DESIGN OF AN AIRBORNE SPACING DIRECTOR TO MINIMISE PILOT SPEED ACTIONS

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Abstract

A flight deck tool was designed to assist pilots in acquiring and maintaining a required time delay behind a lead aircraft. A system architecture for manual and automatic ‘merge behind’ and ‘remain behind’ modes is proposed with performance requirements and design constraints. A manual ‘remain behind’ guidance mode suggesting calibrated airspeed was developed. The control law minimised pilot speed actions by using lead aircraft history to anticipate large speed changes. This guidance mode was tuned and validated using descent profiles recorded from real-time experiments, and a pilot model in the loop. A sequence of four aircraft was modeled to investigate potential benefits. The number of calibrated airspeed adjustments needed to maintain spacing was found to decrease by at least a factor of three for all trailing aircraft when the lead aircraft history based prediction was used.

Introduction

A new allocation of tasks between controller and flight crew is envisaged as one possible option to improve air traffic management and in particular the sequencing of arrival flows [4]. It relies on a set of new spacing instructions where the flight crew can be tasked by the controller to maintain a given spacing (in time or in distance) with respect to a designated aircraft. This task allocation, denoted airborne spacing [2], is expected to increase controller availability. This could lead to improved safety, which in turn could enable better quality of service and, depending on airspace constraints, more capacity. In addition, it is expected that flight crews would gain in awareness and anticipation by taking an active part in the management of their situation with respect to a designated aircraft.

Airborne spacing assumes airborne surveillance such as Automatic Dependent Surveillance Broadcast (ADS-B) along with an Airborne Separation Assistance System (ASAS), see [2], [14]. No significant change to ground systems is initially required. Two new main kinds of spacing instruction for arrival flows, ‘merge behind’ and ‘remain behind’, are being evaluated in air traffic controller and pilot in the loop real-time simulation based experiments, see [4] and [5]. The ‘merge behind’ along with its variant ‘heading then merge behind’ instructions have been devised to assist the air traffic controller create sequences. Similarly the complementary ‘remain behind’ instruction is intended to help air traffic controllers maintain sequences.

Past studies have investigated both distance and time based airborne spacing of sequences of aircraft using fast time [8], [12] and real-time experiments [13], [15] (and references therein). Time based spacing has been found to have several potential advantages over distance based spacing [1], [6], [14].

From real-time experiments, pilots expressed the need for assistance in gauging the spacing and closure rate, and deriving the corresponding desired calibrated airspeed (CAS). Previous prototype CDTIs (Cockpit Display of Traffic Information) have included a suggested CAS based on an intuitive algorithm which takes into account the current spacing error and closure rate to achieve the desired spacing performance [5]. Pilots appreciated the suggested CAS tool but it tended to make large changes in small steps, hence inducing an unnecessary workload for pilots.

The objective of this paper is to describe a proposed architecture for a component of the ASAS, hereafter referred to as an airborne spacing director. An important requirement was to reduce pilot workload by reducing the number of manual speed adjustments that have to be made to the autopilot without degrading desired spacing performance.

1 The name ‘airborne spacing director’ was inspired by the cockpit ‘flight director’ in which human in the loop design principles are fundamental aspects.
The paper is organised as follows: the ‘remain behind’ and ‘merge behind’ applications are described followed by the airborne spacing director requirements, architecture and detailed design. Then the environment model is presented. The evaluation method of the airborne spacing director focuses on ‘remain behind’ application and describes the test scenarios, metrics and range of experimental parameters used. The performance of the spacing director is then tested for a sequence of four aircraft. Results are presented as a series of graphs, followed by discussions and a conclusion.

**Airborne spacing application**

The ‘remain behind’ application involves an air traffic controller asking a pilot to select a neighbouring aircraft as a target on a CDTI. An example of the phraseology developed is:

*Controller*: “DLH456, select target 1234”

*Pilot of DLH456*: “Selecting target 1234, DLH456”

Once the target has been selected, the air traffic controller can then ask the pilot to maintain a given longitudinal distance or time behind the target. This can be achieved by the pilot monitoring spacing on the CDTI and adjusting speed through the autopilot to reduce spacing error. An example of the phraseology developed is:

*Controller*: “DLH456, behind target, remain 90 seconds behind”

*Pilot of DLH456*: “Remaining 90 seconds behind target, DLH456”

An initial prototype CDTI with visual spacing cues has been developed (see Figure 1). The enlarged spacing scale on the left of the navigation display copes with possible different display range requirements between navigation and spacing. For example when navigating the pilot may want to see future waypoints say 80 NM ahead whereas the desired spacing may be an order of magnitude smaller and difficult to see on such a large scale. The suggested airspeed (SUG IAS) at the bottom center of the CDTI is proposed to the pilot for input into the autopilot. Accurate time based calculations of this nature are easily performed by computer but are more difficult for pilots especially in parallel with other tasks.

