Conflict detection and resolution algorithm for en-route conflicts in dense non-segregated aerial traffic

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ABSTRACT
This paper presents a Conflict Detection and Resolution (CDR) method for dense traffic in Air Traffic Management (ATM). The proposed method detects conflicts using an algorithm based on axis-aligned minimum bounding box and the resolution algorithm is based on evolutionary techniques. The method has been validated with experimental results in a scenario with multiple aerial vehicles (quadrotors) in a non-segregated or common airspace. The experiments have been carried out in the multivehicle aerial testbed of the Center for Advanced Aerospace Technologies (CATEC).

Keywords
conflict detection and resolution, air traffic management, cooperative aerial vehicles, evolutionary techniques

INTRODUCTION
During the last decades, air traffic has constantly increased and has almost used all available resources to raise airspace capacity. However, in the future, it is intended to double the air traffic capacity while maintaining the same safety standards and levels [1]. The automation technologies will play an important role in the future Air Traffic Management (ATM) systems to satisfy high air traffic demand. These automation technologies should be supported by methods and algorithms to implement trajectory based operations by increasing airspace capacity and efficiency [2][3]. Moreover, the interest of using Unmanned Aerial Vehicles (UAVs) for civilian purposes has increased during the last years [4][5] and it has been starting to work on how these aerial vehicles will be integrated in the non-segregated airspace. In both cases automated conflict detection and resolution (CDR) is required to ensure aircraft separation.

In the last years, a variety of works have studied the CDR problem presenting different types of techniques [6]. For example, in [7] the speed profile for all the aerial vehicles involved in a collision is computed in a centralized way to solve the conflict.

The method presented in [8] is based on mixed-integer linear program (MILP) and it resolves the conflict by changing speed to a large number of aerial vehicles subject to velocity change constraints. However, some conflicts cannot be solved vehicles. Other methods resolve pairwise conflicts [9] but do not consider more aircrafts. [10] and [11] present a method based on mixed-integer linear program (MILP) to avoid collision. In [12] a method for multiple-aircraft conflict avoidance is proposed. It is assumed that aircrafts cruise at constant altitude with varying velocities and that conflicts are resolved in the horizontal plane using heading change, velocity change, or a combination thereof. The method in [13] is based on Ant Colony Optimization (ACO) algorithm in order to solve large problems involving up to 30 aircrafts but real experiments are not presented. In [14], the application of a game theory approach to airborne conflict resolution is presented. However, these techniques are not well suited for applications with a high level of scalability. In [15], a resource allocation approach to collision avoidance is proposed. The approach divides the airspace into cells; then, to ensure separation, each cell is constrained to be occupied by only one aircraft at a time. Since the algorithm depends on a centralized controller, and requires every agent to have full knowledge of the system, it is not well suited for a scalable distributed system.

The CDR problem with multiple aerial vehicles is NP-hard [16]. Some differential constraints given by the model of the aerial vehicle should be considered to make the problem tractable. Sampling-based techniques, as opposed to combinatorial techniques, are usually preferred in these NP-hard problems. Therefore, the application of evolutionary techniques, [17], [18], and [19], is an efficient and effective alternative for this problem. In these works real experiments are not carried out, only simulations are presented to validate the methods.

This paper presents a CDR method in 3D scenarios where the detection algorithm is based on axis-aligned minimum
bounding box and the resolution algorithm is based on evolutionary techniques. Each aerial vehicle changes its trajectory maintaining its velocity to solve the detected collisions collaborating with the rest of vehicles. The presented approach presents, as advantages, its low execution time and its scalability. Moreover, the algorithms are demonstrated with flight experiments using quadrotors that emulate the trajectories of aerial vehicles in a common airspace.

PROBLEM FORMULATION
The problem considered in this paper is the detection and resolution of conflicts between aircrafts in a dense ATM scenario. The aircrafts share a common airspace in the same or different flight levels and the separation between aircrafts should be greater than a given safety distance. After a collision is detected, the problem is solved when a collision-free trajectory for each aircraft is computed. All aircrafts cooperate to solve the problem changing their initial trajectory. The information that the system needs in order to solve the problem is the following: 1) sequence of waypoints that each aircraft will follow, 2) parameters of the model of each aircraft in the scenario, and 3) initial location and goal location of each aircraft.

The objective is to find collision-free trajectories that minimize the probability of having a collision while minimizing the changes of waypoints for each aircraft. The initial and solution trajectory should have the same initial and goal locations.

DESCRIPTION OF THE CDR METHOD
The proposed CDR method is split into two steps:

Axis-aligned minimum bounding box for detection
The detection algorithm is based on axis-aligned minimum bounding box. This choice is due to the low time of execution, which is required for real-time implementation, and the need of few parameters to describe the system. On the other hand, it presents two disadvantages: it is not very accurate and it depends on the coordinate axes.

