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Optimal air route flight conflict resolution based on receding horizon control

Tang Xin-Min [a,b,*], Chen Ping [b], Li Bo [a]

[a] Civil Aviation College of Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China
[b] The 28th Research Institute of China Electronic Technology Group Corporation, Nanjing, 210007, China

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ABSTRACT

To deal with the air route flight conflicts caused by abnormal situations during four-dimensional based air traffic operation, the air route flight conflict resolution problem for two aircrafts was addressed. Based on the optimized static single heading angle or ground speed adjustment strategy, we proposed an optimized dynamic mixed conflict resolution strategy based on Receding Horizon Control (RHC), which considered the possibility of one aircraft's ground speed variation. In particular, the wind speed vector disturbance during conflict resolution might lead to a model mismatch, so the maximum likelihood estimation method and the Newton–Raphson iterative algorithm were employed to identify the wind speed vector using the aircraft true airspeed inputs and ground based trajectory measurements. Moreover, we considered the convergence of conflict resolution method based on RHC and proposed the pre-condition that local and global optimization resolution can be achieved. We compared three situations, i.e., static single strategy optimization, dynamic mixed strategy optimization using RHC with one aircraft's ground speed variation, and dynamic mixed strategy optimization using RHC with the wind speed vector disturbance. We demonstrated that the dynamic mixed strategy responds to one aircraft's ground speed disturbance quickly, and resolved conflict by track angle and ground speed adjustments in an effective manner after the wind speed vector being identified accurately.

1. Introduction

Four-dimensional (4D) trajectory operation is an effective strategy for reducing aircraft spacing to facilitate the implementation of high density airspace in the future. Both Next Generation Air Transportation System (NGATS) and Single European Sky Air traffic Management Research (SESAR) employ 4D trajectory based air traffic operation as the core mechanism. However, even if aircraft are equipped with conflict-free 4D trajectories before flight, it is inevitable that they will fail to execute exact the conflict-free 4D trajectories due to disturbances caused by meteorological conditions or various types of emergencies. Therefore, it is necessary to conduct real-time conflict detection and optimal conflict resolution to avoid flight conflict, thereby ensuring the safety and smooth of air traffic operation.

The most recent studies on conflict resolution can be categorized into four areas. First, according to the type of decision maker, they can be divided into centralized or distributed decision making, where the former focuses mainly on the conflict resolution for multiple aircraft from the perspective of ground air traffic control system [1], whereas the latter focuses on conflict resolution from the perspective of the onboard aircraft [2,3]. Furthermore, from the perspective of constraints on of trajectory resolution, these approaches can be divided into free flight and air route flight conditions, where the former only considers aircraft performance constraints, so airspace and air route constraints are not considered [4,5], whereas the latter considers both types of constraints together [6,7]. In addition, depending on the optimization model and method employed, these approaches can be divided into continuous optimization and mixed methods. Continuous optimization methods plan an optimal flight trajectory to facilitate conflict avoidance based on optimal control theory [8,9]. The hybrid optimization method requires optimization of two areas, i.e., the discrete decision variables and the continuous resolution variables [10–15]. Finally, the process of conflict resolution optimization can be divided into static and dynamic optimization, where the former only provides a constant and feasible resolution strategy [16], whereas the latter requires the real-time computation of resolution strategy according to the state of the aircraft until the conflict is resolved [17]. In the expectable future, air traffic

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[*] Corresponding author at: Civil Aviation College of Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China. Tel.: +8613813952160.
E-mail address: tangxinmin@nuaa.edu.cn (X.-M. Tang).

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Nomenclature

v_{TAS}	true airspeed
v_{GS}	ground speed
φ	heading angle
θ	track angle
ω	drift angle
x	horizontal coordination in the ground inertial reference frame
y	vertical coordination in the ground inertial reference frame
z	flight level of aircraft
$\boldsymbol{x}$	position of aircraft
$\boldsymbol{x}_r$	relative orientation vector of aircraft b to aircraft a
$d_{\min}$	minimal horizontal separation of two aircrafts
$\dot{\boldsymbol{x}}$	ground speed vector
$\dot{x}$	horizontal component of ground speed
$\dot{y}$	vertical component of ground speed
α	crossing angle between the relative speed vector and the motion direction of aircraft a
β	crossing angle between the relative orientation vector and the motion direction of aircraft a
$\Delta\theta_b$	track angle adjustment of aircraft b
$\Delta v_{\mathrm{GS},b}$	ground speed adjustment of aircraft b
$\Delta v^*_{\mathrm{GS},b}$	the optimal ground speed adjustment of aircraft b
$\Delta\theta^*_b$	the optimal track angle adjustment of aircraft b
a_b	acceleration of aircraft b
$\Delta\Gamma$	receding horizon
$\boldsymbol{w}$	wind speed vector
w_1	the first component of wind speed vector
w_2	the second component of wind speed vector
$\Delta\boldsymbol{w}(p_i)$	wind speed forecast error at p_i
$\hat{\boldsymbol{w}}$	maximum likelihood estimation of the wind speed vector
$\boldsymbol{e}_w$	identification error of wind speed vector
$r(p_i, p_j)$	covariance of wind speed error between p_i and p_j
$\boldsymbol{z}_b(k)$	discrete trajectory measurement vector
$\hat{\boldsymbol{z}}_b(k)$	discrete trajectory measurement vector after smoothing
$\Delta\tau$	sampling interval of aircraft position
$\boldsymbol{\lambda}$	position measurement error of aircraft b
$\boldsymbol{R}$	covariance matrix of position measurement error
$\varphi^*_b(k)$	the optimal aircraft heading angle of aircraft b
$v^*_{\mathrm{TAS},b}(k)$	the optimal aircraft true airspeed of aircraft b

