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Multiobjective optimization for aircraft conflict resolution. A metaheuristic approach

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ABSTRACT

The conflict resolution problem in Air Traffic Management is tackled in this paper by using a mixed integer linear approximation to a Mixed Integer Nonlinear Optimization (MINO) model that we have presented elsewhere. The aim of the problem consists of providing a new aircraft configuration such that every conflict situation is avoided, a conflict being an event in which two or more aircraft violate the minimum safety distance that they must keep in flight. The initial information consists of the aircraft configuration in a certain time instant: position, velocity, heading angle and flight level. The proposed approach allows the aircraft to perform any of the three possible maneuvers: velocity, turn angle and flight level changes. The nonlinear model involves trigonometric functions which make it difficult to solve, in addition to the integer variables related to flight level changes, among other auxiliary variables. A multicriteria scheme based on Goal Programming is also presented. In order to provide a good solution in short computing time, a Sequential Mixed Integer Linear Optimization (SMILO) approach is proposed. A comparison between the results obtained by using the state-of-the-art MINO solver Minotaur and SMILO is performed to assess the solution's quality. Based on the computational results that we have obtained in a broad testbed we have experimented with, SMILO provides a very close solution to the one provided by Minotaur practically for all the instances. SMILO requires a very small computing time that makes the approach very suitable for helping to solve real-life operational situations.

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1. Introduction and problem description

In last years the interest on improving Air Traffic Management (ATM) has grown. One of the problems involved in ATM is the aircraft Conflict Detection and Resolution (CDR) which has been studied from different fields in mathematics and engineering. Given a set of aircraft configurations, the aim of the problem consists of providing a new 4D trajectory for each aircraft involved in such a way that every conflict situation is avoided. We consider in this paper the short term in which an answer in 2–5 minutes is needed and, so, given the shortness of the time horizon, an air sector is enough to be taken into account. A conflict is understood as an event in which two or more aircraft violate the minimum safety distances that must be kept in flight. These distances are decomposed in horizontal (5 nautical miles) and vertical (generally 2000 feet) ones; however, International Civil Aviation Organization (ICAO) proposes 1000 feet in the Reduced Vertical Separation Minimum (RSVM) program (see International Civil Aviation Organization, 2015). It produces a cylindrical safety region around each aircraft with radius 2.5 nautical miles and height 2000 feet (1000 feet if RSVM is applied) where the aircraft is located in its center. Three different maneuvers may be taken into account: velocity (VC), angle turn (TC) and altitude flight level (hereafter, altitude) (AC) changes. The objective is to minimize the impact of the conflict resolution and this issue can be studied from different points of view, namely economic and comfort terms, among others. This issue makes the problem interesting to be studied from a multicriteria point of view. Jointly with our work (Alonso-Ayuso, Escudero, & Martín-Campo, 2015), as we know, it is the first time that multicriteria methods are applied to the problem.

We refer to Kuchar and Yang (2000) and Martín-Campo (2012) for literature reviews up to 2000 and 2012, respectively, on mathematical optimization approaches for the CDR problem. Recently, due to a fast answer needed to avoid conflict situations in real-life instances, some heuristic schemes have been studied. Most of metaheuristic algorithms for CDR are based on evolutionary and genetic computation, such as Ant Colony optimization, see Durand and Alliot (2009), Meng and Qi (2012) for TC maneuvers; Genetic algorithms,

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see Durand (1996) also for TC; Particle Swarm optimization, see Gao, Zhang, and Guan (2012) for TC; Variable Neighborhood Search (VNS), see Alonso-Ayuso, Escudero, Martín-Campo, and Mladenović (2014c) for TC; Hybrid methods, see Omer and Farges (2013); Linear approximations by using iteratively Taylor polynomials, see Alonso-Ayuso, Escudero, and Martín-Campo (2012); Sequential Integer Linear Optimization (SILO), see Alonso-Ayuso, Escudero, and Martín-Campo (2014a) for TC; and Neural Networks, see Durand and Alliot (2000), Christodoulou and Kontogeorgou (2008), Cetek (2009) for VC; among others. Those methods are efficient in computing time terms, but the global optimal solution and even a feasible one (i.e., a solution with no conflict situations) are not guaranteed to be achieved.

In this paper we propose a metaheuristic based on iteratively solving a Mixed Integer Linear Optimization (MILO) model as an approximating scheme for solving the Mixed Integer Nonlinear Optimization (MINO) model that we have presented elsewhere, see Alonso-Ayuso et al. (2015). The main idea lies on discretizing the feasible range of the angle of motion such that the trigonometric functions in the original model are converted to fixed parameters and, so, jointly with the addition of new binary variables, the resulting model becomes linear. The iterative approach reduces the bounds of the angle variations until a stopping criterion is satisfied.

Different maneuver-driven objectives are dealt with by using Goal Programming (GP) with a lexicographical ordering, see good surveys in Ignizio (1985), Romero (1991), among others. This type of multicriteria schemes needs to solve some optimization models by including constraints in which the maneuver changes are not allowed to be exceeded by a given aspiration level.

The CDR problem can be solved for three different time terms: Long Term, Medium Term and Short Term, whose lookahead times for an answer are 20–60 minutes, 5–20 minutes and 2–5 minutes. Our approach is located in the latter, that is the one that requires the intervention from the ATCo (see Shakarian & Haraldsdottir, 2001). So, the aim of our approach is to provide solutions in almost real-time.

