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Probabilistic multi-aircraft conflict detection approach for trajectory-based operation

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ABSTRACT

Conflict detection (CD) is one of the key functions used to ensure air transport safety and efficiency. In trajectory-based operation (TBO), aircraft are provided with more flexibility in en route trajectory planning and more responsibility for self-separation. The high flexibility in trajectory planning enables random changes in pilot intent, thus increasing the uncertainty in trajectory prediction and CD. This study proposes a novel probabilistic CD approach for TBO in which the uncertainty of pilot intent is taken into account by quantifying the aircraft reachable domain constrained by the flight plan. First, a probabilistic model for aircraft trajectory prediction is developed using the truncated Brownian bridge method. Based on this model, a novel conflict probability estimation method is developed. Finally, the performance of the proposed probabilistic CD approach is demonstrated through an illustrative air traffic scenario.

1. Introduction

Conflict detection (CD) is the key function of the future Air Transport Management (ATM)[1] system envisioned by the Next Generation Air Transportation System (NextGen).[2] CD determines whether two aircraft would violate the safe separation criteria during the look-ahead period based on the predicted aircraft trajectory. This trajectory can be predicted based on the aircraft's current and historical trajectories, flight plan or intention, wind and other external environmental and regulatory information. Presently, CD is conducted by an air traffic controller, and pilots are required to follow the specific instructions of the air traffic controller.

Aircraft trajectory prediction has been studied using deterministic models in which the aircraft is assumed to fly straight toward the target waypoint, and the future geographical location of the aircraft is predicted based on an aircraft dynamic model. Building on this approach, probabilistic trajectory predictions improve the prediction accuracy by considering the uncertainties caused by tracking, navigation, and positioning errors (Paielli and Erzberger, 1997). The classical aircraft position prediction model assumes that aircraft heading and lateral position prediction errors follow a Gaussian distribution with zero mean (Kuchar and Yang, 2000; Yepes et al., 2007). Variance in the aircraft heading position prediction error increases linearly with time, and variance in the lateral position prediction error is a constant value and does not increase over time (Paielli et al., 2009). Additionally, an aircraft position

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[1] Air traffic management (ATM) encompasses all systems that assist the aircraft from departure to landing, including air traffic services, airspace management, and air traffic flow and capacity management.

[2] NextGen is the modernization of national air transportation systems aiming to increase aviation safety, efficiency, capacity, and predictability.

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prediction model based on stochastic differential equations has been constructed in which the disturbance of the external environment on aircraft velocity is considered to follow a Gaussian distribution (Seah and Hwang, 2009; Matsuno et al., 2015). The position vector is determined by the flight velocity vector and a Gaussian white noise disturbance. Further studies involved the consideration of aircraft position predictions as random linear hybrid systems in which the aircraft state vector is in a continuous state and the airplane flight mode is in a discrete state (Soler et al., 2016; Yang et al., 2017). The airplane flight mode is a flight process that can be described by an aircraft kinematics model, such as a uniform linear motion flight mode. Recently, wind uncertainty propagation and intent uncertainty has appealing to researcher's interest (Hernández et al., 2016; Kim and Hwang, 2018). Besides, intelligent algorithm has shown great potential in trajectory prediction, and conflict avoidance process (Sathyan et al., 2017; Pritchett and Genton, 2018).

However, the ATM in NextGen is converted from aircraft-based operation to trajectory-based operation (TBO) (Ruiz et al., 2013). The implementation of TBO is an important step toward the realization of free flight, in which an aircraft is provided the freedom to follow a continuously changing optimum trajectory (Alam et al., 2009; Devika and Thomas, 2017). In addition, the pilots are responsible for the separation assurance task rather than the air traffic controller (Guo et al., 2011; Yokoyama, 2018). The controllers devote considerable time to surveillance rather than adjusting the aircraft state unless interference is extremely necessary (Alam et al., 2009; Hwang and Seah, 2008; Lim and Zhong, 2018). Compared with the case of free flight, TBO constrains the waypoints' locations and corresponding times to pass through them; in other words, the pilots can freely plan their trajectory as long as the constrained time of arrival (CTA) of each waypoint is assured (Ruiz et al., 2014; Zúñiga et al., 2013).

