A Next Generation Architecture for Air Traffic Management Systems[1]

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Abstract

In an effort to increase the efficiency and safety of air travel while accommodating the growing demand for air traffic, the aviation community is working towards designing next generation *Air Traffic Management* (ATM) systems. ATM will replace the completely centralized, ground based, Air Traffic Control procedures. Within ATM, the concept of *Free Flight* allows each aircraft to plan four dimensional trajectories in real time, thus replacing the rigid and inefficient discrete airspace structure. These changes are feasible due to GPS and various other technological innovations. In this paper, we propose a *decentralized* ATM architecture, where much of the current ATC functionality is moved on board each aircraft. Within this framework, we present various issues that arise in the emerging area of hybrid systems based on our work in conflict resolution strategies between aircraft, and in flight mode switching logic.

1 Introduction

Air transportation systems are faced with soaring demands for air travel. According to the Federal Aviation Administration (FAA), the annual air traffic rate in the U.S. is expected to grow by 3 to 5 percent annually for at least the next 15 years [1]. The current National Airspace System (NAS) architecture and management will not be able to efficiently handle this increase because of several limiting factors including inefficient airspace utilization, increased Air Traffic Control (ATC) workload, and obsolete technology.

In view of the above problems and in an effort to meet the challenges of the next century, the aviation community is working towards an innovative concept called *Free Flight* [2]. Free Flight allows pilots to choose their own routes, altitude and speed and essentially gives each aircraft the freedom to self-optimize. Aircraft flexibility will be restricted only in congested airspace in order to ensure separation among aircraft, or to prevent unauthorized entry of special use airspace (such as military airspace).

The economic benefits of Free Flight are immediate. Direct great circle routes, optimal altitudes, optimal avoidance of developing weather hazards and utilization of favorable winds will result in fuel burn and flight time operating cost savings. Free Flight is potentially feasible because of enabling technologies such as Global Positioning Systems (GPS), Datalink communications [3], Automatic Dependence Surveillance-Broadcast (ADS-B) [3], Traffic Alert and Collision Avoidance Systems (TCAS) [4] and powerful on-board computation.

The technological advances will also enable air traffic controllers to accommodate future air traffic growth by restructuring NAS towards a more decentralized architecture. The current system is extremely centralized with ATC assuming most of the workload. Sophisticated on-board equipment allow aircraft to share some of the workload, such as navigation, weather prediction and aircraft separation, with ground controllers. In order to improve the current standards of safety in an unstructured, Free Flight environment, automatic conflict detection and resolution algorithms are vital. The resulting air traffic management system requires coordination and control of a large number of semi-autonomous aircraft. The number of control decisions that have to be made and the complexity of the resulting decision process dictates a hierarchical, decentralized solution. Complexity management is achieved in a hierarchy by moving from detailed, decentralized models at the lower levels to abstract, centralized models at the higher levels. Coordination among the agents is usually in the form of communication protocols which are modeled by discrete event systems. Since the dynamics of individual agents is modeled by differential equations, we are left with a combination of interacting discrete event dynamical systems and differential equations, the so called *hybrid systems*.

Hybrid systems also arise in the operation of a single

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aircraft because of *flight mode switching*. The use of discrete modes to describe phases of the aircraft operation is a common practice for pilots and autopilots and is dictated partly by the aircraft dynamics themselves. The modes may reflect, for example, changes in the outputs that the controller is asked to regulate: depending on the situation, the controller may try to achieve a certain airspeed, climb rate, angle of attack, etc. or combinations of those.

In this paper we present an overview of our research effort in the area of ATM. In Section 2 we discuss the architectural issues regarding ATM. Sections 3 and 4 present the balance between ground and air automation systems in the proposed distributed ATM system. In Section 5, we present hybrid system issues which arise due to the hybrid nature of two problems pursued within this framework: conflict resolution and flight mode switching.

2 A Distributed Decentralized ATM

One of the most important conceptual issues to be addressed in the architecture of large scale control systems is their degree of decentralization. Completely decentralized systems are inefficient and lead to conflict, while completely centralized ones are not tolerant of faults in the central controller, are computationally and conceptually complicated, and slow to respond to emergencies.

The tradeoff between centralized and decentralized decision making raises a fundamental issue that has to be addressed by any proposed ATM. The current ATC system is primarily centralized; all safety critical decisions are taken centrally (at the ATC units) and distributed to the aircraft for execution. Because of the complexity of the problem and the limited computational power (provided primarily by the human operators in the current system) this practice may lead to inefficient operation.

