Fuel-efficient interval management for air traffic descending operation

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***Abstract*—To improve the operational efficiency of civil aviation, advanced technology in the interval management of aircraft needs to be developed. In this manuscript, the design of a fuel-efficient interval management algorithm is addressed: ensuring proper interval of arriving aircraft with altitude control. The effectiveness of the presented algorithm is verified in a simulation with arrival aircraft at Kansai International Airport.**

***Index Terms*—Air traffic management, Fuel-efficiency**

I. INTRODUCTION

In recent years, the aviation industry has been expecting an increase in aircraft demand. This causes a problem of fuel consumption and heavy traffic conditions. To further increase traffic volume with a safety guarantee, advanced technology of air traffic management (ATM) needs to be developed. Focusing on the descent phase, to realize a fuel-efficient flight, a concept of continuous descent operations (CDO) was proposed in [1]: aircraft descend continuously from their cruising altitude to the runway while maintaining the engine at idle thrust without any altitude control. However, a drawback of CDO is the difficulty of adjusting the arrival time of aircraft, which limits its applicability to real-world operations. To expand the application of CDO, we have to improve the "time controllability" of CDO aircraft by utilizing altitude control.

In this manuscript, we formulate the interval management by placing altitude constraints, whose concept is presented in [2]. To this end, an altitude-dependent regression model is derived, and a logic for optimal interval management is developed.

II. PROBLEM STATEMENT

A. Overview of Inteval Management Algorithm

The aim of the interval management algorithm is to maintain appropriate intervals between arrival aircraft while descending on fuel-efficient trajectories. We impose altitude control on the aircraft. For altitude control, an air traffic controller (ATCo) instructs altitude constraints to aircraft at predefined waypoints called indication points (IPs). For simplicity of notation, we fixed the number of IPs to two in this paper: IP-A and IP-B. Fig. 1 summarizes the series of operations for aircraft with the interval management algorithm. The interval management algorithm calculates the altitude constraints at each IP for each aircraft based on the aircraft's position and wind conditions before the aircraft reaches the top of descent (TOD). The altitude constraint for aircraft i is denoted as $H_i = [H_{\mathrm{A},i}, H_{\mathrm{B},i}] \in \mathbb{R}^2$. The ATCo instructs H_i to the aircraft. By following the instructions, the aircraft can achieve fuel-efficient descent while maintaining appropriate separation.

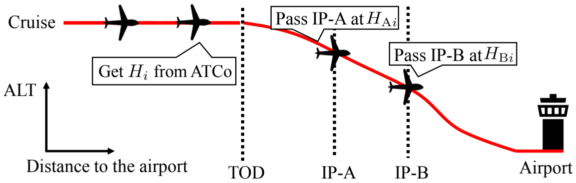

Fig. 1: Series of operations for aircraft with the interval management.

B. Optimization Problem for Interval Management Algorithm

We state the altitude control problems for the interval management algorithm. The aim of the algorithm is to maintain appropriate arrival intervals $t_{\min}$, i.e., all aircraft spacing to be at least $t_{\min}$. The altitude control logic determines the altitude constraints based on the aircraft's positions and wind conditions. The logic also calculates the CDO trajectory, which does not have altitude constraints and is used as a baseline trajectory for each aircraft: it determines H_i of aircraft i before its arrival at the TOD point. Then the control logic K is formulated as follows:

$$K: \begin{cases} \displaystyle\min_{\{H_{\mathrm{A,i}}, H_{\mathrm{B,i}}\}} \quad \sum_{i=1}^{N} \|\Delta H\|_1 & (1) \\ \text{sub. to} \quad \hat{t}_{i+1} - \hat{t}_i \geq t_{\min}, & (2) \\ \qquad\qquad \hat{t}_i = f(d_i, H_{d,i}, H_{\mathrm{A,i}}, H_{\mathrm{B,i}}, \boldsymbol{w}), & (3) \\ \qquad\qquad\qquad \forall i \in \mathcal{N}, & \end{cases}$$

where $\mathcal{N}$:=$\{1, \ldots, N\}$ be a set of labels for aircraft to be managed. t_i, d_i, and $H_{d_i,i}$ are the arrival time, the distance from the current point to the Airport, and the altitude at the current point, respectively. $\boldsymbol{w} \in \mathbb{R}^2$ is wind conditions,

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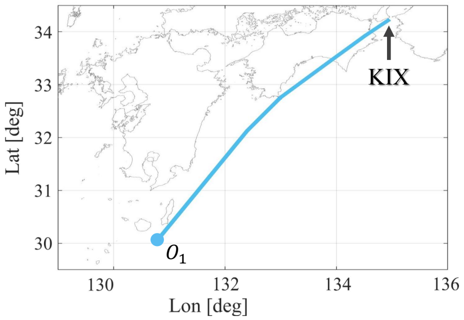

Fig. 2: The horizontal route in the numerical experiment. The horizontal route was fixed for the interval management.

which contain a west wind and a south wind at each altitude. The wind conditions are sent every three hours to ATCo. Further, the altitude constraint and CDO trajectory at IP-A of aircraft i be denoted by $\Delta H_{\mathrm{A},i}{:=}H_{\mathrm{A},i}-H_{\mathrm{A,CDO}}$. In the same manner, we denote $\Delta H_{\mathrm{B},i}$ for IP-B, where are shown $\Delta H=[\Delta H_{\mathrm{A},1},\Delta H_{\mathrm{B},1},\dots,\Delta H_{\mathrm{A},N},\Delta H_{\mathrm{B},N}]$.