operations will still only be allowed on the fix air route, where the aircraft state is still obtained by discrete sampling mechanism such as secondary surveillance radar (SSR) or automatic dependent surveillance-broadcast (ADS-B), while air traffic management will still employ a ground based centralized control automation system. Therefore, centralized and dynamic conflict resolution for a fix air route seems to be more beneficial for the future air traffic management.

In related research into dynamic ground conflict resolution includes, Bousson proposed a conflict resolution method based on model predictive control (MPC), which allows the real-time computation of speed and heading for each aircraft to generated conflict-free trajectories along the predetermined waypoint [18]. Roussos et al. studied collision avoidance under wind uncertainty using MPC and decentralized navigation functions [19]. Chaloulos et al. proposed a hierarchical control structure for air traffic management, which allows medium-term conflict resolution using MPC when combined with aircraft dynamics constraints [20]. Rey proposed a receding horizon loop to deal with the uncertainty on aircraft positions, and a Mixed Integer Linear Program problem was then solved for all the potential conflicts detected within the time windows [21]. Peyronne presented a practical method to solve tactical conflicts and model trajectories to avoid conflicts with B-splines on the considered time horizon [22]. These studies assumed that the wind field could be acquired from meteorological forecast, however, the performance of conflict resolution is clearly affected by the wind field uncertainty. Thus, Mondoloni developed a statistical model of wind prediction uncertainty and analyzed the impact of wind prediction uncertainty on the accuracy of aircraft trajectory prediction [23]. Chaloulos et al. proposed a correlation model for simulating the difference between the actual wind and the meteorological wind forecasts to analyze the impact of wind correction on the probability of conflicts [24]. Matsuno et al. proposed a stochastic optimal control method for determining three-dimensional conflict-free aircraft trajectories under wind uncertainty [25]. Delahaye et al. proposed a wind estimation method using a Kalman filter based on radar tracking provided that onboard true airspeed measures are available, but the observability analysis showed that wind could be estimated only if the trajectories included one or two turns in a given area [26].

According to these studies on dynamic ground conflict resolution method, the wind speed vector variation during conflict resolution might lead to mismatch of predictive model, and estimating the actual wind speed vector in the area of conflict is an issue that affects performance of dynamic conflict resolution. In addition, whether one can get some theoretical guarantees on the convergence haven't been considered yet, and local optimization within a short time horizon may result in failure of resolving potential and global conflicts. In this work, we employed parameter identification to estimate the wind speed vector using the aircraft true airspeed input and ground based trajectory measurements to avoid the failure of conflict resolution caused by wind uncertainty on the accuracy of aircraft trajectory during dynamic conflict resolution. Moreover, we considered the convergence of conflict resolution method based on receding horizon optimization and proposed the pre-condition that the local and global optimization resolution can be achieved.

The remainder of this paper is organized as follows. In Section 2, we describe a horizontal flight conflict detection model based on relative motion before discussing a static single optimal resolution strategy. In Section 3, we propose an optimal dynamic mixed conflict resolution strategy based on receding horizon control (RHC) and a real-time parameter identification method is used to identify wind speed vector, we considered the convergence of conflict resolution method based on RHC and proposed the pre-condition that local and global optimization resolution can be achieved. In Section 4, we consider some cases to verify the performance of conflict resolution based on RHC with an uncertain wind speed vector.

2. Static conflict resolution strategy without disturbance

2.1. Aircraft conflict detection model

In this study, we focus mainly on conflict resolution, so the aircraft can be treated as a mass point and its attitude can be neglected. Let true airspeed and ground speed be v_{TAS} and v_{GS}, respectively, and let heading angle and track angle be φ and θ respectively, if drift angle is small enough and can be ignored, then