COMPARING CENTRALIZED AND DECENTRALIZED MULTI-AGENT APPROACHES TO AIR TRAFFIC CONTROL

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ABSTRACT
Air traffic has been increasing in the last decades, representing a major mode of transportation. The FAA (Federal Aviation Administration) and the aeronautical industries are both predicting a growth between 150% to 250% over the next two decades. In this paper, we present and compare centralized and a decentralized agent-based approaches to autonomously manage air traffic. Agents assuming the roles of aircraft and that of the air traffic controller detecting possible mid-air collisions and proposing new routes for the aircraft to avoid such collisions, while attempting to minimize the cost of the deviations. During simulations we were able to avoid collisions between aircraft from a minimum maneuver area of 12.25 km² per aircraft and identified that the centralized approach has a better performance, when compared to the decentralized approach.

INTRODUCTION
Estimates point to an average increase of the number of flights of 2.8% per year until 2030 for the European continent alone. This means that on a typical day we will have 500-1500 new flights to be monitored and all this demand should be accompanied by new technologies, equipment and processes to assist the Air Traffic Management (ATM) (EUROCONTROL, 2013). Thus, it became increasingly necessary to provide all who use it greater safety and better efficiency in the processes. This project aims to provide new systems that can assist the ATM through methodologies associated with multi-agent systems. We propose and demonstrate that the use of multi-agent systems for air traffic control (ATC) can be effectively applied to solve the problems of detection and resolution of air conflicts, thereby increasing the safety of the air space and reducing the workload of air traffic controllers.

In section 2 we present some past proposals to use multi-agent technology on ATM. Section 3 describes the way in which this proposal was implemented and the resources that were used. In Section 4 we present the testing scenario and discuss the results. Finally Section 5 draws some conclusions and presents some lines of future work.

BACKGROUND
This section describes some studies and proposals on the inclusion of multi-agent concepts and technology in ATC.

Conflict Detection and Resolution Systems
As to automate and increase the efficiency of some ATC processes, the scientific community has proposed numerous ways of inserting multi-agent systems in civil and military aviation. Among these, we highlight the centralized and decentralized approaches, taxiways management, air traffic flow management and aid in the decision making process.

In (Chiang et al., 1997), the authors propose a centralized approach in which the ATM can be solved using a simple iterative method called "Space-Time Flow" (STF). This solution can be deployed in an air traffic control center, where through an agent you can look for possible collisions and propose multiple secondary routes, all free of collisions. Both the proposed solutions by these authors as well as the solution presented in this article fall within the same range of solutions, but with some different approaches that can be better understood in the following sections.

In (Wollkind et al., 2004), the authors propose that a decentralized approach would increase the efficiency of the airspace, because in the case of a possible mid-air collision the aircraft themselves could negotiate measures to prevent the accident. This article proposes the use of the Monotonic Concession Protocol (MCP) which has been shown to capture the ideas of negotiation involving relatively simple calculations and most importantly, this protocol behaves robustly, and doesn't allow being controlled by other agents in order to win some kind of advantage in the system. Other solutions involving this type of approach can also be found in (C. Hill et al., 2005) and (Kroze et al., 2001).

In the work proposed in (Valkanas et al. 2009), a platform (NAMA) of oriented implementations based on free flight agents was presented. It also proposed a decentralized approach where each aircraft is simulated by an agent. The communication between agents occurs through diffusion, and transmitted information includes the state and location of a plane. In implementing this, each agent makes use of two basic behaviors, Navigation and Communication, which are executed in separate threads. In this work, a new approach to the detection and resolution of role-based utility conflicts was also presented, and a comparison was made of two systems with and without hierarchy.