A number of issues should be considered when deciding on the appropriate level of centralization. An obvious one is the *optimality* of the resulting design. Even though optimality criteria may be difficult to define for the air traffic problem it seems that, in principle, the higher the level of centralization the closer one can get to the globally optimal solution. However, the complexity of the problem also increases in the process; to implement a centralized design one has to solve a small number of complex problems as opposed to large number of simpler ones. As a consequence the implementation of a centralized solution requires a greater effort on the part of the designer to produce control algorithms and greater computational power to execute them. One would ideally like to reach a compromise that leads to acceptable efficiency while keeping the problem tractable.

Another issue that needs to be considered is *reliability* and *scalability*. The greater the responsibility assigned to a central controller the more dramatic are likely to be the consequences if this controller fails. In this respect there seems to be a clear advantage in implementing a decentralized design: if a single aircraft's computer system fails, most of the ATM system is still intact and the affected aircraft may be guided by voice to the nearest airport. Similarly, a distributed system is better suited to handling increasing number of aircraft, since each new aircraft can easily be added to the system, its own computer contributing to the overall computational power. A centralized system on the other hand would require regular upgrades of the ATC computers. This may be an important feature given the current rate of increase of the demand for air travel.

Finally, the issue of *flexibility* should also be taken into account. A decentralized system will be more flexible from the point of view of the agents, in this case the pilots and airlines. This may be advantageous for example in avoiding turbulence or taking advantage of favorable winds, as the aircraft will not have to wait for clearance from ATC to change course in response to such transient or local phenomena. Improvements in performance may also be obtained by allowing aircraft to individually fine tune their trajectories making use of the detailed dynamical models contained in the autopilot. Finally, greater flexibility may be preferable to the airlines as it allows them to utilize their resources in the best way they see fit.

The focus of our research has been to strike a compromise in the form of partially decentralized control laws for guaranteeing *reliable, safe control of the individual agents* while providing *some measure of unblocked, fair, and optimum utilization of the scarce resource. In our design paradigm, agents have control laws to maintain their safe operation, and try to optimize their own performance measures. They also coordinate with neighboring agents and a centralized controller to resolve conflicts as they arise and maintain efficient operation.* In the next section we propose a control architecture that implements what we believe is a reasonable balance between complete centralization and complete decentralization.

3 Automation on the Ground

The next two sections describe the balance between the ATM on the ground and in the air. Currently, ATC in the United States is organized hierarchically with a single *Air Traffic Control System Command Center (ATCSCC)* supervising the overall traffic flow management. This is supported by 20 *Air Traffic Control System Command Centers (ARTCCs)* or simply Centers organized by geographical area. Coastal Centers have jurisdiction over oceanic waters. Around large urban airports there are *Terminal Radar Approach Control facilities (TRACONs)* numbering over 150. The TRACONs are supported by control towers at more than 400 airports. The overall system is referred to as *National Airspace System (NAS)* [5].

The main goal of both the ARTCCs and the TRACONs is to maintain safe separation between aircraft while guiding them to their destinations. In an effort to increase the runway throughput, airport capacity as well as reduce delays, fuel consumption and controller workload in the vicinity of highly congested urban airports, NASA has designed the Center-TRACON Automation System (CTAS) [6]. CTAS is a collection of planning and control functions which generate advisories to assist, but not replace, the controllers in handling traffic in the Center and TRACON areas. CTAS consists of three main components: the *Traffic Management Advisor (TMA)*, the *Descent Advisor (DA)* and the *Final Approach Spacing Tool (FAST)*. TMA and DA coexist and operate in Center airspace whereas FAST operates as a standalone in TRACON airspace. CTAS receives input from radar sensors which transmit the aircraft state; from Center and TRACON controllers who allocate runways and routes to particular aircraft as well as alter the capacity or acceptance rate of the TRACON, airport or runway; and finally from weather reports which include wind, temperature and pressure profiles. The main of outputs of CTAS are arrival schedules which meet all the capacity, separation and flow rate constraints as well as advisories to Center or TRACON controllers. CTAS is currently being field tested at Denver and Dallas-Fort Worth. A similar ground system called User Request Evaluation Tool (URET) has been developed by MITRE Corp. [7] and is being field tested at Indianapolis.

