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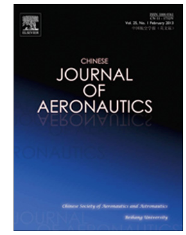

A multi-aircraft conflict detection and resolution method for 4-dimensional trajectory-based operation

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Abstract Conflict Detection and Resolution (CD&R) is the key to ensure aviation safety based on Trajectory Prediction (TP). Uncertainties that affect aircraft motions cause difficulty in an accurate prediction of the trajectory, especially in the context of four-dimensional (4D) Trajectory-Based Operation (4DTBO), which brings the uncertainty of pilot intent. This study draws on the idea of time geography, and turns the research focus of CD&R from TP to an analysis of the aircraft reachable space constrained by 4D waypoint constraints. The concepts of space–time reachability of aircraft and space–time potential conflict space are proposed. A novel pre-CD&R scheme for multiple aircraft is established. A key advantage of the scheme is that the uncertainty of pilot intent is accounted for via a Space-Time Prism (STP) for aircraft. Conflict detection is performed by verifying whether the STPs of aircraft intersect or not, and conflict resolution is performed by planning a conflict-free space–time trajectory avoiding intersection. Numerical examples are presented to validate the efficiency of the proposed scheme.

1. Introduction

For a long time, the description and definition of aircraft trajectory have been three-Dimensional (3D). The importance of time dimension has been explored in recent decades. In the 1980s, the United States Federal Aviation Administration proposed the concept of a National Airspace System to address the rapid growth of air traffic, in which the idea of four-Dimensional (4D) navigation and guidance of aircraft was proposed. The concept of 4D Trajectory-Based Operation (4DTBO) has gradually become a reality with the development of navigation and communication techniques.[1] 4D trajectory refers to a sequence of waypoints that consist of 3D coordinates and reliable and reachable timestamps at which a flight reaches these points. In the context of 4DTBO, an aircraft can be controlled by arranging the specific time (Controlled/Constrained Time of Arrival, CTA) of a sequence of waypoints.

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Conventional Conflict Detection and Resolution (CD&R) is based on aircraft rather than trajectory. The process of CD&R follows the steps of trajectory prediction (TP)-conflict detection-conflict resolution.[2] Geometric deterministic algorithm[3,4] has been the mainstream at the beginning of the CD&R study. Specifically, during a flight, an air traffic controller needs to monitor the flow of the sector and the location of the aircraft. Firstly, a predicted trajectory is generated using a deterministic TP method according to the position, current state, and flight plan of the aircraft. Then, the air traffic control center determines the conflict by comparing the distance between the aircraft and the safety separation criterion based on the predicted trajectory. The air traffic controller needs to conduct interventions on the aircraft with a distance less than the minimum safety separation. Conflict resolution aims to generate a conflict-free trajectory after the potential conflict is determined. Correspondingly, many deterministic methods have been studied to generate conflict resolution trajectory for interventions. The Dijkstra algorithm and the A^* algorithm[5] need to build a model of environment before path searching, whereas methods such as the artificial field method[6] and the rapid random tree method[7,8] do not need a model of environment. Conflict resolution can also be solved as an optimal control problem or a convex optimization issue.[9–11]

With the increasing depth of the research, people are increasingly aware that uncertainties, such as wind gust, navigational error, and aircraft intent, are pervasive in current air traffic systems and have significant effects on the accuracy of TP.[12] A probabilistic method models uncertainties to describe potential variations by developing all possible future trajectories using a probability density function.[13–19] One approach is to predict the future position of an aircraft by using a stochastic model of the aircraft dynamics. Prandini et al.[14] used a stochastic kinematic model with uncertainties represented by a 2D Brownian motion. This approach does not require knowledge of the aircraft intent. However, the prediction error tends to increase quadratically with time. Moreover, this approach may be less accurate when a trajectory has maneuvers. Providing additional intent information may help reduce some of these uncertainties. An alternative approach is to add a position error to a nominal trajectory.[20–23] Based on the flight plan, aircraft dynamics, and wind data, some studies[14,24,25] computed a nominal aircraft trajectory by modeling aircraft dynamics using the stochastic linear hybrid system, in which the aircraft state vector is a continuous state and the aircraft flight model is a discrete state, and then a position uncertainty (or covariance) was added to the computed trajectory. This approach requires good knowledge of aircraft intents.