In (Pechoucek et al., 2006), the authors propose a prototype ATC system for autonomous routing of aircraft and auto-
flight trajectory optimization, complemented by a simple rule-based deconfliction mechanism. In this prototype, two kinds of display system are introduced: real-time and distance using a web browser. The solution is based on agents with multiple external data sources that provide various information such as soil conditions or location of airports, among others. The separation strategies not only ensure aircraft safety in the flight phase, but there is also the need to provide greater security to all aircraft maneuvering on the ground and also to other vehicles that may transit on the taxiway. Because of the similar characteristics between the management of taxiways with other scenarios such as urban traffic control and train traffic control, we could replicate their solutions to the problems of managing taxiways, whereas in both of them we find traffic restrictions in certain areas, intersections, holding points (light) and others. (Guerrero et al., 2002) proposed the use of multi-agent systems to achieve control of train traffic, specifically the resolution of conflicts in points of intersection of the railroads. In this approach agents are inserted in the crossings of railroads that manage the passage of trains (also represented by agents) to ensure the safety of all vehicles.

Unlike the approaches that deal with separation strategies, in (Dib et al., 2007) the authors propose the inclusion of multi-agent systems in air traffic flow management (ATFM). This proposal aims to identify in advance the congestion in the queues of aircraft held in the air waiting for permission to land, preferring a deliberate retention of the aircraft at the airport of origin until such a time that it is possible for it to land “immediately” at its arrival at the destination. This approach contrasts with the current model, that ends up holding the aircraft in the airspace above the destination airport, increasing the problems of aircraft safety, as the increased density of these airspaces implies a greater effort from air traffic controllers to ensure the safety of all aircraft. Also, by eliminating the holding time of aircraft, it also saves fuel, thus presenting itself as a ‘greener’ alternative.

In (Hexmoor and Heng, 2000) the authors present an example of a class of solutions that use multi-agent systems to propose solutions to the most diverse professionals who work in ATM. They designed a system to assist the controller process requests for landing or detect and avoid collisions, unlike (Dib et al. 2007), who use agents to identify in advance the congestion of airport queues and therefore try to reduce them.

**PROPOSED SOLUTION**

This section will look at the internal architecture of the developed ATC module, the simulation platform used for the tests, the centralized and decentralized solutions and how its utility functions are used in the decision-making process of the ATCO and the Aircraft agents.

**Centralized Approach**

In this approach, the ATC agent centralizes all necessary activities for the resolution of air conflicts, leaving only the aircrafts on its domain to execute its orders. This has the main advantage of providing a better view of the airspace as well as identifying problematic areas. However, its disadvantage lies in the fact that a failure in this agent would compromise the entire airspace over its domain. In order to monitor all aircraft, the controller agent has a “Radar” at its disposal, in which it can see, at all times, the locations of all aircraft (and distances between them). For that, two spheres of radius $R$ and $2R$ are simulated around the aircraft, being the Red Zone (inner zone) responsible for initiating the process of generating alternate routes if another aircraft enters that area, and the Blue Zone (outer zone) used in the detection of new collisions generated by evasion maneuvers, similar to that proposed by (Valkanas et al., 2009) and (Pechoucek et al., 2006), but with differences in the number of zones around the aircraft and the distances between them. By using these two areas it is expected that even during the evasive maneuvers, other possible collisions are not generated, since the controller agent uses a sixty seconds “time window”, taking into account speed and direction, and can thus predict the generation of new collisions and avoid regions of higher traffic density.

Figure 1 presents an overview of the processes adopted for the detection and resolution of aerial conflicts. It’s based on the constant monitoring of the airspace by the ATCO agent, constantly seeking situations where two or more aircraft end up invading their respective red zones.

![Activity Diagram for the Centralized Approach](image)

After identifying all possible collisions between two or more aircraft, it starts the process of generating alternative routes for all involved aircraft. Due to the tight response time in which aircrafts must change their routes, the number of iterations to generate these routes must be limited. During the process of generating new routes, for each idealized new route, two things are checked: if the average of the utilities is greater than or equal to 0.75; and if one or more aircrafts will create a new condition of collision with the aircrafts present in the blue zone. When these conditions are met, the aircraft in conflict can perform their maneuvers. However, if during this process, the maximum number of iterations is exceeded, the solution with the highest utility value thus far will be executed, regardless of generating future collisions within the blue zone. After the controller agent sends the new routes, it continues to observe the airspace until other collisions are detected. Any aircraft that receives an order from the ATCO Agent to change its course complies with it, altering its route, thus avoiding a mid-air collision.
Decentralized Approach

In this approach, each individual aircraft is responsible for monitoring the airspace around it. In case a possible collision is detected, a negotiation process begins between the aircraft in question. The major advantage on this technique is the autonomy and independence of the aircraft in respect to the ATCO Agent. However, the main drawbacks are related to a lower airspace monitoring capability, when compared to the centralized approach – to simulate actual aircraft limitations, in this approach each aircraft has only a single sphere, the Red Zone, associated with it, which means that the aircraft are capable of foreseeing possible collisions that come from changes in course only in a short-term future.

