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Coordinated multi-aircraft 4D trajectories planning considering buffer safety distance and fuel consumption optimization via pure-strategy game

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ABSTRACT

In this paper, we consider a coordinated multi-aircraft 4D (3D space plus time) trajectories planning problem which is illustrated by planning 4D trajectories for aircraft traversing an Air Traffic Control (ATC) sector. The planned 4D trajectories need to specify each aircraft's position at any time, ensuring conflict-free and reducing fuel and delay costs, with possible aircraft maneuvers such as speed adjustment and flight level change. Different from most existing literature, the impact of buffer safety distance is also under consideration, and conflict-free is guaranteed at any given time (not only at discrete time instances). The problem is formulated as a pure-strategy game with aircraft as players and all possible 4D trajectories as strategies. An efficient maximum improvement distributed algorithm is developed to find equilibrium at which every aircraft cannot unilaterally improve further, without enumerating all possible 4D trajectories in advance. Proof of existence of the equilibrium and convergence of the algorithm are given. A case study based on real air traffic data shows that the algorithm is able to solve 4D trajectories for online application with estimated 16.7% reduction in monetary costs, and allocate abundant buffer safety distance at minimum separation point. Scalability of the algorithm is verified by computational experiments.

1. Introduction

Each day, thousands of aircraft are flying in the sky. Air Traffic Management (ATM) system is a system that coordinates traveling aircraft to ensure safety and enhance efficiency. In the current ATM system, airspace is divided into sectors. A team of air traffic controllers is assigned to be in charge of each sector. After take-off, an aircraft flies along airways traversing sectors one after another, according to its flight plan, under the direction of air traffic controllers responsible for each sector, until its destination airport is approached.

With the development of global economy, air traffic volume is undergoing a rapid growth, particularly in emerging-market countries. The International Civil Aviation Organization (ICAO) estimates that air traffic in the Asia Pacific region will triple by 2030 (ICAO, 2012). The rapid growth of air traffic volume is placing huge challenges on the current clearance-based ATM system. To address such imminent challenges, both United States and Europe initiate research and development

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programs, namely the Next Generation Air Transportation System (NextGen) (FAA, 2013) and the Single European Sky ATM Research (SESAR) (EUROCONTROL, 2015), for the future ATM system. Both the two programs envision 4D-trajectory-Based Operation (4D-TBO), in which 4D (3D space plus time) trajectories are calculated and followed using advanced navigation technologies. Aircraft will fly negotiated trajectories and air traffic control (ATC) moves to trajectory management (FAA, 2013). Air traffic controllers will direct aircraft not only based on their current positions and speeds, but their future intended 4D trajectories as well.

Before an aircraft enters a sector, its airborne Flight Management System (FMS) will calculate and submit its preferred estimated 4D trajectory traversing the sector (FAA, 2016). Since the trajectories are planned individually and independently, they may cause conflict or congestion, which leads to high systemwise cost. The ATM system, or air traffic controllers, needs to coordinate among the received 4D trajectories, carrying out necessary modifications or even re-planning, to ensure the safety of air traffic and improve its efficiency, with the help of decision support tools.

In this paper, we consider a multi-aircraft 4D trajectories planning problem in the en-route phase, and aim at providing a tool for air traffic controllers to change/re-plan trajectories for each individual aircraft traversing a sector that contains a 3D network of airways and waypoints. Given required entry and exit waypoints, expected entry time windows and exit times of aircraft, our proposed algorithm framework coordinates among aircraft's preferred 4D trajectories and compute final 4D trajectories which ensure conflict-free, and reduce overall fuel consumption and sector exit delay. To solve the problem, a negotiation-based coordinating process is proposed and modeled as a pure-strategy game among aircraft. The proposed negotiation need not be physically carried out among aircraft and air traffic controllers. It can be automatically realized as a part of the algorithm within the tool to facilitate timely decision making for air traffic controllers. The tool can efficiently compute 4D trajectories through the automatic negotiation process, which both guarantees safety and improves efficiency. Moreover, although the tool is developed for ATC, pilots and their airlines can also benefit from it because the tool takes aircraft's preferred trajectories into account and reduces both delay and fuel consumption, which creates incentive for them to participate in the process.

Regarding air traffic safety, en-route aircraft are required to keep separation from each other throughout their flight. Two aircraft are defined to be in-conflict if their relative distance is less than 5 nm (nautical miles) horizontally and 300 m (in China) vertically. The safety zone of one aircraft is depicted as the cylinder in Fig. 1. If one aircraft is in the safety zone of another, the two aircraft are in conflict. The 5 nm horizontal separation is referred as safety distance, which means the minimum separation that two aircraft must keep if vertical separation is not in work. If separation is lost, air traffic controllers in charge will face punishment. In real practice air traffic controllers' priority is to ensure air traffic safety and they intend to maintain separation between aircraft several times greater than the required safety distance. The surplus portion of separation, called buffer safety distance in this paper, is used to accommodate potential emergency, and also as a critical tool to regulate air traffic controllers' workload (Averty et al., 2004; Loft et al., 2007; Nagaoka and Brown, 2015; Djokic et al., 2010). For example, Djokic et al. (2010) points out that "The higher horizontal proximity, i.e. the closer the aircraft in the horizontal plane, the higher was controller workload." If aircraft are always kept far from each other, air traffic controllers will experience relatively low workload. However, excessive buffer safety distance interferes with the efficiency of air traffic, resulting in unnecessary delay and sector capacity loss. Different air traffic controllers will keep different amount of buffer safety distance due to the variance within air traffic controllers' skills, experience and characters. Therefore, a decision support tool is needed to allocate buffer safety distance and manage its tradeoff with air traffic efficiency. To address the problems relating to buffer safety distance which is desired in practical ATC operation, we propose an algorithm framework for 4D trajectories planning, with the guarantee of conflict-free and taking buffer safety distance into account.

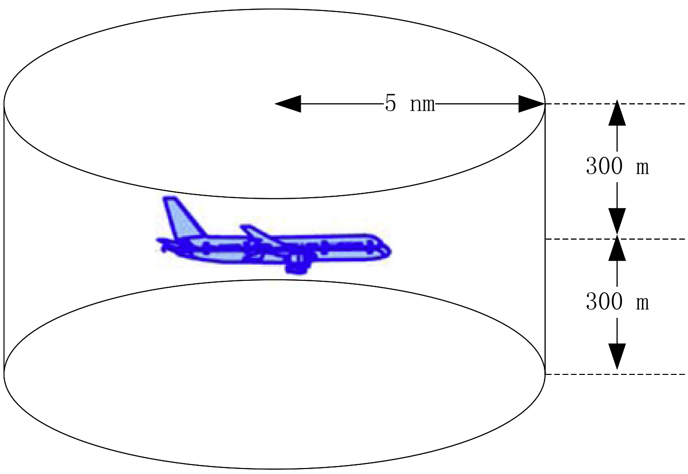

Fig. 1. Aircraft safety zone.