The main contributions of this paper are as follows: (1) Introducing a Sequential Mixed Integer Linear Optimization (SMILO) approach able to solve the problem in short computing time providing a good feasible solution, by allowing the aircraft to perform the three possible maneuvers: VC, TC and AC, which is known as Velocity, angle Turn and Altitude Changes (VTAC); (2) a scheme for replacing quadratic terms that involve continuous and binary variables with a strong set of constraints by using the structure of the MILO models to be solved in the SMILO approach; (3) the minimization of the cost of the maneuvers is based on a GP scheme within a multi-objective framework and, so, for each of its steps model MINO is solved either by a MINO engine or by the SMILO approach; and (4) a broad computational experience is reported to assess the validity of the approximating VTAC–SMILO approach in terms of solution's quality and required computing time. Additionally, a computational comparison is performed on the solution's quality and required computing time to solve model VTAC–MINO by using the state-of-the-art MINO solver Minotaur (Leyffer, Linderoth, Luedtke, Mahajan, & Munson, 2011) and the SMILO approach by using the state-of-the-art MILO solver Cplex (2014).

The rest of the paper is organized as follows: Section 2 is devoted to the geometric construction presented in Pallottino, Feron, and Bicchi (2002) which supports model VTAC-MINO. Section 3 introduces the SMILO approach by linearizing the VTAC nonlinear constraints in order to have a model able to be iteratively solved by using a MILO solver. Section 4 is devoted to the multicriteria GP-based approach proposed to solve the CDR problem. Section 5 reports a broad computational experience; and, finally, Section 6 concludes and outlines the main lines of future research.

2. Preliminaries

The SMILO approach (for short, SMILO) that is proposed for solving the VTAC problem is based on the MINO model presented in Alonso-Ayuso et al. (2015) and whose constraint system is briefly given in Appendix. It is based on the geometric construction presented in Pallottino et al. (2002), that itself was improved in our work (Alonso-Ayuso, Escudero, & Martín-Campo, 2011), where some unsolved cases were taken into account, see below. SMILO allows to detect if a conflict situation occurs involving any pair of aircraft, and they resolve the conflicts by using the VTAC maneuvers that are allowed.

A geometric construction for detecting conflict situations is studied in Pallottino et al. (2002), see Fig. 1. Let $\vec{v}_i$ and $\vec{v}_j$ denote the velocity vectors of aircraft i and j, respectively. The main idea lies on the construction of the relative velocity vector $\vec{v}_i - \vec{v}_j$. The two parallel straight lines to the relative velocity vector depicted in the figure with respect to the safety circle of aircraft j define a region where the intersection with the trajectory of aircraft i is a segment so-named the 'shadow segment'. Notice that if the intersection of that segment with the safety circle of aircraft i is empty, then there is no potential conflict situation between the two aircraft. Otherwise, the conflict should be resolved. Assume that ω_{ij} and α_{ij} denote the arctan $(\frac{y_i-y_j}{x_i-x_j})$ and arcsin $(\frac{(r_i+r_j)/2}{d_{ij}/2})$, respectively, where x_i and y_i are the abscissa and ordinate (in a cartesian coordinates system) of the current position of aircraft i, respectively, r_i is the safety radius of aircraft i, and d_{ij} is the Euclidean distance between aircraft i and j. Depending on the tangent of angles $l_{ij} = \omega_{ij} + \alpha_{ij}$ and $g_{ij} = \omega_{ij} - \alpha_{ij}$, a conflict situation can be detected.

The α-angles can be calculated based on the symmetry in the geometric construction if the two safety radii are the same. Considering different safety radii constitute a good approximation to the realistic problem since each aircraft has a different configuration, depending on the aircraft weight, the aerodynamic configuration and the aircraft size. If two different aircraft radii are considered, the two interior straight line slopes have to be computed. The expression for the α-angle can be represented by using an arctangent of the slope as,

$$\alpha_{ij} = \arctan \frac{r_i + r_j}{\sqrt{d_{ij}^2 - (r_i + r_j)^2}},$$

see Appendix A.2 in Martín-Campo (2012). Notice that d_{ij}^2 must be greater than $(r_i + r_j)^2$. If this condition is not satisfied, the two aircraft are violating the minimum safety horizontal distance. For considering that situation, 0–1 variable δ_{ijz}^5 is taken into account in model VTAC–MILO (see below), allowing both aircraft to fly at different altitude levels.

In the geometric construction the notation is based on vectors, but they can be decomposed into the two components, abscissa and ordinate, in the mathematical model. Therefore, no potential conflict occurs between aircraft i and j if any of the following expressions is satisfied,

$$\frac{(v_i + \nu_i)\sin(m_i + \mu_i) - (v_j + \nu_j)\sin(m_j + \mu_j)}{(v_i + \nu_i)\cos(m_i + \mu_i) - (v_j + \nu_j)\cos(m_j + \mu_j)} \geqslant \tan(l_{ij}) \quad (1a)$$

$$\frac{(v_i + \nu_i)\sin(m_i + \mu_i) - (v_j + \nu_j)\sin(m_j + \mu_j)}{(v_i + \nu_i)\cos(m_i + \mu_i) - (v_j + \nu_j)\cos(m_j + \mu_j)} \leqslant \tan(g_{ij}), \quad (1b)$$

where m_i is the current direction of motion, μ_i is the angle change and ν_i is the velocity change to be obtained, such that now the new angles of motion $m_i + \mu_i$ and $m_j + \mu_j$ and the new velocities $v_i + \nu_i$ and $v_j + \nu_j$ avoid the conflict between the aircraft i and j. Depending on the sign of the denominators of expressions (1), two cases must be taken into account for each situation represented by (1), so, four different blocks of constraints in total for each pair of aircraft must

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