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A Pilot Decision Support Tool for Merging behind a Lead Aircraft

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Abstract—**This air traffic management study designed a cockpit tool for assisting pilots to achieve a constant time delay behind a lead aircraft. A system architecture for manual and automatic 'merge' and 'remain' modes was proposed with required design and performance requirements. A manual 'merge' guidance mode suggesting calibrated airspeed was developed for aircraft on converging trajectories. The control law reduced pilot speed actions by using lead aircraft history to anticipate large speed changes. This control mode was tuned and validated using descent profiles recorded from real-time experiments and a pilot model in the loop. The number of calibrated airspeed adjustments needed to maintain spacing was found to significantly decrease when the lead aircraft history based prediction was used.**

I. INTRODUCTION

A new allocation of tasks between air traffic controller and flight crew is envisaged as one possible option to improve air traffic management and in particular the sequencing of arrival flows (see [4] and references therein). 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 recently developed airborne surveillance technology (ADS-B) along with cockpit automation (Airborne Separation Assistance System, ASAS), see [2]. No significant change to ground systems is initially required.

Two new main kinds of spacing instruction 'merge behind' and 'remain behind' are being evaluated in air traffic controller [4] and pilot in the loop [5] real-time simulation based experiments. 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 [1], [6], [10] and real-time experiments [8], [14], [15] (and references therein). Time based spacing has been found to have several potential advantages over distance based spacing ([1], [13] and references therein).

In 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 [6]. Pilots appreciated the suggested CAS tool but it tended to make large changes in a series of small steps, hence inducing an unnecessary workload for pilots (see [5]).

The objective of this paper is to describe an improved spacing tool, hereafter referred to as an airborne spacing director[1]. An important requirement was to reduce the number of manual speed adjustments that have to be made to the autopilot without degrading desired spacing performance.

The paper is organised as follows: the chosen application 'merge behind' is described followed by the airborne spacing director objectives, architecture and design. Then the environment model is presented. The evaluation method of the airborne spacing director describes the test scenarios, metrics and range of experimental parameters used. Performance of the spacing director is then tested. Results are presented as a series of graphs, followed by discussions and a conclusion.

II. AIRBORNE SPACING APPLICATION

The time-based airborne spacing 'Merge behind' application involves an air traffic controller instructing a pilot to select a neighbouring aircraft as a target on a Cockpit Display of Traffic Information (CDTI). An example of the phraseology developed [4] 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 instruct the pilot to merge behind the target at a given merge waypoint ahead with a given time spacing.

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[1] The name 'airborne spacing director' was inspired by the cockpit 'flight director' in which human in the loop and system trust building principles are fundamental aspects of the design.

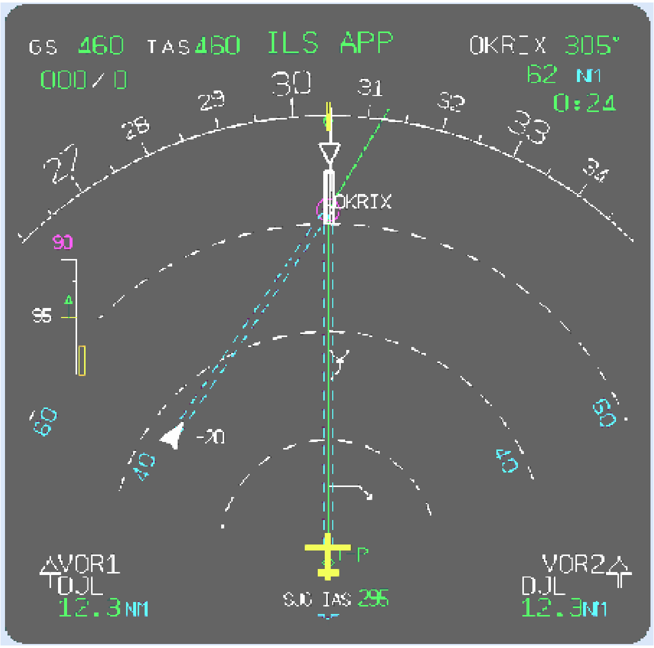

Figure 1: Merge behind application on CDTI in real time experiments.

An example of the phraseology developed is:
-***Controller***: *"DLH456, behind target, merge to way point to be 90 seconds behind"*
-***Pilot of DLH456***: *"Merging to way point to be 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. The suggested airspeed[2] (SUG IAS) at the bottom centre 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.

Conceptually, for the purposes of closed-loop guidance law design, this operational goal can be extended upstream of the merge waypoint by defining and minimizing a continuous 'shadow' time spacing error t_{error}, at time t. This error $t_{error}(t)$ is defined as the difference between the elapsed time ($t - t^*$) since the lead aircraft was at the same distance from the merge waypoint as the trailing aircraft is currently and the desired time spacing $t_{spacing}$:

$$t_{error}(t) = t - t^* - t_{spacing} \qquad (2.1)$$

where t^* satisfies:

$$d_{lead}(t^*) = d_{trail}(t) \qquad (2.2)$$

This 'shadow' time spacing error was rewritten as an equivalent constant distance based expression. The equivalent 'shadow' distance spacing error d_{error} was defined as the difference between the delayed position where the lead aircraft had been $t_{spacing}$ seconds ago and the current position of the trailing aircraft.

$$d_{error}(t) = d_{lead}(t - t_{spacing}) - d_{trail}(t) \qquad (2.3)$$

[2] For the purposes of this paper, indicated airspeed (IAS) and calibrated airspeed (CAS) are considered to be the same.

III. Airborne Spacing Director

A. *Airborne spacing director requirements:*

The airborne spacing director is a tool to help pilots manage along track time or distance spacing with respect to a lead aircraft. In this paper only time spacing controlled through speed adjustments is considered. Path deviations to achieve spacing such as in the applications 'heading then merge' are not considered in this study.

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 design requirements:

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 > 2 minutes)

Such that, the following performance requirements are met:

a) at merging waypoint spacing error shall be < 2.5 s, and speed difference shall be < 10 knots

b) in maintain mode the mean 'shadow' time spacing error along track shall be < 2.5 s with a standard deviation σ such that mean error ± 2σ shall be <±5s

These values are consistent with pilots in real time simulations being able to manually achieve spacing at the merging waypoint within 5s.

- Automatic mode

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

B. *Airborne spacing director architecture*

Figure 2 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. In manual mode, the ideal desired CAS is filtered and rounded in

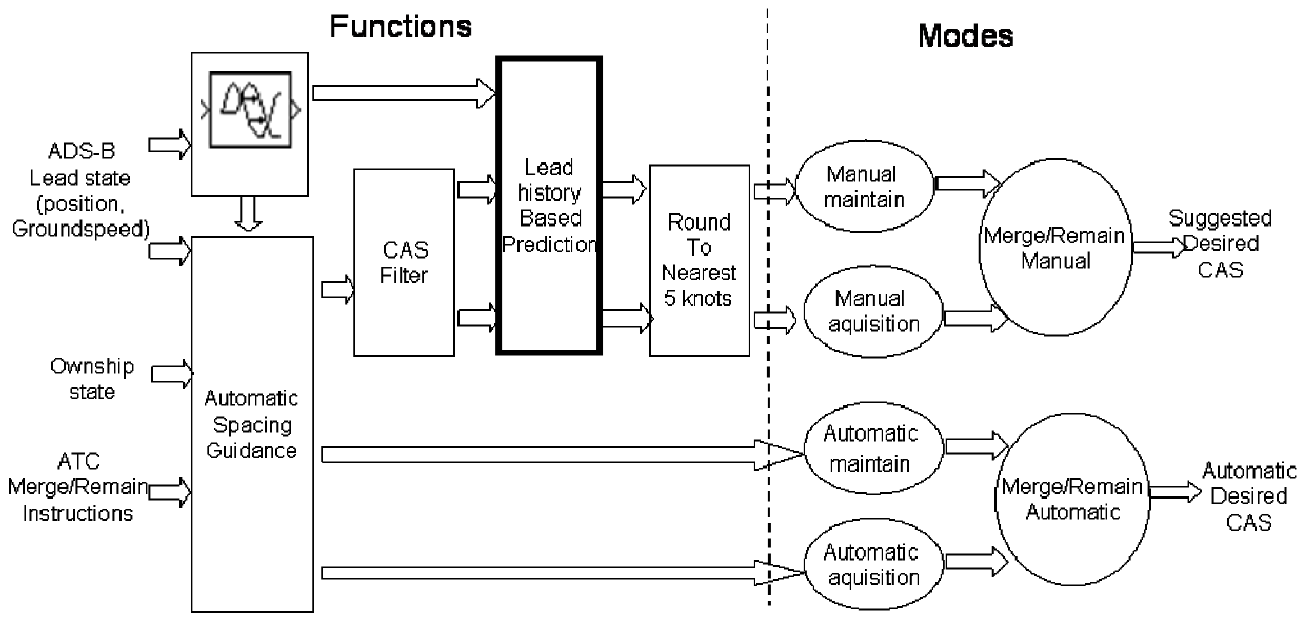

Figure 2: Airborne spacing director architecture.

preparation for presentation to the pilot. Lead aircraft history is used by the automatic spacing guidance, and by manual guidance to anticipate future trends and simplify the CAS demand still further.

C. Airborne spacing director design

1) 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 ($CAS_{automatic}$) of the aircraft model. The desired altitude ($h_{desired}$) is fed independently, and depends on the top of descent scenario.

The following spacing guidance law was derived respecting performance requirements:

$$CAS_{automatictarget} = GS \rightarrow CAS_{conversion}\left(GS_{automatictarget}\right) \quad (3.1)$$

where the desired CAS of the trailing aircraft $CAS_{traildesired}$ is derived by converting the desired groundspeed of the trailing aircraft $GS_{traildesired}$ to the equivalent CAS. The desired groundspeed of the trailing aircraft is based on the groundspeed of the lead aircraft where it was $t_{spacing}$ seconds before $GS_{lead}(t - t_{spacing})$ plus a corrective speed term derived from the spacing distance error d_{error} divided by the time to go before the lead aircraft arrives close to the merging waypoint $t_{leadtogo}$.

$$GS_{traildesired}(t) = GS_{lead}(t - t_{spacing}) + \frac{d_{error}}{t_{leadtogo}} \quad (3.2)$$

where $t_{leadtogo}$ is given by:

If $d_{lead} \geq 2\, t_{spacing}\, GS_{lead}$ then

$$t_{leadtogo} = \frac{d_{lead}}{GS_{lead}} - t_{spacing} \quad (3.3)$$

else

$$t_{leadtogo} = t_{spacing} \quad (3.4)$$

Note that this proportional and derivative time delay control algorithm was validated by real-time experiments (see [5]).

2) Filtered CAS

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

if $\left|CAS_{out}(t-1) - CAS_{in}(t)\right| \geq Filter_{threshold}$ then

$$CAS_{out}(t) = CAS_{in}(t) \quad (3.5)$$

else

$$CAS_{out}(t) = CAS_{out}(t-1) \quad (3.6)$$

where $Filter_{threshold}$ is set to 5 knots, and CAS_{out} is the filtered CAS of the trail aircraft. This algorithm meets performance requirements a) and b), (for validation see [5] and [6]) but leads to a large number of speed adjustments. Figure 3 shows the large number of small steps in suggested CAS (solid blue line) and corresponding steps in CAS (broken red line) selected by the pilot in a real time experiment. 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 3, blue line).

