspace, where: \( V \) (the set of vertices) represents fixed points (in the ground and in the air) characterized by different capacities; \( E \) (the set of edges), each edges represents the existence of an airway between two nodes.

4 Air space model
The airspace is partitioned into a set of sectors. Related to each sector there is a control agent, that can decide the schedule of the flights for each nodes of its sector, considering different constrains. We focalize our attention on the delay and capacity constraints. At this aim, each sector is represented by a sub network \( S \) of the whole airspace \( G \). A sector \( S \) is model by the nodes are fixed points (in air and in ground), and the edges are the airways.
The nodes can be airports or controller points. In Fig. 1 an example of aircraft sector is reported, the blue dot line is the frontier line between different sectors and the stars are the border points. The capacity of each node represents the maximum number of aircraft controlled by sector controller to guarantee the sector safety. Each aircraft agent has its personal route composed by nodes and edges, it is divided in sub route, one for each sector that the aircraft crosses. The star/end node in the sub route is called origin/destination of the aircraft in the sector and until the aircraft does not reach the destination airport all the other sub destinations are border points.

A congestion occurs when a safety constrain is not satisfied (i.e. maximum number flights that a CSA can control for a single node is reached). The CSA must find another flight scheduling for the aircraft associated to the congested node. In general, not all the aircraft associated to the congested node can change their route; only the flight those are not on an airway direct to the congested node can change their route. For each of those aircraft, the CSA must resolve a re-routing problem. The CSA analyzes the network and tries to find a new solution without congestions, if it is possible, otherwise it finds a solution with congestions that are far from temporal point of view.

Two different situations arise, one without and one with cooperation between CSAs respectively called single sector and different sectors case.

### 4.1 Single sector case

In this case, there is not cooperation between CSAs and it implies that the sub destination of each aircraft in the sector is fixed. When there is a forecast of congestion, the CSA resolves a routing problem on a set of partial subgraphs, one for each flight associated to the congested node. A partial sub-graph has a fixed pair of input/output points, that represent input/output of the route in that sector, that are the points of intersection with the other sectors. With this hypothesis, the cooperation between CSAs is not necessary at this level. The basic concept of our approach is the dynamic structure of the solution. It is possible that during the construction of the new solution the CSA introduces new congested nodes, at the end of this recursive algorithm the solution may be acceptable with all constrains respected, but some flights (more then one) have changed their routes. It is important to underline that the partial sub-network is characterized by a single flight, but all the information connected to the nodes are related to the whole sector for a fixed time slot, then to re-solve a routing problem a CSA uses global information about the sector and information on the single Aircraft Agent. For each of those aircraft, the CSA, in order to individuate an improved routing, solves a k-shortest path problem (KSP) on the dynamical network containing information about nodes and flights.

The KSP problem is defined as the problem of finding the k best alternatives in the case that we need more than one route to get from an origin to a destination. This type of solution is especially meaningful in the Air Traffic Management context, in which a number of aircraft has to be routed in order to satisfy capacity and time requirements. It may be that there is more than one possible route and some routes may be more efficient when flown by a particular aircraft. Moreover, due to capacity limitations, it may be beneficial to have alternative routes available if more nodes become overly congested. In this context, it is useful to know several of the best routes to get from an origin point to a destination point in a sector. We have tested different k-shortest path algorithms, the known Yen algorithm and a generalized Dijkstra approach (see Fig. 2 for a scheme of this algorithm).

#### Fig. 2 – Scheme of generalized Dijkstra approach

### 4.2 Different Sectors case

We want study the importance of collaborative aspect between agents. In the single sector output points of each aircraft is fixed; in this case the border point can be changed. Different levels of cooperation are under study, and the aim of this
analysis is to find a compromises between exchange of information and goodness of solution. The basic idea is cooperate between neighboring CSAs to find the best border point for the congested sector. Obviously the best solution is find when the cooperation is total (i.e. the behavior of the two adjacent sectors is the same of a whole sector composed by these two sectors, and the exchanged information is absolute). When a congestion occurs the CSA must find k shortest path for each border points between the two adjacent sectors but the exchange of the border point is admitted only with the permission of the other engaged sector.

5 Computational Results
Experiments are carried out considering as a reference Italy test case. From the study we have tested different instances. For the single case we have tested two different k shortest paths algorithms (Yen algorithm and generalized Dijkstra approach). We have notice that it is more important for this type of problem to find k different paths instead the shortest one, it is because with different paths it is more simple jump out of congestion area.
For different sectors case we are testing more level of cooperation from no-one information to total information between different control agents. This cooperation needs to choice the best border point when an aircraft must be rerouted. The analysis in under study.

References: