Conceptual Design of a Speed Command Algorithm for Airborne Spacing Interval Management

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Abstract — Airborne Spacing Interval Management is a sophisticated Air Traffic Management solution, that allows to minimize excessive spacing between aircraft, increase air traffic efficiency and runway utilization. In recent years a Flight-deck based Interval Management solution using a dedicated speed control algorithm has been developed and tested with favorable results but operational concerns remaining. In this conceptual design study an alternative speed command algorithm is introduced, aiming to further promote the usability and efficiency of Interval Management systems under operational aspects.

Keywords: Interval Management, Air Traffic Management, Speed Control Law, Workload

I. INTRODUCTION

Increasing traffic flow efficiency and runway utilization while ensuring safe and environmentally friendly operation through sophisticated Interval Management (IM) is one of the working tasks found in the International Civil Aviation Organization (ICAO) Global Air Navigation Plan [1]. Proposed Airborne Spacing (ASPA) IM solutions are either ground based (GIM) or Flight-deck based (FIM), with the latter moving the responsibility for maintaining the airborne separation from the Air Traffic Controller (ATCo) to the pilots of the aircraft engaged in FIM operation [2-5]. Simulations and flight tests have shown that the application of FIM can significantly improve spacing goal observance, achieving a standard deviation of only 5 seconds, compared to 18 seconds using ATCo guided metering operations [6-11]. While this could result in a promising 10% increase in aircraft throughput, the same research work also revealed that the operational workload on pilots during FIM operation is remarkably increased, thus indicating the need for further studies on IM speed logics and their operational feasibility [12].

This paper is organized as follows. Section II gives an outline of the functional concept of FIM and the underlying speed logic. Section III introduces our proposed IM speed control concept and gives an outlook on our future work. Section IV includes a discussion about the concept’s robustness, advantages and disadvantages as well as future challenges, before Section V concludes this paper.

II. FLIGHT-DECK INTERVAL MANAGEMENT (FIM)

A. Operational Overview

FIM is a trajectory-based, airborne IM concept, independent of ground equipment. It operates by computing the trajectory of the own aircraft (“Ownership”) and a predefined preceding target aircraft (“Traffic-to-follow”, TTF), to compare the estimated time of arrival (ETA) of both aircraft for a common waypoint. While data for the Ownership’s trajectory is obtained from the Flight Management System (FMS), data for the TTF relies on Automated Depended Surveillance Broadcast (ADS-B) In [13].

The ETA of the TTF, plus the pairing-specific, distance- or time-based spacing goal time (Δ) equals the desired or scheduled time of arrival (STA) for the Ownership. The difference between this value and the Ownship’s ETA leads to the spacing error,

\[ e(t) = \text{ETA}_{ownship}(t) - (\text{ETA}_{TTF}(t) + \Delta) \]  

the central input variable and time that needs to be compensated. Based on this value and the underlying control logic a command speed is advised to counteract this error [13].

Originally planned as a fully automated tool for integration into the auto-pilot and auto-throttle system, consumer demand called for an immediate, easy to add federated solution for the current Flight-deck setup. As a result, development has shifted towards an Electronic Flight Bag (EFB) based application, requiring the pilots to input computed IM speeds in to the auto-pilot control panel or FMS manually, as shown in [6,12].

B. Airborne Spacing for Terminal Arrival (ASTAR)

ASTAR is a speed control algorithm for FIM developed by NASA since 2002. Throughout its development ASTAR has been revised multiple times to fulfil the requirements given by the federated system concept and NASA’s Air Traffic Management Technology Demonstration-1 (ATD-1) project. Its current version, ASTAR13, was published in 2015 and evaluated in flight tests in early 2017 [3-5,6,12]. ASTAR features two operational modes with different speed control logics. First, a Trajectory Based Operation mode (TBO, Fig. 1), for traffic on different routes merging towards a common
waypoint (or Achieve-by-Point, ABP). Second, a Constant Time Delay (CTD, Fig.2) station keeping mode, for in-trail traffic. The controller map for the TBO logic can be seen in Fig. 3. Gain parameters are determined by the remaining Time-to-Go (TTG) and Distance-to-Go (DTG). All signals are directly fed forward, giving an immediate speed command within ±15% of the aircraft's current trajectory calibrated airspeed (CAS).

Simulations showed that for in-trail traffic, STAs with a standard deviation of 5s or less could be achieved. However, for merging operations higher deviations are observed under certain conditions [10,11]. An example for an ASTAR generated CAS profile, using 5kt speed setting intervals, is presented in Fig. 4. The solid orange line shows the actual CAS, the violet dotted line the selected CAS. Additional to occasional uneconomical behavior (acceleration immediately after deceleration), speed commands can occur quite frequently. Pilot comments from the actual flight test also highlighted this matter, calling to limit the number of speed changes to a maximum of one per minute [12].

C. Other control logic concepts

A different approach was introduced by Bai & Weitz [14,15], who explored the use of Model Predictive Control and Non-Linear Programming for the IM speed command algorithm. In their concept the speed profile is gradually changed over a predefined planning horizon. Certain constrains (e.g. inhibiting accelerations) benefitting economic behavior were also added. Though showing promising results, challenges remain with the rise in computation time over the length of the planning horizon.

III. PROPOSED CONCEPT

A. Introduction and Basic Concept

The goal of this research is to propose an IM speed logic solution that provides a satisfactory balance between spacing performance and computation time, considering operational and economic factors with a strong focus on minimizing application induced workload. To achieve this goal, the concept in this work aims to change the descent speed profile from initiation to ABP as a whole, by predicting the ETA for a range of speed profiles, and selecting the most suitable, e.g. the one closest to the STA. The range in which alternative speed profiles are searched for is defined by a speed envelope, based on aircraft specific operational limitations and route profile specific constrains.

Over this envelope a map, containing the required travel time \( t_{req} \) for a defined distance \( d_{step} \), is calculated for all available speeds in the interval of \( CAS_{step} \). The resolution of the map can be adjusted to the required precision and desired computation time by changing the values of \( d_{step} \) and \( CAS_{step} \).

Each \( t_{req} \) value is calculated based on the Ground Speed (GS), given by the True Airspeed (TAS) and wind forecast data. Air pressure and density information, necessary for the conversion from TAS to CAS, is obtained from the aircraft's altitude, given by its vertical flight path.

The conversion formulas used in this concept are in accordance with EUROCONTROL’s Base of Aircraft Data (BADA), Version 3.12, [16].

Next, a reference profile, e.g. the speed schedule stored in the FMS, is applied to the generated map, indicating the ETA.
TTG and adjustment margin for the current trajectory. Based on this profile a rule-based search algorithm tries to find time error compensating profiles, i.e. close to the STA, within the envelope.

To reduce the number of required pilot interactions, the algorithm makes adjustments based on planned speed changes given by the reference profile. These adjustments can either be in time (e.g. delayed deceleration for earlier arrival) or in target speed (faster speed for earlier arrival) as demonstrated in Fig. 5. Additional steps are considered where necessary or advisable.

The purpose of this paper is to give a design overview of the proposed alternative IM speed control concept. The functional details of the underlying algorithms used in this proposal will be presented in the author’s future papers.

B. Exampleary Speed Profile

Fig. 6 shows the reference CAS profile (solid black line), selected speed (dashed red line) and speed envelope (colored area) in relation to the DTG for a Boeing 787-8 on the KAIHO Arrival to Tokyo International Airport (RJTT/HND), Runway 34L, based on the BADA model and route and waypoint given restrictions. Further the following pre-conditions have been set:

- Initial position: 224NM to RWY Threshold at 38.000ft
- Continuous Descent Operations (CDO) with a fixed geometric Flight Path Angle from Top-of-Descent until Glideslope Capture of -2.2°, then -3° on Glideslope
- International Standard Atmosphere (1013.2 hPa)

The envelopes minimum and maximum speeds are given by:

- Aircraft type and configuration specific speed limits at reference mass (as per BADA 3.12)
- Legal limitations (Max. 250kts below 10.000ft)
- Acceleration and deceleration performance limits

The background colors indicate the required time for a single distance step, here $d_{step} = 0.02NM$, calculated on a CAS$_{step} = 1kt$ grid. In this example $t_{req}$ ranges from 0.1385s to 0.4896s.

Table 1 shows the TTGs for characteristic profiles for the given envelope. If $e(t)$ lies within the indicated borders (here: -121.27s / + 635.19s) a compensating profile can be calculated and displayed to the pilots, who either enter the new profile into the FMS or set it manually on the auto-pilot control panel.