Each aircraft is represented with two boxes, horizontal and vertical box, joined in order to detect the conflicts (see Figure 1). Each box is defined by the intersection of three intervals, one by axis. The measurement of the horizontal box is related to the minimum horizontal separation between aircrafts and the vertical box is related to the vertical separation. It is also possible to relate the dimensions of these boxes to the uncertainty in the predicted trajectories [7]. Thus, the minimum separation, $S$, between two aircrafts is defined by the dimension of both joined boxes. A collision is detected when there is an overlapping between the intervals that define each box. Thus, the 3D problem is reduced to three problems of overlapping, one in each coordinate. Let us consider the intervals in one coordinate $A=[A_x,A_y]$ and $B=[B_x,B_y]$. The condition of overlapping for this coordinate is given by:

$$A_x > B_x \land A_y < B_y$$  

(1)

Resolution algorithm based on genetic algorithms
The proposed conflict resolution algorithm is based on evolutionary techniques and has an optimal, or near-optimal, performance under specific constraint conditions. It computes the collision-free trajectories of each aircraft by generating an intermediate waypoint (IW) between the initial location and the goal location. Figure 2 shows a schema of the algorithm. The individuals are coded by sequences of three waypoints that represent a possible trajectory for each aircraft. The fitness of each individual is computed by mean of the following cost function:

$$Cost_i = L_i + P_{i,collision}$$  

(2)

where $L_i$ is the length of the $i$th aircraft trajectory and $P_{i,collision}$ is the penalty of the $i$th trajectory when a collision is detected. The crossover and mutation operators are considered in the algorithm. By iteration of the selection and reproduction processes, the algorithm ends up computing a near-optimal trajectory that ensures a collision-free trajectory for each aircraft.

A model of the aircraft is needed to simulate and evaluate the suitability of the generated trajectories. Complex models can be used [20] [21]. However, the trade-off with the required computing time should be considered. Other models could be used since the developed algorithm can be adapted to different mathematical models of the aircrafts. On the other hand, aircraft simulator can be used to generate the aircraft trajectories from real flight data [19].

![Figure 1. Detection algorithm based on axis-aligned minimum bounding box. Each aircraft is described by two boxes.](image1)

![Figure 2. Schema of the resolution algorithm based on evolutionary techniques.](image2)

EXPERIMENTS
Many experiments have been carried out to validate the proposed method. Taking into account the characteristics of
the aircrafts in the experiments (see Figure 3), the following dimensions were considered in the detection: horizontal box $1.5\times1.5\times1m^3$ and vertical box $0.8\times0.8\times2m^3$. Thus, the minimum separation, $S$, between two aircrafts is defined by the dimension of the box. The minimum horizontal separation between aircrafts in XY plane was $S_{xy}=1.5m$, and the vertical separation in Z axis, $S_z=1.6m$. The model to generate the trajectories is the one in [7]. The results obtained in the experiments show that computed trajectories are very similar to the real trajectories. The algorithms have been run in a PC with a 2GHz Dual Core processor and 2 GB of RAM. The operating system used was Kubuntu Linux with kernel 2.6.32. The code was written in C++ language and compiled with the gcc-4.4.1.

**Indoor multivehicle aerial testbed**

CATEC facilities count with an indoor multivehicle aerial testbed that can be used to develop and test cooperation algorithms applied to multiple aerial platforms (see Figure 3). The useful volume where tests can be conducted is a cube with a base of 6x6 meters and 5 meters height. The testbed has installed an indoor localization system based on 20 VICON cameras (see Figure 3) that only needs the installation of passive markers on each of the aerial vehicles. This system is able to provide, in real-time, the position and attitude of each aerial vehicle with centimeter accuracy, even if we are conducting test with more than 10 aircrafts. For these experiments, we have used 4 Hummingbird quadrotors as aerial platforms that emulate the trajectories of different aircrafts on a common airspace. The quadrotors used in these experiments are from Ascending Technologies and have 200gr payload and up to 20 minutes of autonomy.

An experiment is presented to validate the proposed methods in the CATEC’s testbed (see Figure 4). The quadrotors fly with constant speed, $v=0.5m$.

CONCLUSIONS

In this paper, we have presented a CDR algorithm that solves possible trajectory conflicts in a common airspace by means of the cooperation among multiple aerial vehicles. The presented algorithms only change the heading of the aerial vehicles while maintain their velocities in order to avoid the detected conflict. These algorithms have been validated in the CATEC multivehicle aerial testbed and the obtained results have been presented.
The main advantages of the algorithms are their low execution time and scalability. In fact, the presented algorithm improves continuously the result from a very fast first solution, so it can be adapted to different applications that require different response times.

Future is the validation of these techniques with a larger number of aircraft (up to 10) in the CATEC’s testbed. Moreover, we plan to perform experiments with tactical UAVs in a segregated airspace of 30x35km. On the other hand, new models will be used to handle different sources of uncertainty like sensors, aerial vehicle model, wind, etc. to predict the aircraft trajectory in the conflict detection.

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