Correspondingly, trajectory planning has used many probabilistic methods, including probability map methods and intelligent methods, such as the genetic algorithm, particle swarm optimization, the neural network method, the simulated annealing method, ant colony optimization, the bee colony algorithm, and the memetic algorithm.[26–32] The aforementioned studies mostly treated an uncertainty as an open-loop problem in which an aircraft operates independently and controllers do not interfere with flight paths.

However, aircraft intent information could dynamically change over time in the context of 4DTBO, which allows an aircraft the flexibility of changing flight routes (or flight plans) in response to changing conditions, that is, theoretically, the aircraft can freely plan its trajectory while ensuring that the time constraints of waypoints are reached.[33] Although free does not refer to an absolute, no-constraint condition, the uncertainty of trajectory and the difficulty in TP are increased. Thus, the aircraft intent is difficult to describe with an accurate model, which presents a big challenge for CD&R.[34]

The new context of 4DTBO emphasizes the importance of time dimension, offering new perspectives in solving CD&R. Due to the difficulties in travel path prediction caused by the uncertainties of an individual purpose, Hagerstrand[35] originally transferred the study focus of individual travel path analysis from prediction of the individual purpose to analysis of the space–time range of individuals constrained by the environment, and proposed the concept of time geography. The time-geographical framework focuses on the behavioral possibilities of individuals.

Similarly, uncertainties caused by pilot intent increase difficulties in TP. Therefore, based on the theory of time geography, the study focus of aircraft conflict avoidance can be transferred from prediction of the flight trajectory of the aircraft to analysis of the influence of the 4D waypoint constraints on the space–time reachability of the aircraft activity. A novel pre-CD&R scheme based on the key elements of time geography, space–time path, and space–time prism is proposed.

In the proposed novel pre-CD&R scheme, the entire 4D trajectory of the aircraft is divided into a few route segments by a sequence of waypoints with CTAs. The CTAs must be satisfied during the entire travel lifecycle to ensure the safety of the overall air transport system. The process of an ordinary CD&R scheme TP – conflict detection – conflict resolution trajectory planning is transformed into potential path space calculation – space–time potential conflict space detection – conflict-free space–time trajectory planning in the novel pre-CD&R scheme. The flight support management system is designed to add a module that calculates the space–time reachability of each aircraft on each route segment between two waypoints in advance. The quantification of space–time reachability and Space-Time Potential Conflict Space (STPCS) offers an intuitive sight on the environment and surrounding aircraft states for the pilot and an optimal conflict-free trajectory as reference for pilots or air traffic controllers. The potential conflict probability is expected to decrease significantly. In addition, the application of the proposed pre-CD&R scheme is expected to help reduce the workloads of air traffic controllers because the responsibility of conflict resolution trajectory planning is delegated to an individual aircraft.

The rest of this paper is organized as follows. Section 2 presents the design architecture and process of the proposed pre-CD&R scheme, and elaborates the method for Space-Time Prism (STP) calculation and conflict detection by developing a case. Section 2.1 describes the developed case and assumptions. Section 2.2 demonstrates the application of space–time path in describing the flight plan. Section 2.3 shows how the airspace is discretized for further calculation. Section 2.4 describes the measurement theory for space–time reachability for aircraft and the calculation of space–time prism for aircraft. Section 2.5 introduces the method of conflict detection under the proposed pre-CD&R scheme. Section 3 elaborates the process of conflict-free Space-Time Trajectory (STT) planning using the Ant Colony Optimization (ACO) algorithm. Simulation is conducted and numerical results are analyzed