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An online speed profile generation approach for efficient airport ground movement

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ABSTRACT

The precise guidance and control of taxiing aircraft based on four-dimensional trajectories (4DTs) has been recognised as a promising means to ensure safe and efficient airport ground movement in the context of ever growing air traffic demand. In this paper, a systematic approach for online speed profile generation is proposed. The aim is to generate fuel-efficient speed profiles respecting the timing constraints imposed by routing and scheduling, which ensures conflict-free movement of aircraft in the planning stage. The problem is first formulated as a nonlinear optimisation model, which uses a more flexible edge-based speed profile definition. A decomposed solution approach (following the framework of matheuristic) is then proposed to generate feasible speed profiles in real time. The decomposed solution approach reduces the nonlinear optimisation model into three tractable constituent problems. The control point arrival time allocation problem is solved using linear programming. The control point speed allocation problem is solved using particle swarm optimisation. And the complete speed profile between control points is determined using enumeration. Finally, improved speed profiles are generated through further optimisation upon the feasible speed profiles. The effectiveness and advantages of the proposed approach are validated using datasets of real-world airports.

1. Introduction

As many airports approach their maximum capacity, the ever growing air traffic demand starts to put more pressure on airport ground movement operations (Eurocontrol, 2013). Congestion will frequently occur even with the support of advanced ground movement management systems. This leads to both economic and environmental concerns, such as excessive delay, increased fuel consumption and emissions. A non-negligible factor contributing to congestion is the lack of effective information sharing and collaboration between stakeholders. Aircraft usually taxi along standard routes and avoid conflict in a purely reactive way as a result. This leads to unnecessary uncertainty and inefficiency, making it difficult to maximise the utilisation of the existing airport infrastructure. To address the above issues, collaborative decision support systems (Eurocontrol, 2012; FAA, 2012) are being developed, and research into new operational concepts based on such systems is under investigation (JPDO, 2007).

The concept of trajectory-based taxi operations has been recently proposed to achieve more efficient ground movement (Okuniek et al., 2016). Instead of using standard taxi routes and purely reactive surface guidance, the trajectory-based approach generates

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conflict-free four-dimensional trajectories (4DTs) for all aircraft on the airport surface, and uses more sophisticated on-board or ground-based guidance technologies to keep pilots aware of the 4DT conformance status and the required maneuvers during taxiing (Bakowski et al., 2015; Biella et al., 2015; Foyle et al., 2011; Haus et al., 2011; Jones et al., 2014). This will largely eliminate the temporal uncertainty in the taxiing phase, making the holistic optimisation of interconnected airport operations (such as departure management and runway scheduling) more tractable (Weiszer et al., 2015a). Furthermore, the application of trajectory-based operations will also enable a smoother transition between the en route and ground movement phases, facilitating the development of the future generation of airspace systems (Eurocontrol, 2015; FAA, 2016).

On the airport, 4DTs are generally described by the route aircraft should follow and the detailed speed profiles along the route. To generate conflict-free 4DTs, a two-stage 4DT design procedure is developed in Cheng and Sweriduk (2009) and Cheng (2004). In the first stage, a desirable taxi route and the corresponding required times of arrival at selected waypoints (e.g., taxiway intersections or runway crossings) are determined during routing and scheduling. In the second stage, speed profiles complying with the designated route and the required times of arrival are generated for guidance. Although speed profiles are generated online in this approach, the fuel-efficiency cannot be ensured due to the stringent constraint of the required times of arrival (Chen et al., 2016a). Another 4DT generation approach is typified by the Active Routing framework (Chen et al., 2016a, 2016b). Active Routing aims to produce greener and more cost-effective 4DTs by combining routing, scheduling and speed profile generation into one integrated multi-objective optimisation framework. In this way, different costs (e.g., taxi time and fuel consumption) of each candidate 4DT can be precisely evaluated in routing and scheduling, and a set of conflict-free 4DTs with nondominated costs can be found for each aircraft. This enables controllers to select suitable 4DTs for a group of aircraft according to the current scenario. However, due to the restriction of the computational cost, currently the Active Routing framework generates speed profiles offline for different taxiway segments and then recompose them to form a complete speed profile for a certain route in routing and scheduling.