Currently, nominal trajectories through the airspace are defined in terms of *waypoints*, which are fixed points in the airspace defined by VOR (VHF Omni-Directional Range) points on the ground. The waypoints are a necessary navigation tool for aircraft which are not equipped with GPS. Waypoints have resulted in a discrete airspace structure and an underutilization of airspace. On the other hand, they have resulted in a predictable environment which allows controllers to resolve conflicts in congested airspace. GPS and Free Flight will remove this structure which will lead to greater efficiency and airspace capacity. Aircraft may choose their own routes instead of following a sequence of waypoints. However, inside the crowded TRACONs, airspace structure will be necessary in order to simplify the controller's task of landing aircraft while resolving conflicts.

In our proposed ATM system, we will assume that a ground system (either CTAS or URET) will have jurisdiction over highly congested TRACON airspace, that airspace structure exists inside the TRACON and that controllers have active control over aircraft in the TRACON, sending the aircraft heading, speed and altitude advisories. The advisories provide a suggested arrival schedule at the destination airport, which is designed to meet the announced arrival times while resolving conflicts. The schedule reflects compromises between airline schedules as well as possible negotiation between ATC and the aircraft.

However, in the less congested Center airspace, aircraft are allowed to choose their own routes in the spirit of Free Flight. In addition, aircraft may resolve potential conflicts by inter-aircraft coordination. The role of the ATC in Center airspace is limited to performing flow management, providing the aircraft with global information about en-route traffic and weather conditions as well as providing advisories in case aircraft are unable to resolve conflicts on their own.

4 Automation in the Air

In our proposed ATM structure, each aircraft is equipped with various planning and control algorithms. The aircraft will perform real time trajectory planning and tracking, conflict detection and resolution, as well as automatic mode switching. These smart aircraft of the future will be extremely complex and each will be a large scale system in its own right. In order to reduce the resulting complexity and assist pilots in better performing their task, each aircraft is architected using the hierarchical structure shown in Figure 1. The levels of architecture below ATC reside on the aircraft and comprise what is known as the aircraft's *Flight Management System*, or FMS. The FMS consists of four layers, the strategic, tactical, and trajectory planners, and the regulation layer. Higher levels of the FMS architecture are associated with higher objectives and coarser models. Each layer of this architecture is described below:

Strategic Planner: The main objectives of the strategic planner are to design a coarse trajectory for the aircraft and to resolve conflicts between aircraft. The trajectory has been designed from origin to destination in some optimal sense, and is frequently redesigned in order to adapt to changes in the environment, such as weather patterns, potential conflicts and airport traffic. Inside TRACONs, the Strategic Planner may simply accept the advisories of the controllers. In Center airspace, the strategic planners of all aircraft involved in the potential conflict determine a sequence of maneuvers which will result in conflict-free trajectories, either using communication with each other through satellite datalink, or by calculating safe

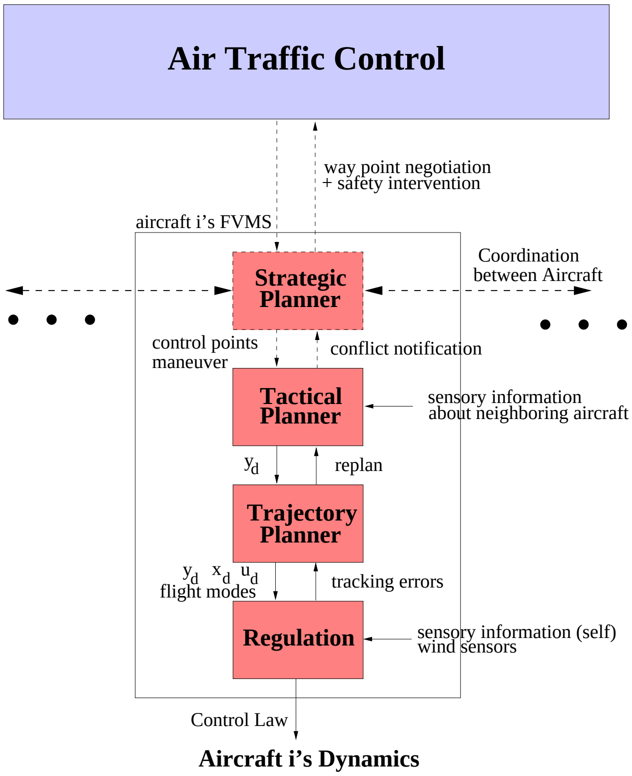

Figure 1: Proposed ATM Structure

trajectories assuming the worst possible actions of the other aircraft [8]. Each strategic planner sends its most recently designed trajectory to the Tactical Planner in the form of a sequence of control points and/or a maneuver.