**Figure 2: Remain behind.**

Conceptually, for the purposes of closed-loop guidance law design, the operational goal can be modelled by defining and minimizing a continuous time spacing error \( t_{error} \), at time \( t \). The spacing error \( t_{error} \) is defined as the difference between the elapsed time \( (t - t^*) \) since the lead aircraft was at the same position along track as the trailing aircraft is currently and the desired time spacing \( t_{spacing} \):

\[
t_{error}(t) = t - t^* - t_{spacing}
\]

where \( t^* \) satisfies:

\[
d_{lead}(t^*) = d_{trail}(t)
\]

This time based spacing error was rewritten as an equivalent constant distance based expression. The

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2 Note: The target is identified by a unique code other than the callsign to avoid confusion over the ‘party-line’.

3 For the purposes of this paper, indicated airspeed (IAS) and calibrated airspeed (CAS) are considered to be the same.
equivalent distance based spacing error \( d_{\text{error}} \) was defined as the difference between the delayed position where the lead had been \( t_{\text{spacing}} \) seconds ago and the current position of the trailing aircraft.

\[
d_{\text{error}}(t) = d_{\text{lead}}(t - t_{\text{spacing}}) - d_{\text{trail}}(t) \quad (3)
\]

For a description of the ‘merge behind’ application see [6].

**Airborne spacing director**

**Airborne spacing director requirements**

The airborne spacing director is a tool to assist pilots manage along track time or distance spacing with respect to a lead aircraft. In this paper only time spacing and spacing managed through speed adjustments are addressed. Two modes are considered: manual pilot in the loop mode and an automatic mode.

- Manual pilot in the loop mode
  
The airborne spacing director should present to the pilot a suggested desired CAS with the following performance requirements:
  
  a) **Accuracy**: mean spacing error < 2.5 s and standard deviation (\( \sigma \)) such that mean error ± 2\( \sigma \) shall be < ±5 s
  
  b) **Stability**: trail CAS overshoots due to a step demand should be no greater than 5 knots

Such that, the following design constraints are met:

i) rounded to the nearest 5 knots (for display purposes)

ii) a minimal number of speed adjustments (i.e. average interval between two consecutive speed adjustments greater than 2 minutes and greater than 3 minutes between any three consecutive speed adjustments)

(These values are consistent with pilots in real time simulations being able to manually maintain spacing within 5 s.)

- Automatic mode

  The airborne spacing director should feed the autopilot with a continuous desired CAS respecting the previous performance requirements.

**Airborne spacing director architecture**

Figure 3 shows the main functional component (blocks) architecture with corresponding modes (bubbles) of the airborne spacing director and the relationship with the automatic spacing guidance. The automatic spacing guidance is common to all modes and generates a continuous ‘ideal’ desired CAS. In both the automatic acquisition and maintain modes the desired CAS is fed directly as an input to the ownship autopilot.

![Airborne spacing director architecture](image)

Figure 3: ‘Airborne spacing director’ architecture.
In manual mode, the ideal desired CAS is filtered and rounded in preparation for presentation to the pilot. Lead history is used by the automatic spacing guidance, and by manual guidance to anticipate future trends and simplify the CAS demand still further.

**Airborne spacing director design**

**Automatic spacing guidance**

The automatic spacing guidance law aims at establishing a given time spacing along track to a lead aircraft. The guidance law receives surveillance data from the lead aircraft and feeds the desired CAS input \( \text{CAS}_{\text{automatic}} \) of the aircraft model. The desired altitude \( h_{\text{desired}} \) is fed independently, and depends on the top of descent scenario.

The following spacing guidance law was derived respecting the performance requirements:

\[
\text{CAS}_{\text{automatic}} = GS \rightarrow \text{CAS}_{\text{conversion}}(GS_{\text{automatic}})
\]  

where the desired CAS of the trail aircraft \( \text{CAS}_{\text{automatic}} \) is derived by converting the desired groundspeed of the trail aircraft \( GS_{\text{automatic}} \) to the equivalent CAS. The desired groundspeed of the trail aircraft is based on the groundspeed of the lead aircraft where it was \( t_{\text{spacing}} \) seconds before, \( GS_{\text{lead}}(t - t_{\text{spacing}}) \), plus a corrective speed term derived from the spacing distance error \( d_{\text{error}} \) divided by a constant time value \( t_{\text{decay}} \) which is set to 120 s.

\[
GS_{\text{automatic}}(t) = GS_{\text{lead}}(t - t_{\text{spacing}}) + \frac{d_{\text{error}}(t)}{t_{\text{decay}}}
\]  

Note that this algorithm was validated in real-time experiments (see [5]).

**Filtered CAS**

To cope with design constraint i) the desired CAS of the trailing aircraft \( CAS_{\text{automatic}} \) is passed though a filter to reduce variations:

If \( |CAS_{\text{out}}(t-1) - CAS_{\text{in}}(t)| \geq Filter_{\text{thresh}} \) then

\[
CAS_{\text{out}}(t) = CAS_{\text{in}}(t)
\]  

else

\[
CAS_{\text{out}}(t) = CAS_{\text{out}}(t-1)
\]

where \( Filter_{\text{thresh}} \) is set to 5 knots, and \( CAS_{\text{out}} \) is the filtered CAS of the trail aircraft. This algorithm meets the accuracy requirement, (for validation see [5] and [6]) but leads to a large number of speed adjustments (Figure 4).

When the lead aircraft makes a large change in CAS, the trail aircraft follows the speed profile but, instead of performing the equivalent CAS, as the lead did, in one step only, it makes this change by many consecutive adjustments (Figure 4, blue line).

**Lead aircraft history based prediction**

To avoid the undesirable stepping effect (Figure 4) and to meet design constraint ii), large variations in CAS were anticipated by taking into account the lead CAS history. Such an enhancement is feasible since the spacing guidance concept already uses the delayed lead profile.

The algorithm is based on an analogy with human pilot behaviour in similar conditions. Searching through the lead CAS history, the moment when the lead performed a CAS change can be detected and corresponding magnitude of change estimated. This value is thereafter taken into account to derive the suggested desired CAS.

The algorithm takes the following form:

1. Estimate the CAS of the lead aircraft (CAS and TAS are not available via ADS-B):

\[
\text{CAS}_{\text{leadestimated}} = GS \rightarrow \text{CAS}_{\text{conversion}}(GS_{\text{lead}} , altitude_{\text{lead}})
\]

where the estimated CAS of the lead aircraft \( CAS_{\text{leadestimated}} \) is derived by converting the groundspeed of the lead aircraft \( GS_{\text{lead}} \) to the equivalent CAS. For the purposes of the airspeed conversion the atmospheric data experienced by the lead aircraft is approximated by that measured by ownship.

2. Detect the moment in the past when the lead changed CAS:

The \( CAS_{\text{leadestimated}}(t - \text{lead } _{\text{history } } \text{time}) \) derivative is calculated. When the magnitude of the

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derivative is found to be greater than a threshold value $CAS_{\text{threshold}}$ this is considered to be a change and the magnitude is estimated.

3. Estimate the amount and duration of change

For this purpose, the lead CAS history is retrieved at constant search intervals. By comparing consecutive retrieved discrete CAS values, the total magnitude of change in CAS is estimated as follows (Figure 5): starting with the earliest available value, the difference between each two consecutive discrete CAS values is computed. While these differences are above a given threshold, the consecutive differences are cumulated to obtain the total magnitude of the change.

### Aircraft model

The aircraft model (Airbus 320) includes the basic equations of motion, aerodynamic model, engine model, auto-pilot, auto-throttle control system, aircraft sensors and air-data model. The aircraft model is based on point mass equations of motion but with additional realistic rotational dynamics about the centre of gravity (see [9] and [10]). The model includes lateral motion of the centre of gravity and dynamic characteristics of the engines. A detailed description can be found in [11]. An admissible speed envelope model based on physical limits like stall speeds and maximum airframe speeds is incorporated in the aircraft model. These limits may not be as conservative as airline normal operational limits.

### Wind model

The wind model is based on that of the Joint Aviation Requirements All Weather Operations (JAR-AWO) autoland certification process [7]. In this model the mean wind speed is altitude dependent, and directly associated with the wind as measured at 30 feet AGL (Above Ground Level). The mean wind speed determines the turbulence intensity, and the wind velocity increases with altitude.

#### Mean wind

The magnitude of the mean wind increasing with altitude is defined by the following expression:

$$V_{\text{mean}}(h) = V_{30} \left(\frac{h}{30}\right)^\frac{1}{7},$$

where $V_{\text{mean}}$ is the mean wind speed (knots) measured at $h$ metres AGL and $V_{30}$ is the mean wind speed (knots) at 30 feet AGL.

#### Turbulence spectrum

The turbulence model has a Gaussian distribution, conforming to the Dryden spectrum. The turbulence provided disturbances of the aircraft airspeed and angle of attack.

### Evaluation method

#### Simulation platform

The airborne spacing director for the ‘remain behind’ application was simulated in fast-time using aircraft (Airbus 320), pilot and wind models implemented with MATLAB/Simulink. Perfect airborne surveillance transmission quality of lead aircraft position and velocity to the trail aircraft was assumed, i.e. continuous update rate, no delay, and perfect accuracy.
**Airborne spacing director validation**

**Validation scenario**
To validate the airborne spacing director using lead history based prediction, the following scenario was simulated:

The lead and trailing aircraft were in descent from 25,000 feet to 5,000 feet, flying along the same 3D trajectory. At the initial time the trailing aircraft was 10 NM behind the lead. Both aircraft were initialised with a CAS of 300 knots.

At the initial time the desired spacing (90 s) and closure rate were already achieved and the trail aircraft had to maintain spacing by using the manual mode of the airborne spacing director.

**Metrics**
The following metrics were used to evaluate the performance of the trail aircraft spacing director:

1. Mean and standard deviation of along track time spacing error between aircraft (s).
2. Average interval between two consecutive speed adjustments performed by the pilot of the trail aircraft to maintain spacing (minutes).
3. Minimum time between three consecutive speed adjustments performed by the pilot of the trail aircraft to maintain spacing (s).

The intermediate speed profiles were also checked for operational acceptability (see section “Airborne spacing director design”).

**Experimental parameters**
The following parameters were varied:

1. The constant search interval of lead CAS history was varied between the values [10, 20, 30, 45, 90] seconds.
2. The lead CAS profile. Five lead descent profiles with varying frequency and magnitude of speed changes were used as experimental parameters. All profiles were recorded from real time experiments and the travelled time in all cases was 30 minutes.

**Sequence of aircraft**
To investigate potential benefits, the new airborne spacing director with lead history based prediction was tested and compared with the previous one (without lead history based prediction) for a sequence of four aircraft performing ‘remain behind’.

**Operational scenario**
The following operational scenario was simulated:

A lead aircraft followed its own descent profile and a sequence of three trailing aircraft of the same type adjusted their own speeds to maintain the desired spacings with respect to each preceding aircraft. All aircraft started at 25,000 feet and 300 knots CAS and descended to 5,000 feet. All aircraft started their descent at the same location. The lead aircraft reduced CAS from 300 knots to 250 knots starting at 15,000 feet and from 250 knots to 220 knots when passing 10,000 feet. The scenario was conducted under realistic atmospheric conditions with light turbulent cross winds from -45° (i.e. from the north-west), of mean strength 5 knots at 30 feet altitude and 25 knots at 25,000 feet altitude.

At the initial time the desired spacing (90 s) and closure rate were already achieved and the trail aircraft had to maintain spacing by using the manual mode of the airborne spacing director.

**Metrics**
See previous metrics.

**Experimental parameters**
Manual mode was executed with lead aircraft history based prediction and without.

**Results:**

**Results: Airborne spacing validation**

Figure 6 shows how the mean spacing error (an average of all profiles) increases as pilot activity decreases and search interval increases. The mean spacing error is always less than 2 s, therefore accuracy requirement a) is met for all search intervals. Figure 6 shows also how standard deviation (2σ) increases as search interval increases and that accuracy requirement b) is met for search intervals of 45 s or less.

Figure 6 shows that the average interval between two consecutive speed adjustments is always greater than 3 minutes and figure 7 shows how the shortest time between three consecutive speed adjustments is greater than 3 minutes for search intervals of 30s and longer. Therefore the design constraints are met for search intervals of 30 s and greater. As a comparison, figure 6 shows (left hand side) how the average interval between speed adjustments is less than 1 minute without lead history based prediction, i.e. lead history based prediction reduces pilot speed actions by at least a factor of 3. Although not shown on the graph, the shortest time...
between three consecutive speed adjustments without lead history based prediction was less than 20 s. Note that the mean values correspond to absolute magnitudes, but the actual values were all negative, i.e. less than the desired spacing.

Figure 6: Mean spacing error as function of pilot activity for various search intervals (10, 20, 30, 45 and 90 s).

Figure 7: Shortest time between three consecutive speed changes as function of search intervals.

Figure 8 shows how the demanded CAS (suggested CAS with pilot reaction delay) of lead and trail aircraft varies with time for a perturbed descent profile. It is interesting to note that even though the lead aircraft made seven speed adjustments (including both accelerations and decelerations), the trail aircraft only needed four speed adjustments to maintain spacing.

Figure 8: Demanded CAS – Perturbed descent profile.

