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Innovative Applications of O.R.

A multiobjective distance separation methodology to determine sector-level minimum separation for safe air traffic scenarios

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ABSTRACT

A precursor question to increase the capacity of an airspace is to determine the minimum distance separation required to make this airspace safe. A methodology to answer this question is proposed in this paper. The methodology takes sector volume, number of crossings and crossing angles of routes, and the number of aircraft as input, and generate air traffic scenarios which satisfy the input values. A stochastic multi-objective optimization algorithm is then used to optimize separation values. The algorithm outputs the set of non-dominated solutions representing the trade-off between separation values and the best attainable target level of safety. The results show that the proposed methodology is successful in determining the minimum distance separation values required to make an air traffic scenario safe from a collision risk perspective, and in illustrating how minimum separation values are affected by different sector/traffic characteristics.

1. Introduction

One of the key challenges facing air navigation service providers (ANSPs) is how to accommodate the continuing growth in air traffic demand while meeting safety targets. The rapid increase in air traffic compelled ANSPs to investigate ways to relax the International Civil Aviation Organization (ICAO) standards for separating aircraft in time and space to accommodate extra flights (Netjasov & Janic, 2008). Decreasing separation negatively impacts safety since separation is a fundamental milestone in maintaining low collision risk in an airspace. Although mid-air collision is a rare event, it is a significant event due to its consequences, which normally result in a large number of fatalities.

Separation is a vital factor considered in many air traffic management problems such as demand-capacity balancing (DCB), and conflict detection and resolution (CDR). In DCB problem, a safe, efficient and orderly air traffic flow needs to be achieved while considering – among other factors – the capacity of departure and arrival airports to meet a certain demand of flights. This is achieved by several means such as ground holding (i.e., delaying the departure time of aircraft), airborne holding, rerouting of aircraft, flight cancelation, and speed/level changes. For ground holding, a single destination airport was considered in Richetta and Odoni (1993 1994) and Terrab and Odoni (1993), effect of delays over a network of destination airports was consider in Vranas, Bertsimas, and Odoni (1994), while dealing with airspace capacity in addition to airport capacity was considered in Lulli and Odoni (2007). Integer programming models (whether deterministic Agustin, Alonso-Ayuso, Escudero, and Pizarro, 2012a; Bertsimas and Patterson, 1998 or stochastic Agustin, Alonso-Ayuso, Escudero, and Pizarro, 2012b; Mukherjee and Hansen, 2005, 2009 in nature) using aircraft rerouting were introduced. In Bertsimas and Patterson (1998) and Mukherjee and Hansen (2005), aircraft rerouting was used in association with ground holding and airborne holding, and in addition to flight cancelation in Agustin et al. (2012a, 2012b). Speed (Bertsimas, Lulli, & Odoni, 2008, 2011) and level (Barnier & Brisset, 2004) changes solutions were used along with ground holding, airborne holding and flight cancelation. On the other hand, there are many studies addressing the CDR problem (see Kuchar and Yang, 2000; Martin-Campo, 2010 surveys on CDR models and algorithms), where the aim is to detect when two or more aircraft are in conflict and violate the horizontal and/or vertical separation (i.e., conflict detection) and resolve such conflict.

In all the previous studies on DCB and CDR problems, separation values were pre-defined according to the current standard values, and were mainly treated as constraints which must not be violated. This is reasonable since such studies aim for solutions within the current air traffic management (ATM) policies. However for new ATM policies, such as relaxing the ICAO standards for

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separating aircraft in time and space, separation should be treated as decision variables rather than pre-defined constraint values. Finding ways to determine the minimum separation in an airspace sector which does not compromise safety is crucial for a number of reasons:

- It can assist sector designers to design/re-design safe airspaces.
- It can help researchers to design risk free synthetic scenarios to be used within their air traffic simulation environment.
- It can be used as a Monitor/Alert Parameter in a real-time environment to trigger an alarm if the expected demand on a sector exceeds its capacity.

Collision risk assessment (EUROCONTROL, 2001) provides vital indicators for airspace safety in two stages. The first stage is risk estimation, where collision risk models (CRMs) are developed and used to estimate the collision probability of aircraft in a given airspace. The second stage is risk evaluation, which compares the estimated risk with either an estimated risk of a similar airspace that is considered safe historically or a level of risk that is deemed acceptable known as the target level of safety (TLS) (ICAO, 2001).

Collision risk in an air traffic scenario (ATS) is greatly influenced by the non-linear interactions between different factors, mainly sector characteristics, traffic characteristics and the separation among aircraft (Whittle, Kwan, & Saboo, 2005). Therefore, addressing the distance separation required for an airspace to be safe cannot be done in isolation from the sector and traffic characteristics of this airspace. Here a number of subproblems need to be solved. First, procedures to generate air traffic scenarios (ATSs) with different sector/traffic characteristics need to be designed. Second, generic and flexible procedures which can separate aircraft in an ATS given any values of distance separation. Third, an optimization procedure needs to be designed to discover the minimum distance separation values which make an ATS safe.