Tactical Planner: The tactical planner refines the strategic plan by interpolating the control points with a smooth output trajectory, denoted by y_d in Figure 1. The tactical planner uses a simple kinematic model of the aircraft for all trajectory calculations. Simple models are used at this stage since very detailed models may unnecessarily complicate the calculations, which are assumed to be approximate and have large safety margins. The output trajectory is then being passed to the Trajectory Planner.

Trajectory Planner: The trajectory planner uses a detailed dynamic model of the aircraft, sensory data about the wind magnitude and direction, and the tactical plan consisting of an output trajectory, to design full state and input trajectories for the aircraft, and a sequence of *flight modes* necessary to execute the dynamic plan. The flight modes represent different modes of operation of the aircraft and correspond to controlling different variables in the aircraft dynamics. A derivation of the flight mode logic necessary for safe operation of a CTOL (Conventional Take Off and Landing) aircraft is presented in [9].

The resulting trajectory, denoted y_d, x_d, and u_d in Figure 1, is given to the regulation layer which directly controls the aircraft. The task of the trajectory planner is complicated by the presence of non-minimum phase dynamics [10], [11] and actuator saturation [12].

Regulation Layer: Once a feasible dynamic trajectory has been determined, the regulation layer is asked to track it. Assuming that the aircraft dynamic model used by the trajectory planner is a good approximation of the true dynamics of the aircraft, tracking should be nearly perfect. In the presence of large external disturbances (such as wind shear or malfunctions), however, tracking can severely deteriorate. The regulation layer has access to sensory information about the actual state of the aircraft dynamics, and can calculate tracking errors. These errors are passed back to the trajectory planner, to facilitate replanning if necessary.

The hierarchical structure of the proposed Flight Management System leads to various interesting questions regarding hierarchical systems. First, the convergence of the overall scheme to an acceptable and safe trajectory needs to be shown. Due to the complexity of the overall system and very nonlinear nature of the continuous dynamics it is unlikely that timed automata techniques will be adequate in this setting. More elaborate (possibly hybrid) techniques, such as those in [9] may be useful here. In addition, higher level of the hierarchy, utilize coarser system models or coarser abstractions. This raises the interesting notions of consistent abstractions or implementability, which is the ability of a lower level system to execute the commands of a higher level system. Preliminary work along this direction may be found in [13].

5 Hybrid System Issues

The operation of the proposed ATM involves the interaction of continuous and discrete dynamics. Such *hybrid* phenomena arise, for example, from the coordination between aircraft at the strategic level when resolving a potential conflict. The conflict resolution maneuvers are implemented in the form of discrete communication protocols. These maneuvers appear to the (primarily continuous) tactical planner as discrete resets of the desired waypoints. One would like to determine the effect of these discrete changes on the continuous dynamics (and vice versa) and ultimately obtain guarantees on the minimum aircraft separation possible under the proposed control scheme.

Research in the area of conflict detection and resolution for air traffic has been centered on predicting conflict and deriving maneuvers assuming that the intent of each aircraft is known to all other aircraft involved in the conflict, for both deterministic [14],[15],[16], and probabilistic [17],[18] models.

In our research, we differentiate between two types of conflict resolution: *noncooperative* and *cooperative* [8]. In noncooperative conflict resolution, if an aircraft detects that a conflict may occur between itself and another aircraft, and it is not able to communicate with this aircraft to determine its intentions or to resolve the conflict, then the safest action that this aircraft can take is to choose a strategy which resolves the conflict for the *worst possible action of the other aircraft*. We therefore formulate the noncooperative conflict resolution strategy as a zero sum dynamical game of the pursuit-evasion style. The aircraft are treated as players in this game. Each player is aware only of the possible actions of the other agents. These actions are modeled as disturbances, assumed to lie within a known set but with their particular values unknown. Each aircraft solves the game for the worst possible disturbance. The performance index over which the aircraft compete is the relative distance between the aircraft, required to be above a certain threshold (the Federal Aviation Administration requires a 5 mile horizontal separation in en-route airspace). Assuming that a saddle solution to the game exists, the saddle solution is *safe* if the performance index evaluated at the saddle solution is above the required threshold. The sets of *safe states* and *safe control actions* for each aircraft may be calculated: the saddle solution defines the boundaries of these sets. The aircraft may choose any trajectory in its set of safe states, and a control policy from its set of safe control actions; coordination with the other aircraft is unnecessary. The saddle solution for the game may be abstracted linguistically in the form of a hybrid automaton.