Minimization (1) of ΔH tends to promote sparsity in ΔH: most of the elements in $\Delta H_{\mathrm{A},i}$ and $\Delta H_{\mathrm{B},i}$ tend to be zero. Recall that ΔH is the difference between the CDO and the altitude constraints calculated by the interval management algorithm.

We address the modeling problem (3) for aircraft and derive a computationally tractable model. The aim of the modeling is to predict t_i based on $H_{\mathrm{A},i}$, $H_{\mathrm{B},i}$, d_i, $H_{d,i}$ and $\boldsymbol{w}$. Then, the prediction model is described by linear regression.

In addition, wind conditions vary greatly depending on the arrival time. Therefore we need to predict and modify wind conditions in real-time using a modification model. Details of the wind prediction are omitted in this manuscript. They are given in the conference presentation.

III. NUMERICAL EXPERIMENT

A. Set Up

We performed numerical experiments by applying the proposed methodology to the arrival traffic simulator developed in [3]. We set IP-A and IP-B at 100 and 50 NM from the arrival airport, respectively. We consider six Airbus A320 aircraft descending from cruising altitude to Kansai International Airport (KIX). We planned the vertical component of the route of Fig. 2 in the interval management algorithm while fixing the horizontal component to the conventional route used in the actual operations.

The following constants are set: $t_{\min}$=120 s, which is determined by the typical arrival separation. The allowable ranges for the altitude constraints at IP-A and IP-B are 20,000 ft–33,000 ft and 14,000 ft–19,000 ft, respectively. The aircraft descending with CDO, which is the most fuel-efficient, cross the altitudes at IP-A and IP-B at $H_{\mathrm{A,CDO}}=32,990$ ft and $H_{\mathrm{B,CDO}}=17,322$ ft, respectively.

B. Experimental Scenario

We considered a heavy traffic scenario to evaluate the proposed interval management algorithm for the six aircraft. We set initial positions $d{=}[140,155,175,210,235,245]$ NM under CDO. In the scenario, the separations without the interval management were $\Delta t_{\mathrm{CDO}}=[\underline{104},140,247,177,\underline{70}]$ s. Note that some separations are predicted to be less than $t_{\min}$, and therefore altitude control is needed.

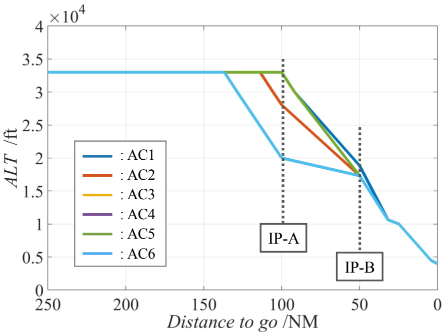

Fig. 3: Result of the simulation. Altitude constraints were imposed and showed the vertical trajectory.

TABLE I: Initial condition for heavy traffic. All separations between aircraft are greater than $t_{\min}$ from the beginning.

	d_i[NM]	H_{A_i}[ft]	H_{B_i}[ft]	t_i[s]	Δt_i[s]
AC1	140	32,990	**$\underline{18{,}843}$**	1329	
					$\underline{123}$
AC2	155	**$\underline{28{,}061}$**	17,322	1452	
					127
AC3	175	**$\underline{32{,}969}$**	17,322	1579	
					247
AC4	210	32,990	17,322	1826	
					177
AC5	235	32,990	17,322	2003	
					$\underline{126}$
AC6	245	**$\underline{20{,}011}$**	17,322	2129	

C. Experimental Results

In the scenario, some $H_{\mathrm{A},i}$, $H_{\mathrm{B},i}$ and Δt values highlighted by underbars differed from the values for $H_{\mathrm{A,CDO}}$, $H_{\mathrm{B,CDO}}$ and Δt_{CDO}. We see in Table I and Fig. 3 for the scenario that AC1, AC2, AC3, AC6 performed altitude control once, and AC4, AC5 did not perform it and followed the CDO trajectory. We also confirmed that all separations between aircraft were more than $t_{\min}$ at the terminal point in the simulation, even though several separations without the interval management were less than $t_{\min}$.

IV. CONCLUSION

Our proposed interval management algorithm extends CDO to control the arrival time, enabling arriving aircraft to descend close to the CDO trajectory while maintaining proper separation. The management algorithm comprises altitude control logic, which is based on a prediction model for the arrival time caring for unexpected winds. We conducted numerical experiments considering a scenario simulating a heavy traffic condition.

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