3) Lead aircraft history based prediction

To avoid the undesirable stepping effect (Figure 3) and to meet design requirement ii), large variations in CAS were

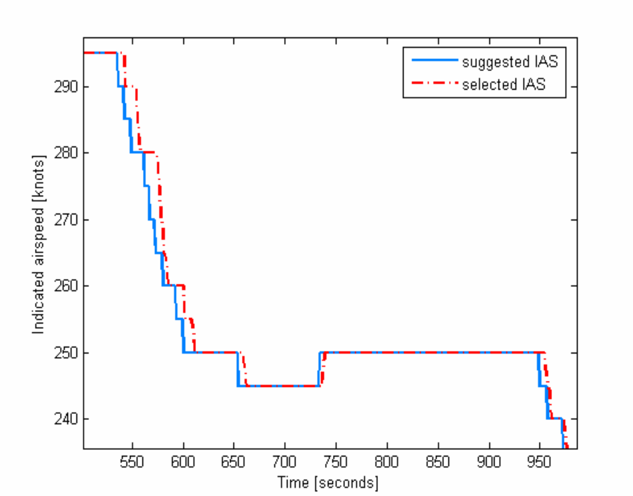

Figure 3: Human pilot following suggested speed in real time experiment.

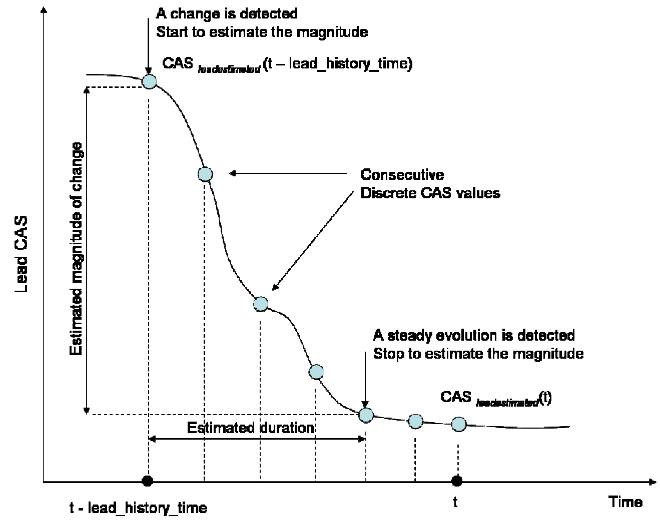

Figure 4: The use of the lead aircraft CAS history.

anticipated by taking into account the lead aircraft CAS history. Such an enhancement is feasible since the spacing guidance concept already uses the delayed lead aircraft profile. The algorithm is based on an analogy with human pilot behaviour in similar conditions. Searching through the lead aircraft 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:

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

$$CAS_{leadestimated} = GS \rightarrow CAS_{conversion}(GS_{lead}, altitude_{lead}) \quad (3.7)$$

where the estimated CAS of the lead aircraft $CAS_{leadestimated}$ is derived by converting the groundspeed of the lead aircraft GS_{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.

(ii) Detect the moment in the past when the lead aircraft changed CAS:

The $CAS_{leadestimated}(t - lead\_history\_time)$ derivative is calculated. When the magnitude of the derivative is found to be greater than a threshold $DER_{threshold}$ (0.15 knots/s) it is considered to be a change and the magnitude is estimated.

(iii) 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 4): 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 $CAS_{threshold}$ (5 knots), the consecutive differences are cumulated to obtain the total magnitude of the change and corresponding duration.

The search always starts from the end of the last change found, so that once a change has been suggested, undesirable stepwise modifications are avoided.

(iv) The suggested desired CAS from the filter (step 2) is enhanced in manual mode (see Figure 2) by adding the anticipated total CAS change from lead aircraft history based prediction (see step iii above).

