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A Multi-Criteria Decision-Making Scheme $f_{\rm orb}$ Multi-Criteria Decision-Making Schem
for Multi Aircraft Conflict Resolution * Multi-Criteria Decision-Making Schen for Multi-Aircraft Conflict Resolution \star

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(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 α 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. Abstract: Multi-Aircraft Conflict Resolution (MACR) is a Multi-Criteria Decision-Making Abstract: Multi-Aircraft Conflict Resolution (MACR) is a Multi-Criteria Decision-Making $\frac{\Delta E}{\Delta E}$ absolution, which and incomponentially but the conflict $\frac{\Delta E}{\Delta E}$ and $\frac{\Delta E}{\Delta E}$ model is a model of the paper proposes a two-step μ CDM echomo to the solution of MACR. In the first stan, a second order, cono program is and α is computed to separate a set of candidate resolution strategies with different minimum separations ω scheme to the solution of ω condition of ω is the solution of ω in the criterial modeling ω adopted to generate a set of the stable later α in the second star the Technique for Order of Preference between trajectories. Each candidate strategy in the evaluate of the community of the criteria model is the criteria model in the strategy in the criteria model is used to determine the best strategy the interests of the stakeholders. In the second step, the Technique for Order of Preference \mathbf{S} incomposition (Topsidiate United Solution (Topsidiate incomposition) and \mathbf{S} approximate the best strategy of the proposed $t_{\rm{re}}$ realizations and additional α realization is an addition of α and α and α is a constant α is a constant α in α is a constant α in α is a constant α is a constant α is a constant $\frac{1}{2}$ incommensurability, since $\frac{1}{2}$ results are proposed to show the effect from the energy of the proposed to show the energy of the proposed to show the energy of the proposed to show the energy of the propose schemes of the minimum separations associated with the minimum separations associated with the best resolution according to the called the air that of the aircraft both differences.

© 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved. Keywords: Multi-Aircraft Conflict Resolution, Multi-Criteria Decision-Making, Aerospace,