In contrast with the activity diagram shown above, the decentralized approach has an additional negotiation phase before the “execute maneuver” step. The aircraft that first detected the collision generates an alternative route plan for the involved aircraft and sends the suggestion to the other aircraft. If the suggestion is accepted, both execute the route changes, but if the second aircraft does not agree with the suggested change (because its utility value is low), it then generates a counter-proposal with a higher utility value. This process is repeated until both aircraft are in agreement, or the maximum negotiation time is reached.

Architecture of the ATC Module

The internal architecture of the ATC Module is presented in Fig. 2 below, resulting from an adaptation and further developments on the architecture proposed in (Silva, 2011). The used simulation engine was Flight Simulator X (FSX) (Microsoft, 2012), chosen due to its realistic simulation engine, the ability to interact with external applications via an Application Programming Interface (API) called SimConnect, among other reasons (Gimenes et al., 2008).

To carry out air traffic control, a Conflict Detection and Resolution (CDR) submodule was implemented. To do that, the Radar submodule had to be adapted to allow for flexible monitoring areas around the aircraft (red and blue zones), so the new sub-modules could follow surrounding aircraft in real-time and generate secondary routes when necessary.

Utility Functions

The Multicriteria Utility Theory (MAUT) is derived from the theory of utility associated with the decision-making process, used to define the importance of attributes with higher priority over lower priority by building a mathematical function (Teixeira and Belderrain, 2011).

In this project, MAUT was used in the decision-making processes to verify that the new evasive route fits the needs of the ATCO agent, which may not always be met in full. During the decision-making process, some measures were taken to avoid the continuous search for the best possible solution, such as the limitation of the number of iterations, or the minimum acceptable utility value. To calculate the additive utility function, the worst and best values for each attribute were initially established: for heading variation (HV), the best value is 0 degrees (no variation) and the worst is larger or equal to 25 degrees; for speed variation (SV), the best value is 0, and the worst is a value larger or equal to 30% of current speed; finally, for traffic density (TD), the best value is 0, and the worst value is half the testing aircraft. Based on these values, we can then interpolate the intermediate utility values for each attribute, when generating an evasive maneuver.

For the next step we need to set the weight "K" of each attribute; this value depends mainly on the level of importance associated with each attribute. There are situations when the heading variation is the most relevant criteria and others where speed variation is more important. For testing purposes, we use equal weight values and the ratio $6/1/3$ for $HV$, $SV$ and $TD$ respectively. We can now calculate the additive utility function (see Equation 1), where $U_i$ is the interpolated utility value for each parameter. The results are in the range of 0 to 1, where zero is worst outcome and one the best result.

$$U(x_1, x_2, x_3, ..., x_n) = \sum_{i=0}^{n} K_i U_i(x_i)$$  

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EXPERIMENTAL SETTINGS

Tests were performed using two types of aircraft, the Beech Baron 58 and the Cessna 172 Skyhawk, both small and traditional in general aviation. Simulations were performed using 2, 4, 6, 8 and 10 aircraft, with the same proportion of both aircraft types. After going through the takeoff procedures, the aircraft are routed to an area near the airport, with approximately 49 km² (a circle with a radius of 3945m), with the goal of generating the highest possible traffic density, thus leading to a higher probability of conflicts. If an aircraft leaves the test region, a new route is generated to take it back to the test zone. If two aircraft are less than 3600 meters apart (occurrence of an event), the process of conflict resolution starts. A collision is considered to occur if the distance between the aircraft is less than 30 meters. However, the aircraft involved in these events will not be excluded from the simulation, thus maintaining a fixed number of aircraft throughout the entire simulation time, set for 10 hours.