In TBO, pilot intent may change randomly over time during the flight because the aircraft may need to avoid adverse weather areas or restricted airspace, attain conflict resolution with other aircraft, or meet the flexibility requested by air carriers (Yokoyama, 2018). The high flexibility in trajectory planning provided by TBO produces the problem of pilot intent uncertainty and increases the difficulties for aircraft trajectory prediction and CD. Hence, the emerging uncertainties caused by pilot intent must be addressed.

Inspired by the concept of time geography, our study proposes a novel probabilistic CD approach to fix the pilot intent uncertainties in CD. Instead of directly modeling the uncertainties caused by pilot intent and navigation, tracking, and positioning errors, the proposed CD approach attempts to analyze aircraft trajectory predictions under pilot intent uncertainty through the study of the spatial and temporal reachable domain of the aircraft limited by the flight plan; in addition, a Brownian bridge movement model is developed for estimating the expected trajectory of the aircraft. Based on the predicted aircraft trajectory, the conflict probability for aircraft pairs and multiple aircraft can be estimated. The proposed method can quantify the conflict probability without modeling the intricacies of the pilot intent and thus is of great significance for aircraft CD in the NextGen context.

The remainder of this paper is organized as follows. Section 2 describes the framework of the probabilistic CD approach. Section 3 introduces the theoretical basis of the time geography method and the description of the aircraft reachable domain by a space-time prism (STP). Section 4 describes the development of the probabilistic model for aircraft trajectory prediction using the truncated Brownian bridge method. Section 5 addresses the conflict identification and conflict probability estimation method for aircraft pairs and multiple aircraft. Section 6 illustrates the model application and discusses the results. Section 7 concludes the paper and describes the contributions of this work and directions for future studies.

2. Framework of the probabilistic conflict detection approach

In TBO, the aircraft is allowed to perform certain air management operations, including CD, conflict resolution and self-separation. These operations are enabled by an automated support system (Hoekstra et al., 2002; Paielli et al., 2009). To provide a quantitative basis for decision-making by the air traffic control (ATC)[3] center and aircraft crew, a novel probabilistic CD approach is designed in which the uncertainties caused by pilot intent are considered. The proposed probabilistic CD approach is designed to identify the location and occurrence of conflicts and quantify the conflict probability. This approach includes the following steps (Fig. 1).

First, the reachable domain of each aircraft at each instantaneous time is described based on the information extracted from the flight plan, including the waypoints of the subsequent route segment, aircraft type and environmental information. The continuous variation of the spatially reachable domain over time can be described using a STP. Additionally, conflict location and occurrence are determined by identifying the STP intersection of each aircraft pair.

Second, for each moment, the position prediction probability of each aircraft within the reachable domain is calculated. The position prediction probability is unevenly distributed within the reachable domain. Therefore, we use the truncated Brownian bridge method to model the position prediction probability distribution with reachable domain constraints (described in Section 3.2).

Third, the conflict probabilities for aircraft pairs and multiple aircraft are estimated based on the results for conflict identification and position prediction probability.

The proposed probabilistic CD approach is based on the following assumptions.

- Pilots strictly implement the flight plan.
- The initial flight plan is feasible, meaning that the distance between the waypoints is smaller than the product of the maximum velocity and the time limit between the waypoints.
- The study focuses on cruising phase, in which aircraft rarely change their altitude in consideration of passenger comfort.

[3] Air traffic control (ATC) is a service provided by ground-based controllers. The primary purpose of ATC is to prevent collisions, organize the air traffic flow, and provide support for pilots.