In cooperative conflict resolution, safety is ensured by full coordination among the aircraft. The aircraft follow predefined maneuvers which are proven to be safe. The class of maneuvers constructed to resolve conflicts must be rich enough to cover all possible conflict scenarios. In this case, the predefined resolution protocols dictate a hybrid nature in the overall system.

Consider for example the *HeadOn* conflict, shown in Figure 2 where aircraft 1 is heading towards aircraft 2 along the x_r axis. A potential conflict exists regardless of the speeds of aircraft 2 and aircraft 1. In order to ensure that the HeadOn conflict is safe by design, a protocol is designed where both aircraft deviate a horizontal distance of 5 miles (the minimum aircraft separation) away from their original paths. Similar protocols may be designed for other situations, such as the *Overtake* maneuver. For each maneuver, the safe set of initial conditions are calculated and their union must cover all initial conditions in order to guarantee safety regardless of the conflict scenario.

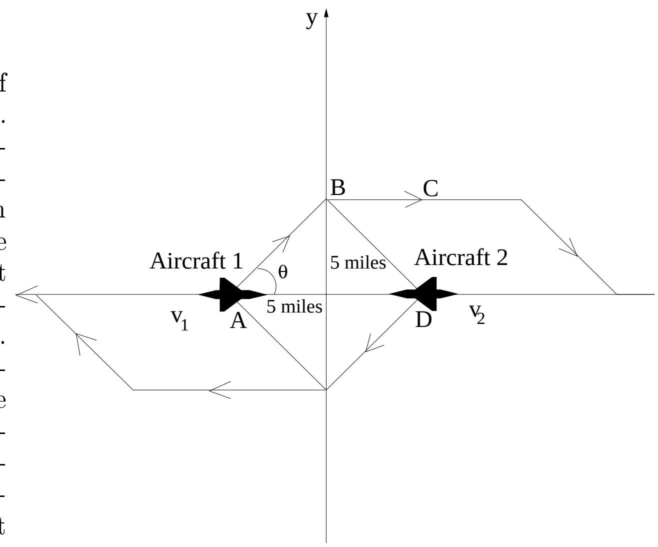

Figure 2: The HeadOn Conflict

In more complicated conflict scenario involving many aircraft, the design of the protocol is not obvious. In order to assist with the protocol design, we employ the method of potential fields which generate the resolution maneuvers [19]. These maneuvers are then discretized and modeled as linear hybrid automata. Computer aided verification techniques from computer science are then used in order to calculate the safe sets of initial conditions.

In addition to the hybrid system issues arising due to the multi-agent nature of air traffic management systems, hybrid issues arise in the operation of a single aircraft. An aircraft, just like any complex system, has various modes of operation or flight modes. The modes are associated with the various tasks of the aircraft such as taxi, take off, cruise, land etc. Additional flight modes reduce the complexity of operation for pilots who may track only certain outputs at a time (such as heading, altitude, flight path angle etc) and can break down a complex task into a sequence of manageable ones.

Flight modes also exist in order to ensure safe aircraft operation. Each aircraft has various flight envelopes, or state constraints, which ensure safe and comfortable aircraft operation. In order to respect these constraints the aircraft may switch mode in order to remain within the envelope. For example in [9], one of the goals of the FMS is to keep the state of the aircraft in a given subset of the state space dictated in principle by stall constraints. The task is complicated by input saturation which also dictates the flight mode switching. A phenomenon called *mode confusion* has resulted in various crashes in recent years. Mode confusion exists when the pilot is not aware of the current mode of the aircraft and may respond inappropriately with catastrophic consequences.

6 Conclusions

Technological advances like GPS and datalinks, and innovative concepts such as Free Flight are creating many interesting issues in next generation ATM systems. As a result, aerospace engineering and control systems are left with a variety of exciting new problems from both a theoretical and applied perspective. Architectural issues in large scale systems, hierarchical and decentralized control systems, conflict resolution and protocol design, flight mode switching and hybrid systems as well as more traditional problems in the areas of path planning and tracking, non-minimum phase systems and input saturation are simply a subset of the research agenda in Air Traffic Management Systems.

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