To this end, we contribute a multiobjective distance separation methodology which investigates the relationship between different airspace sector/traffic characteristics and the minimum separation required for safety (as compared by the TLS). We present procedures to design air traffic scenarios (ATSs) with different sector characteristics (i.e., number and angles of crossings) and traffic characteristics (i.e., number of aircraft and their speeds). Second, we present a procedure which can apply any given values of distance separation in an ATS. Finally and similar to other studies which rely on stochastic optimization techniques in air traffic management (ATM) (Alam, Shafi, Abbass, & Barlow, 2009; Delahaye, Alliot, Schoenauer, & Farges, 1995; Delahaye & Puechmorel, 2006; Gianazza, Durand, & Archambault, 2004), a multiobjective evolutionary algorithm (MOEA) is used to minimize the distance separation among aircraft while minimizing the number of aircraft pairs which violate the TLS.

The methodology outputs the set of non-dominated solutions representing the trade-off between separation values and the best attainable target level of safety. The results show that the proposed methodology is successful in determining the minimum distance separation values required to make an ATS safe from a collision risk perspective, and how minimum separation values are affected by different sector/traffic characteristics. To the best of our knowledge, this is the first study to address these research questions.

In the next section, the problem is formally defined including discussions on collision risk, safety, distance separation and how these concepts are used in this paper in the proposed methodology. In Section 3 procedures for sector design are introduced, and in Section 4 the traffic generation procedure is discussed. Section 5 illustrates the proposed distance separation procedure. Sections 6 and 7 illustrate the experimental design and results of the study, and Section 8 concludes the study.

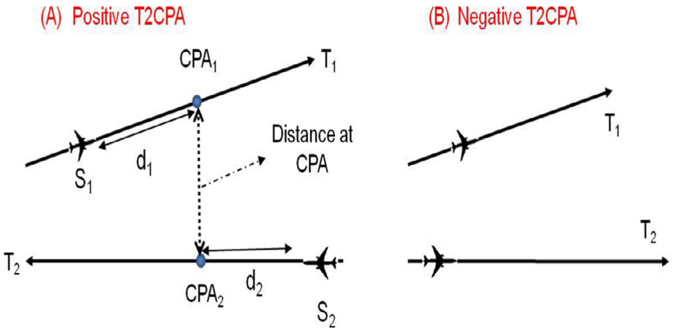

Fig. 1. Two aircraft scenario illustrating CPA.

2. Preliminary concepts and proposed methodology

Collision risk: The collision risk estimate expresses the probability of an aircraft having a collision in an airspace. It is considered a crucial numeric metric and analytic method to guide decision making in regard to airspace safety. Collision risk is computed for a pair of aircraft ac_i and ac_j at a certain time step t for a time interval t_{cr} according to a collision risk function $CR(ac_i, ac_j)$, i.e., the probability that ac_i and ac_j will collide in the next t_{cr} minutes.

The t_{cr} is usually a time interval which allows screen update time in normal automatic dependent surveillance (ADS) operations or downlink in non-ADS operations, controller conflict recognition, controller message composition, uplink, pilot reaction and aircraft manoeuver. This may take from 4 minutes in ADS operations to 6 minutes in non-ADS operations (Anderson, 2005). This study uses the average of these two numbers and set t_{cr} to be 5 minutes.

The collision risk function $CR(ac_i, ac_j)$ implements a collision risk model (CRM), which expresses the risk of a mid-air collision in an airspace in terms of a number of quantifiable parameters. In this study, the Hsu CRM (Hsu, 1981; ICAO, 2001) is used. The Hsu CRM is commonly used by ANSPs and by the ICAO Separation and Airspace Safety Panel (Anderson, 2005) because of its low computational cost.

For completeness, we will briefly discuss here the Hsu CRM (see Anderson, 2005 for a detailed treatment for the Hsu CRM). In the Hsu CRM, the collision risk of a pair of aircraft is computed based on the closest point of approach (CPA). Fig. 1(A) shows two aircraft on two tracks T_1 and T_2, with headings indicated by the tracks' arrows and nominal speeds S_1 and S_2. Given their current positions, headings and speeds, the two points CPA_1 and CPA_2 will be computed. Both aircraft will reach CPA_1 and CPA_2 after a time period known as the time to CPA (*T2CPA*). When both aircraft are at CPA_1 and CPA_2, the distance between them is minimum. The collision risk is computed based on the distances d_1 and d_2 from the current positions of the aircraft to the CPA_1 and CPA_2 points. Collision risk can be only computed if the *T2CPA* is non-negative (Fig. 1(A)). Fig. 1(B) shows a case where the *T2CPA* is negative since the CPA already passed and aircraft are flying away from each other.

The Hsu CRM assumes that aircraft are represented by circular cylinders of diameter λ_{xy} and height λ_z. The collision risk is generally speaking the probability that the two cylinders (i.e., representing two aircraft) intersect. To compute collision risk for a pair of aircraft, the first aircraft is represented by a double-sized cylinder with diameter λ_{xy} and height $2\lambda_z$, denoted by C, while the second aircraft by a point particle, denoted by P. For a collision to occur P must enter C through its vertical side or through its top or bottom. A horizontal overlap of the two aircraft occurs when P enters the infinite cylinder C_∞ of radius λ_{xy} obtained by extending upwards and downwards the cylinder representing the first aircraft.