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A Multi-Criteria Decision-Making Scheme for Multi-Aircraft Conflict Resolution [★]

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Abstract: Multi-Aircraft Conflict Resolution (MACR) is a Multi-Criteria Decision-Making (MCDM) problem, which involves multiple stakeholders (airline, air traffic controller, and aircraft) with competing and incommensurable objectives. This paper proposes a two-step MCDM scheme to the solution of MACR. In the first step, a second order cone program is adopted to generate a set of candidate resolution strategies with different minimum separations between trajectories. Each candidate strategy is then evaluated via three criteria modeling the interests of the stakeholders. In the second step, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach is used to determine the best strategy that realizes an adequate tradeoff among the competing interests while coping with their incommensurability. Some numerical results are presented to show the efficacy of the proposed scheme. Interestingly, the minimum separations associated with the best resolution strategies according to either the interest of the airline or that of the aircraft both differ from the one adopted in the current air traffic control operation.

Keywords: Multi-Aircraft Conflict Resolution, Multi-Criteria Decision-Making, Aerospace, Multi-agent systems.

1. INTRODUCTION

In order to meet the rapid growth of air traffic demand, enhanced technologies, such as satellite based navigation, Automatic Dependent Surveillance-Broadcast (ADS-B), digital communications, System Wide Information Management (SWIM), are widely deployed in the Air Traffic Control (ATC) system operation. This enables Collaborative Decision Making (CDM) of multiple stakeholders, including airline, air traffic controller, and aircraft, during the flight (see Prevot et al. (2003), Prevot et al. (2005), and Sipe and Moore (2009)).However, stakeholders have different decision objectives: airlines are interested in the economic benefits, hence, their aim is to reduce the flight cost by selecting the shortest trajectory from origin to destination; air traffic controllers are in charge of ensuring flight safety by maintaining aircraft at some safe distance; and pilots onboard of the aircraft care more about flight maneuverability in terms of flexibility available for handling safely emergency situations. Thus, ATC is a decision-making process that involved different, not directly comparable objectives, and it is hence necessary to develop solutions that realize a good tradeoff among them.

Multi-Aircraft Conflict Resolution (MACR) is one of the core ATC tasks (Kuchar and Yang (2000), Chaloulos et al. (2010)). As soon as a conflict, i.e., a violation of the prescribed minimum separation between aircraft, is detected, aircraft trajectories have to be modified using horizontal re-routing maneuvers, vertical ascending or descending maneuvers, or speed change strategies. These trajectory redesign process inevitably induces some deviation from the original trajectories, thus typically resulting in increased flight distance and fuel consumption, and flight delay. The minimum cost strategy is the best choice from the airlines perspective, whereas air traffic controllers look for a strategy that does not create any secondary conflicts and thus avoids the *domino effect*. As for the pilots onboard of the aircraft, they favor those resolution strategies that preserve some degree of flexibility so as to be able to handle the occurrence of unpredicted stochastic events during the flight. MACR is hence a Multi-Criteria Decision-Making (MCDM) problem with multiple stakeholders involved. In recent decades, many contributions on MACR have appeared in the literature (see the surveys Kuchar and Yang (2000), Chaloulos et al. (2010)). Approaches can be classified into three categories depending on the adopted stakeholder perspective:

(1) Pioneering works in MACR aim at minimizing the resolution strategy cost and hence are developed from the perspective of airlines. Specifically, the cost is defined as

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the deviation of the modified trajectories from the original ones, in terms of, e.g., extra travel distance, and heading and altitude changes. Pallottino et al. (2002) addresses MACR by reformulating the problem as a Mixed Integer Linear Program (MILP) with conflict-free conditions described via linear constraints and using heading or velocity changes. Non-linear extensions of Pallottino et al. (2002) are proposed in Alonso-Ayuso et al. (2012) and Cafieri and Durand (2014). In Hu et al. (2002) an optimization based approach is pursued leading to a Second Order Cone Program (SOCP) where conflict-free conditions are approximated through convex constraints and the energy of the trajectory is minimized thus favoring straight line resolution trajectories traveled at constant speed. Recently, Rey et al. (2014) studies the fairness issue among airlines and designs fuel-equivalent resolution strategies obtained through velocity changes. Alonso-Ayuso et al. (2015) investigates different costs obtained via heading, altitude, and velocity changes.

(2) The air traffic controllers perspective is taken in Krozel et al. (2001). One of the decision criteria is stability of the multi-aircraft system, which relates to the domino effect. The smaller is the domino effect, the higher are the guarantees of flight safety. The taskload for the air traffic controller defined as the number of flight maneuvers to implement the resolution strategy is investigated in Vela et al. (2010) and Vela et al. (2009). MACR is solved via integer programming implementing velocity changes so as to minimize the taskload.