(v) For display purposes (design requirement i), suggested desired CAS from step iv) is then rounded to the nearest 5 knots before presentation to the pilot model.

IV. Environment Model

A. Pilot model

Pilot reaction to the above suggested CAS from the spacing director, is modelled by a 5 s constant time delay, based on specific measurements from real-time simulations.

B. Aircraft model

The aircraft model [9], [11], [12], includes the basic equations of motion, aerodynamic, engine, auto-pilot, auto-throttle control system, aircraft sensors and air-data models. The aircraft model is based on point mass equations of motion but with additional realistic rotational dynamics about the centre of gravity. The model includes lateral motion of the centre of gravity and dynamic characteristics of the engines. 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. The tuning of the aircraft parameters and the validation of resulting trajectories were performed using [3].

C. 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 wind velocity increases with altitude, and the mean wind speed determines the turbulence intensity. The magnitude of the mean wind increasing with altitude is defined by the following expression:

$$V_{mean}(h) = V_{30}\left(\frac{h}{10}\right)^{\frac{1}{7}}, \tag{4.1}$$

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

D. Simulation platform

The airborne spacing director for the 'merge behind' application was simulated in fast-time using an Airbus 320 aircraft model, pilot model and wind model implemented with MATLAB/Simulink. A wind of 5 knots at sea level along the lead trajectory with light turbulence was used for all scenarios. 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.

V. Evaluation Method

A. Tuning and zero input validation with real-time data

1) Operational scenario

Five lead aircraft descent profiles with varying frequency and magnitude of speed changes were used as experimental parameters. All speed profiles were recorded from real time experiments simulating Paris airspace. The trail aircraft was initialised with no shadow time spacing error i.e. 90 s.

2) Metrics

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

- average interval between two consecutive speed adjustments performed by the pilot of the trail aircraft to maintain spacing (minutes)
- for no initial spacing error, mean 'shadow' time spacing error along track (s)

3) Experimental parameters

The following parameters were varied:

- The lead aircraft CAS profile.
- For each lead aircraft CAS profile, constant search interval of lead CAS history was varied between the values [10, 20, 30, 45, 90] seconds.

B. Step input validation

1) Test scenario

To verify robustness of the airborne spacing director using lead aircraft 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 straight to the same fixed waypoint along tracks converging at an angle of 25°. On initialisation both aircraft had a CAS of 300 knots and the trail aircraft was 104 s behind the lead. By using the manual mode of the airborne spacing director, the trail aircraft had to achieve a desired spacing of 90 s before the lead reached the merging waypoint, 100 NM downstream.

2) Metrics

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

- average interval between two consecutive speed adjustments performed by the pilot of the trail aircraft to maintain spacing (minutes)
- spacing error (s) and speed difference (knots) at merging waypoint.

3) Experimental parameters

The airborne spacing director was used with history based prediction and without.

VI. Results:

A. Tuning and zero input validation with real-time data

Figure 5 shows how pilot activity decreases as search interval increases, while mean 'shadow' time spacing error (an average of all profiles) remains relatively stable. Pilot activity decreasing with search interval is consistent with larger search intervals filtering out small step changes in lead aircraft CAS speed. The mean 'shadow' spacing error is always less than 2 s, therefore performance criterion a) is met for all search intervals. The standard deviation (2σ) increases as search interval increases and performance criterion b) is met for search intervals of 45 s or less.

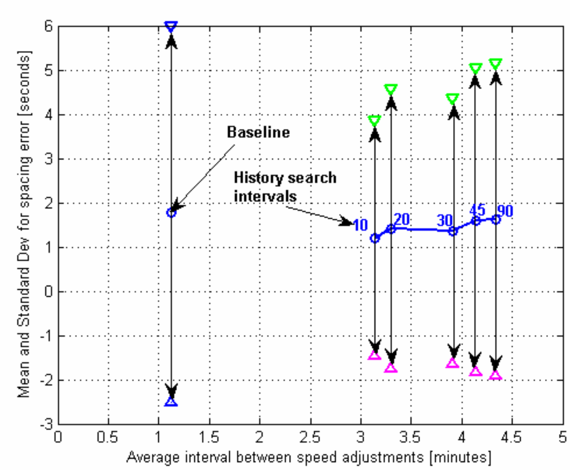

Figure 5: Pilot activity as function of mean spacing error, for different search intervals.