For the following section a value of 30 s was chosen for the lead history based prediction search interval. This value corresponds to a desirably low pilot activity while meeting both performance requirements.

Results: Sequence of aircraft

Results for a sequence of four aircraft are presented in Figures 9 to 12.

Figures 9 to 12 show how the lead history based prediction algorithm significantly reduced the number of speed adjustments for all trailing aircraft (from 15 adjustments per aircraft to 4 or 5 per aircraft) while meeting the spacing error performance requirements (mean of 0.9 s and standard deviation of 1.2 s). The shortest time between three consecutive speed adjustments increased from 18 s to over 200 s due to the use of lead history based prediction.

Figure 9 shows also the important CAS overshoot (15 knots) produced when the aircraft maintained spacing without using lead history based prediction. This overshoot was significantly reduced (to 5 knots) using lead history such that the performance stability requirement b) was met (Figure 10).
Figure 9: Demanded CAS – without lead history based prediction.

Figure 10: Demanded CAS – with lead history based prediction.

Figure 11: Along track spacing errors – without lead history based prediction.

Figure 12: Along track spacing errors – with lead history based prediction.

Conclusions

An airborne spacing director was designed to assist pilots in acquiring and maintaining a required time delay behind a lead aircraft. A system architecture for manual and automatic ‘merge behind’ and ‘remain behind’ modes was proposed with performance requirements and design constraints.

The main contribution of this paper was a manual ‘remain behind’ guidance mode suggesting calibrated airspeed. The control law minimised pilot speed actions by using lead aircraft history to anticipate large speed changes. This guidance mode was tuned and validated using descent profiles recorded from real-time experiments, and a pilot model in the loop.

A sequence of four aircraft was modelled to investigate potential benefits. The number of calibrated airspeed adjustments needed to maintain spacing was found to reduce by at least a factor three when the lead history based prediction was used.

The performance of this new tool needs to be verified in pilot in the loop experiments.

Future work could be to:

i) investigate the interaction between automatic and manual modes,

ii) extend the tool to manual merge mode,

iii) test the robustness of the algorithm for various wind strengths, since the current results were obtained for only wind with light turbulence.
REFERENCES


Keywords
Air traffic management (ATM), airborne separation assistance system (ASAS), guidance, speed control, in-trail, airborne spacing director, aircraft, cockpit display of traffic information (CDTI), pilot, time delay, automatic dependent surveillance broadcast (ADS-B)

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Chris Shaw has been experimenting with air traffic management (ATM) systems for Eurocontrol in France since 1995. Previously he worked for Smiths Industries in England developing avionics for the Boeing 777 airliner and Agusta/Westland EH101 (selected as US presidential helicopter). His ATM research experience includes long-term secondments to NASA in California’s ‘silicon valley’ and the British Royal Aerospace Establishment (RAE). He studied physics (BSc 1987) at the university of Bristol in England and went on to study control systems (MSc 1988) in conjunction with British Aerospace. Chris has flown in trials for NASA and RAE, co-authored several research publications, and participated in standards development for RTCA.

Eric Hoffman is the Scientific & Technical Manager of the Sector Safety & Productivity Research Area at the EUROCONTROL Experimental Centre. Over the past recent years, he has led a number of studies on concepts and benefits of ASAS applications in the context of several collaborative European projects. He has been involved in the writing of PO-ASAS and the ICAO ASAS Circular as well as in the definition of Package 1. Prior to joining EUROCONTROL in 1992, he worked on the use of game theory for the definition of strategic defence systems. Additionally he spent a year in the French Air Force coordinating the flight testing of a UAV. His research interests also include guidance and control, trajectory prediction and distributed simulations. Eric received his Aerospace Engineering (BS) and DEA (MS) degrees in 1987 from ENSAE (Sup'Aero), Toulouse, France and his PhD in 1991 from the Georgia Institute of Technology, Atlanta, Georgia USA. He has authored several papers and is a member of AIAA and IEEE.

Karim Zeghal received his PhD in Computer Science from the University of Paris VI in 1994. His thesis which was conducted at ONERA (French aerospace research agency), focussed on the application of multiagent systems to air traffic control, and proposed a model of "coupled force fields" for multiple mobile co-ordination. During 1994-1996, he worked with the support of CENA (French centre for study in air traffic), to apply and evaluate the model of co-ordination for airborne conflict resolution. In 1996, he joined the Air & Space department of STERIA (software & consulting company), and since then has worked at the EUROCONTROL Experimental Centre. Since 1998, he has been leading the real-time simulations on ASAS, with a special focus on operational concepts and evaluation. Since 2002, he joined EUROCONTROL as project leader of CoSpace.