(3) The trajectory with the maximum flexibility is generated as resolution maneuver for the benefit of the aircraft pilot in Idris et al. (2011), Idris et al. (2007), and Idris et al. (2009). Maneuverability of the aircraft in the velocity space is used as a measure of flexibility. More specifically, the aircraft is supposed to fly along some fixed path with the velocity as only degree of freedom, and the set of velocities such that the aircraft will not encounter other aircraft along its path is defined as reachable velocity set: the larger the reachable velocity set, the larger is the flexibility of the trajectory since the aircraft has a larger maneuverability during the flight.

To the purpose of comprehensively accounting for the different objectives of the stakeholders, a Multi-Criteria Decision-Making (MCDM) scheme for MACR is proposed in this paper. The decision problem is far from trivial since it involves multiple competing and incommensurable objectives. In order to solve this challenge, the proposed scheme is composed of two steps: In the first step, we adopt a SOCP model (Hu et al. (2002), Yang et al. (2017)) to generate a set of candidate conflict resolution strategies with different separations between conflicting aircraft. Each candidate resolution strategy is evaluated in terms of three criteria, i.e., cost, stability as defined in Krozel et al. (2001), and flexibility as measured in Idris et al. (2007), according to the perspective of airlines, air traffic controllers, and aircraft, respectively. In the second step, we resort to a MCDM approach to determine the tradeoff among the competing interests of the multiple stakeholders. Specifically, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon (1981)) is adopted to overcome the issue of incommensurability of different attributes. Some numerical results are presented to show the efficacy of the proposed scheme. Specifically, the conflict resolution strategies associated with a set of separations are investigated for various symmetric conflicting scenarios with a different number of aircraft. Results of this study reveal that the separation corresponding to the best strategy differs from the one currently adopted in the ATC operation if either the perspective of airlines or that of aircraft is highlighted.

The rest of the paper is organized as follows. Section 2 introduces the proposed MCDM scheme for MACR. Section 3 describes the numerical results. Finally, some conclusions are drawn in Section 4.

2. MULTI-CRITERIA DECISION-MAKING SCHEME

In this section we present the proposed MCDM scheme for MACR, which rests on the design of a set of candidate resolution strategies, their assessment based on different criteria, and the application of the TOPSIS for selecting the tradeoff solution.

2.1 Design of the candidate resolution strategies

Consider a multi-aircraft encounter involving n aircraft that fly at constant altitude from some starting waypoints a_i, $i = 1, \dots, n$, to some destination waypoints b_i, $i = 1, \dots, n$, along straight line trajectories during the time horizon $[t_s, t_d]$. In order to guarantee a desired minimum separation, say d_k, between trajectories, we introduce the intermediate waypoints $c_{i,k}$, $i = 1, \dots, n$, at time $\mathrm{t_c} \in [\mathrm{t_s}, \mathrm{t_d}]$ and consider resolution trajectories composed of two consecutive straight line legs from a_i to $c_{i,k}$ and from $c_{i,k}$ to b_i, each leg traveled at constant velocity. The intermediate waypoints $c_{i,k}$, $i = 1, \dots, n$ can be determined by solving the following SOCP (see Hu et al. (2002), Yang et al. (2017) for details):

$$\underset{\{c_{i,k}\}_{i=1}^{n}}{\text{minimize}} \sum_{i=1}^{n} \|c_{i,k} - \bar{c}_i\|^2 \tag{1}$$

$$\begin{aligned}
&\text{subject to:}\\
&c_{i,k} - c_{j,k} \in P_{ij}^{+}(d_k), && (2)\\
&\|c_{i,k} - a_i\| \le \bar{v}(t_c - t_s),\ \|c_{i,k} - b_i\| \le \bar{v}(t_d - t_c), && (3)\\
&\|c_{i,k} - p_{i,1}\| \le r_i,\ \|c_{i,k} - p_{i,2}\| \le r_i, && (4)\\
&1 \le i < j \le n,\ i = 1, \cdots, n.
\end{aligned}$$

By minimizing the quadratic cost function in (1) where $\bar{c}_i = \frac{(t_d - t_c)a_i + (t_c - t_s)b_i}{t_d - t_s}$, $i = 1, \dots, n$, is the intermediate waypoint position that would make the two-legs aligned on the same straight line, one actually minimizes the energy of the multi-aircraft joint maneuver. The linear constraint (2) serves the purpose of guaranteeing a minimum separation distance larger or equal to d_k for the aircraft pair (i, j), being $P_{ij}^{+}(d_k)$ a polytopic approximation of the admissible (conflict-free) region for $c_{i,k} - c_{j,k}$. Constraints on the velocities $v_{i,1} = \frac{\|c_i - a_i\|}{t_c - t_s}$ and $v_{i,2} = \frac{\|b_i - c_i\|}{t_d - t_c}$ for the first and second legs of each aircraft i are given by (3), $\bar{v}$ being the maximum admissible velocity. As it is easily seen in Fig. 1 (right plot), $v_{i,1}$ and $v_{i,2}$ satisfy by construction the condition $v_{i,1}(t_c - t_s) + v_{i,2}(t_d - t_c) \ge v_i(t_d - t_s)$, where $v_i = \frac{\|b_i - a_i\|}{t_d - t_s}$. This provides also a lower bound