In this paper, we propose an improved online speed profile generation approach, which can be embedded within the two-stage 4DT design procedure as well as the Active Routing framework. With a more flexible speed profile generation model and a specifically developed solution approach, feasible and fuel-efficient speed profiles can be generated online according to the current situation. This will facilitate the generation of conflict-free 4DTs under various scenarios, especially when recovery planning is needed due to unprecedented events.

The rest of the paper is organised as follows. Section 2 presents a review of relevant approaches and summarises the contributions of this paper. Section 3 formulates the speed profile generation problem as a nonlinear optimisation model. Section 4 introduces the proposed solution approach. The performance of the proposed method is validated in Section 5 using problem instances based on real-world airport layouts. Conclusions and future directions are presented in Section 6.

2. Literature review and contributions

2.1. Literature review

The problem of 4DT-based ground movement planning has attracted significant attention in recent years (Atkin et al., 2010; Marín, 2006). A full 4DT for ground movement specifies the expected positions of an aircraft at all time during taxiing. Earlier work has aimed to determine the partially defined 4DT (often known as time-based taxi trajectory) for an aircraft, which consists of a taxi route and the corresponding required times of arrival at control points. Here, control points refer to the artificial waypoints set along taxiways for safe separation between aircraft during routing and scheduling. The taxiway between two adjacent control points is referred to as an edge. The control points dividing turning and straight segments of a specific taxi route are referred to as critical points. In addition to the critical points, other intermediate control points may exist on each segment of the taxi route. It should be noted that for guidance purpose, not all required times of arrival at control points will be displayed to pilots, in order to avoid impact on their work load and situation awareness due to frequent checking of the time. In Smeltink and Soomer (2004) and Roling and Visser (2008), aircraft are scheduled using the fixed standard taxi routes. In this case, only scheduling is applied to generate the required times of arrival at control points. In Balakrishnan and Jung (2007), Deau et al. (2009), Gotteland and Durand (2003) and Montoya et al. (2010), multiple standard taxi routes are available for each aircraft. Routing and scheduling are then carried out in this reduced search space. Although using standard taxi routes makes the problem more tractable, better solutions may be obtained using the complete search space (i.e., all taxi routes). In light of this, in Clare and Richards (2011), García et al. (2005) and Marín (2006), routing and scheduling are conducted upon all taxi routes. However, the underlying difficulty with these approaches often makes the computational cost too high for real-world problems. This is especially true when airport traffic is subject to unexpected events and a fast re-planning is mandatory (Clare and Richards, 2011; Marín, 2013). In view of this, methods based on sequential planning have been proposed (Lesire, 2010; Ravizza et al., 2014; Zhang et al., 2016). By dealing with one aircraft at a time, the sequential approach is more computationally efficient and flexible, requiring less interference to the already moving aircraft.

Given a time-based taxi trajectory, the ground movement process of aircraft will be inherently regulated by the speed limit constraints and required times of arrival at control points. However, inefficient movement may still occur as there are still many degrees of freedom for the movement between two control points (Chen et al., 2016a; Cheng and Sweriduk, 2009). A possible solution is to further plan detailed speed profiles between control points (Bakowski et al., 2013; Cheng and Sweriduk, 2009; Cheng et al., 2008). This leads to a full 4DT with which the expected position of the aircraft at any time during taxiing can be determined. In Bakowski et al. (2013), Cheng and Sweriduk (2009) and Cheng et al. (2008), the taxi route for each aircraft is determined using dynamic programming. The required times of arrival at control points are then determined to avoid conflicts between aircraft. Finally, detailed speed profiles between control points complying with the required times of arrival are generated after setting the