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

1. INTRODUCTION 1. INTRODUCTION 1. INTRODUCTION

In order to meet the rapid growth of air traffic demand, In order to meet the rapid growth of air trains demand, enhanced technologies, such as satellite based navigation,
Automatic Dependent Surveillance-Broadcast (ADS-B), Automatic Dependent Surveillance-Broadcast (ADS-D),
digital communications, System Wide Information Mandigital communications, system wide information man-
agement (SWIM), are widely deployed in the Air Traffic agement (SWIM), are widely deployed in the Air Trainc
Control (ATC) system operation. This enables Collabo-Control (ATC) system operation. This enables Condition-
rative Decision Making (CDM) of multiple stakeholders, rative Decision Making (CDM) or inutriple 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 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 economic benefits, hence, their aim is to reduce the inghit cost by selecting the shortest trajectory from origin to fluit safety by selecting and shortest trajectory from origin to destination, an traint controllers are in charge of ensuring
flight safety by maintaining aircraft at some safe distance; ingin safety by maintaining arreat at some safe ustance,
and pilots onboard of the aircraft care more about flight and phots onboard of the afficial care more about fight
maneuverability in terms of flexibility available for hanmaneuverability in terms of nexibility available for nan-
dling safely emergency situations. Thus, ATC is a decisionding salely emergency situations. Thus, ATC is a decision-
making process that involved different, not directly commaking process that involved different, not diffectly com-
parable objectives, and it is hence necessary to develop solutions that realize a good tradeoff among them. enhanced to meet the rapid growth or all trainc demand, destination; air traffic controllers are in charge of ensuring parable objectives, and it is nence necessary to dependent solutions that realize a good tradeoff among them.A Multi-Criteria Decision-Making Scheme economic statistic, hence, their aim is to reduce the ingles making process that involved different, not different 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 orie ATC tasks (Kuchar and Yang (2000), Chaloulos et al. (2010)). As soon as a conflict, i.e., a violation of the pre- (2010) , As soon as a conflict, i.e., a violation of the prescribed imminum separation between arrerant, is detected,
aircraft trajectories have to be modified using horizontal ancraft trajectories have to be modified using norizontal
re-routing maneuvers, vertical ascending or descending re-routing maneuvers, vertical ascending or descending
maneuvers, or speed change strategies. These trajectory maneuvers, or speed change strategies. These trajectory
redesign process inevitably induces some deviation from redesign process mevidially maddes some deviation from
the original trajectories, thus typically resulting in increased flight distance and fuel consumption, and flight de-lay. The minimum cost strategy is the best choice from the lay. The minimum cost strategy is the best choice from the lay. The minimum cost strategy is the best choice from the i airlines perspective, whereas air traffic controllers look for an lines perspective, whereas an trainc controllers look for
a strategy that does not create any secondary conflicts and a strategy that does not create any secondary connects and
thus avoids the *domino effect*. As for the pilots onboard of the aircraft, they favor those resolution strategies that of the affectual, they flavor those resolution strategies that preserve some degree of flexibility so as to be able to handle fluid the occurrence of unpredicted stochastic events during the 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 In recent decades, many contributions on MACR have In recent decades, many contributions on MACR have In recent decades, many contributions on MACR have
appeared in the literature (see the surveys Kuchar and appeared in the interactive (see the surveys Kuchar and
Yang (2000), Chaloulos et al. (2010)). Approaches can be rang (2000), Chaloulos et al. (2010)). Approaches can be classified into three categories depending on the adopted stakeholder perspective: stakeholder perspective: classified into three categories depending on the adopted (1) Pioneering works in MacR and MACR aim at minimizing the minimizing t (2010) . As soon as a connect, i.e., a violation of the precreased flight distance and fuel consumption, and flight depreserve some degree of nexionity so as to be able to nandle mgm. MACR is nence a multi-Criteria Decision-Making (2010)) As soon as a conflict i.e. a violation of the preredesign process increasely induces some deviation from the original trajectories, thus typically resulting in increased flight distance and faith consumption, and flight deof the aircraft, they favor these resolution strategies that the occurrence of unpredicted stochastic events during the
flight. MACR is hence a Multi-Criteria Decision-Making $f(MCDM)$ problem with multiple stakeholders involved stakeholder perspective:

 (1) Pioneering works in MACR aim at minimizing the (1) Floreering works in MACK and at minimizing the
resolution strategy cost and hence are developed from the perspective of airlines. Specifically, the cost is defined as perspective of airlines. Specifically, the cost is defined as 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 $a_i, i = 1, \ldots, n$, to some destination waypoints $b_i, i =$ $1, \ldots, n$, 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 $c_{i,k}$, $i = 1, \ldots, n$, at time $t_c \in [t_s, t_d]$ 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 $c_{i,k}$, $i = 1, \ldots, n$ can be determined by solving the following SOCP (see Hu et al. (2002), Yang et al. (2017) for details):

minimize
$$
\sum_{\{c_{i,k}\}_{i=1}^{n}}^{n} ||c_{i,k} - \bar{c}_{i}||^2
$$
 (1)
subject to:

$$
c_{i,k} - c_{j,k} \in P_{ij}^+(d_k),\tag{2}
$$

$$
||c_{i,k} - a_i|| \le \bar{v}(t_c - t_s), ||c_{i,k} - b_i|| \le \bar{v}(t_d - t_c), \quad (3)
$$

$$
||c_{i,k} - p_{i,1}|| \le r_i, ||c_{i,k} - p_{i,2}|| \le r_i,
$$
\n(4)

$$
1 \leq i < j \leq n, \, i = 1, \cdots, n.
$$

By minimizing the quadratic cost function in (1) where $\bar{c}_i = \frac{(t_d - t_c)a_i + (t_c - t_s)b_i}{t_d - t_s}, i = 1, \ldots, n$, 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

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