The average interval between two consecutive speed adjustments is always greater than 3 minutes for all search intervals. Therefore the design requirements are met for search intervals of 45 s and smaller. As a comparison, figure 5 shows (left hand side) how the average interval between speed adjustments is less than 70 s without lead aircraft history based prediction, i.e. history based prediction reduces pilot speed actions by at least a factor of 2.5.

B. *Step input validation*

Figure 6 shows how selected CAS varied with time for a lead aircraft, a trail aircraft with history based prediction and the same trail aircraft without. Figure 7 shows how the 'shadow' time spacing error decreases as time to go to the merge waypoint decreases.

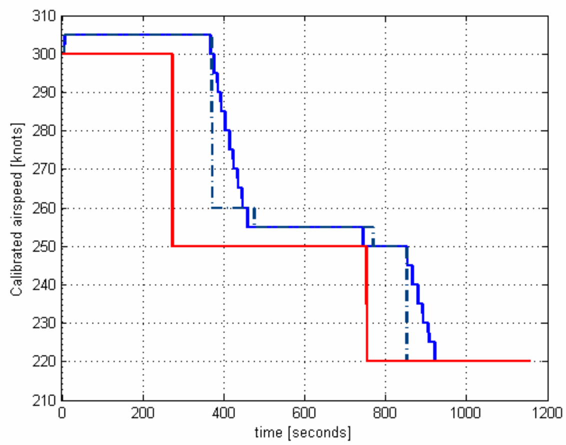

Figure 6: Selected CAS with history based prediction (dotted line) and without (solid line).

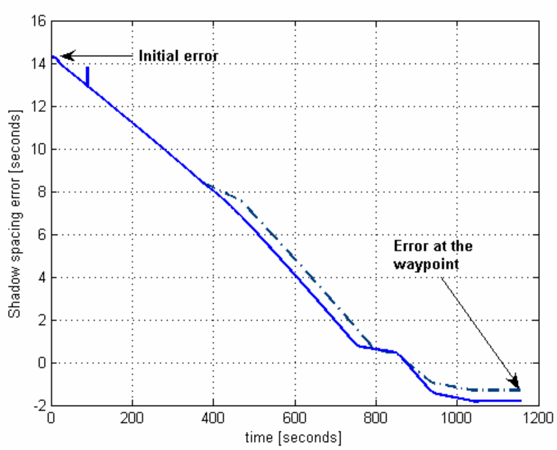

Figure 7: Shadow time spacing error with history based prediction (dotted line) and without (solid line).

In both cases of airborne spacing director with and without history based prediction the performance requirements a) and b) are fulfilled. But the number of suggested CAS adjustments needed to perform spacing significantly decreased (18 speed adjustments reduced to 5) when lead aircraft history based prediction was used.

VII. CONCLUSIONS

An airborne spacing director was designed for a new air traffic control concept enabled by recently developed airborne surveillance technology. The main contribution of this paper was to significantly limit the number of pilot speed actions required to achieve a required time delay behind a lead aircraft on a converging track.

The results were obtained for aircraft of the same type and operating procedures. Future work could investigate the effect of mixing different aircraft types and operating procedures. The proposed speed change detection is based on a derivative search, and works for light turbulence. Further improvements are envisaged to cope with strong turbulence. The interaction between automatic / manual modes, remain / merge, acquisition / maintaining, and aircraft at different altitude levels with different top of descents could also be studied.

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