The acceleration prohibiting profile continues at max. speed after leaving cruise reference speed (here the first deviation from the reference profile occurs just approx. 30NM before the ABP). Though faster, it highlights the only small buffer before error can no longer be compensated (here 7.75s) and also reveals issues in operating close to border limits, e.g. operationally undesirable conditions, like a single step speed reduction of 70kts. Therefore, the no-acceleration paradigm, though ecologically desirable, might not be practical and a strategy on where to insert an acceleration segment should be developed (see IV. Discussion).

<table>
<thead>
<tr>
<th>Speed Profile Name</th>
<th>TTG[s]</th>
<th>Difference to Reference [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Profile (BADA)</td>
<td>2145.10</td>
<td>-</td>
</tr>
<tr>
<td>Slowest (Minimum Speed)</td>
<td>2780.29</td>
<td>+ 635.19</td>
</tr>
<tr>
<td>Fastest (Maximum Speed)</td>
<td>2023.83</td>
<td>- 121.27</td>
</tr>
<tr>
<td>Fastest (Acceleration Prohibited)</td>
<td>2137.35</td>
<td>- 7.75</td>
</tr>
</tbody>
</table>

C. Calculation Time

The simulation in this study was run in a single-threaded Java environment on a 2.6GHz Intel Core i7-6700HQ processor. The initial setup, which includes reading out the route and wind forecast data, setting up the route and aircraft specific envelope, calculating the time required map and TTG values for the fastest, slowest and reference speed profile, using $d_{step} = 0.02NM$ and CAS$_{step} = 1kt$ intervals, takes about 0.9s. As long as the flight path is maintained and the forecast wind information is unchanged, the speed map remains valid (for exceptions see discussion chapter) and does not have to be re-calculated.

The time required to find a compensating profile for a selected spacing error varies with the number of profile changes. An acceptable solution (predicted ETA within STA ± 0.05s) for a single adjustment is usually found within 3 cycles and takes less than 0.01s. Time benefiting methods are currently evaluated, for example during idle time, profiles could be pre-calculated to have an immediate solution in case of a spacing error change.
D. Future Work

While the algorithm used in this concept shows promising results at good speeds, at its current stage, it only finds the first profile that fulfills the STA time requirement. However, multiple solution might exist, from which the best one has to be selected based on different paradigms than time only. Future efforts will focus on the development of a cost function that assigns a value on each cell of the map. Possible discrimination factors could be the fuel consumption, operational and workload factors or “robustness”, e.g. surpluses towards the envelope’s borders.

Once the cost function has been defined and tested in simulations it also planned to evaluate this algorithm and its usability in Human-in-the-Loop (HITL) simulations.

IV. Discussion

A. Model and Prediction Error

As the simulation in the study is based on the BADA model, certain model-based errors are expected. To evaluate the error’s impact, a comparison of data taken from a Full-Flight-Simulator experiment to BADA model calculated data is one planned task.

Given by the nature of the pre-calculated map, inaccuracies e.g. unrepresented values, do exist, however, at the described resolution, the error for the reference profile was less than 0.05s.

In an actual operating scenario, the prediction error can be fathomed by comparing the predicted ETA to the Actual Time of Arrival (ATA). Provided that the error is monotone, a compensation factor could be applied to following calculations.

B. Conceptual Benefits and Disadvantages

One benefit of changing the entire speed profile is the greater planning horizon. As the system allows to delay, fasten or summarize counteractions, the spacing error could diminish due to outside factors, ultimately requiring no intervention at all. As an effect, more ecological profiles with fewer speed changes, reducing workload and engine wear, are expected.

From an operational perspective, the concept can also tolerate user errors to a certain degree, as the effect of missed speed change timings or wrong speed settings can be estimated and included in the next profile calculation.

The disadvantage of the model is the strict reliance on path and speed change timing observation. A threshold to which a deviation remains tolerable must therefore be defined.

C. Remaining Challenges

- Evaluation of the system robustness towards noise and constrains, e.g. wind, route deviation

V. Conclusion

In this design concept we presented an alternative speed control algorithm for Airborne Spacing Interval Management, that showed promising results and fast calculations speed. In succeeding research, a cost function will be developed to select profiles on overall operational conditions rather than just time. Finally, upon evaluation of the algorithm’s robustness, concluding HITL simulations to evaluate the algorithm’s usability are planned.

REFERENCES