RESULTS

Figures 3 and 4 and Table 1 show the average number of collision detections and collisions that actually occurred, as well as the efficiency of both the centralized and decentralized approaches for different traffic loads. The results are an hourly average based on the 10 hour experiments. As shown in Fig. 3, with a small number of aircraft (up to 4), both approaches behave similarly, but with an increasing number of aircraft, we can verify a greater variation between the two approaches. In scenarios with larger number of aircraft (8 and 10 agents), the decentralized approach presents 65% more detected conflicts than the centralized approach. This difference is explained by the smaller area of monitoring airspace in the decentralized approach, which doesn’t allow aircraft to check for possible collisions too far ahead, as it happens in the centralized approach. As such, several of the new routes end up resulting in additional detected events, that could be avoided by an approach with a larger monitoring area.

The actual number of collisions, shown in Fig. 4, has a similar trend to the one shown in Fig. 3 – both approaches behave similarly for few aircraft, but with an increasing number of aircraft, the decentralized approach shows a higher number of collisions. The difference between the two, however, is larger than before: for 10 aircraft, the decentralized approach had 229% more collisions than the centralized approach (contrasting with a 65% difference for events). This can be explained by the increased number of messages required by this approach, which associated with the communications overhead, results in a larger time to reach an agreement. This extra time, when considering the nature of the problem, is crucial, and results in a larger number of collisions.

With the results obtained in the two charts above, we can determine the efficiency of each approach, as shown in Table 1. Both are 100% effective when dealing with a low number of aircraft, but a higher traffic density allows us to identify the decentralized process as less efficient. Again, these results can be explained by the decreased capability of foreseeing new conflicts when proposing evasive routes, leading to a higher number of detected events, and the increased complexity of the negotiation procedure, leading to more actual collisions.

RESULTS ANALYSIS

In (Valkanas et al., 2009), the authors also took into account a Route Utility Function (RUF) for each possible route the aircraft can choose, while avoiding collisions. During tests, the authors eventually secure a safe distance starting at 4.828 Km between aircraft (area of 15.160 km²). As a negative aspect of their work, one can point the large separation between aircraft and the lack of a realistic aircraft model, as this directly impacts the size of the area necessary to maneuver the aircraft to avoid collision; the authors, however, highlight the possibility of improving these results. As a positive aspect, its hierarchical model for the conflict resolution process stands out, as the aircraft prioritises certain aircraft in approximation of their safety zones. In this project, we did not take into account maneuvers that combine vertical movements when generating evasive maneuvers, but only horizontal maneuvers and variations in airspeed. This imposition is a limitation on the possibilities to avoid collisions, but it also allows us to determine the minimum safety area for aircraft operating on the same plane, and point out the possibility of obtaining much better results when considering vertical movements as well. Among works using a larger set of movement combinations, (Pechoucek et al., 2006) also proposed a Collision Avoidance Mechanism to define four sectors around the aircraft and depending on that sector, one solution is applied on the flightplan of the aircraft. Through this study greater flexibility is expected in the way aircraft fly, breaking away from the concept of Jetways, and applying the proposed “Free Flight” safely due to increased air traffic control, enabling more efficient airspace use.
CONCLUSIONS AND FUTURE WORK

With an estimated increase in air traffic of around 150% to 250% over the next two decades, there is great concern regarding the workload of air traffic controllers, considering that this profession is already quite exhausting.

We proposed to implement a simple conflict resolution system using a multi-agent approach, where the role of the air traffic controller is accomplished by an autonomous agent. During tests, it was possible to reach a minimum safety maneuvering area of 12.25 km² per aircraft, thus demonstrating that the use of multi-agent systems can be a potential technique to be applied in future proposals for solutions to air traffic control. As future work of this project, we point to the development of a hybrid approach, bringing together advantages of both centralized and decentralized approaches, where both aircraft agents and the ATCO agent are involved during the negotiation process. Another line of future work is the inclusion of vertical maneuvers to determine the minimum safety volumes per aircraft. Another study to be performed is based on the influence of aircraft size and speed on the results, as larger and faster aircraft are expected to require larger safety areas, as they require additional time and space to execute the selected maneuvers to avoid the detected conflict.

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