Curved and steep approach flight tests of a low-cost predictor-tunnel display for small aircraft

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Abstract: A low-cost display and navigation system for visual guidance information in a three-dimensional format is presented in this paper. The basic constituents of the three-dimensional display are a perspective tunnel image for showing the command flight path and a predictor for indicating the future position of the aircraft at an appropriately selected time ahead. Optionally, an image of the outside world can be displayed in an integrated form. The low-cost predictor-tunnel display is directed at an application for small aircraft in order to provide this type of vehicle with improvements for guidance and control. Manual control issues are considered with regard to the features of predictor-tunnel displays. Results from flight tests involving curved and steep approaches are presented for showing the performance of the system.

Keywords: predictor-tunnel display, three-dimensional guidance information, general aviation

1 INTRODUCTION

Recent developments in the field of cockpit displays are concerned with the presentation of visual guidance information in a three-dimensional format [**1–11**]. A promising concept yields a predictor-tunnel display [**1–3**, **10**, **11**]. The displayed information comprises the command flight path in the form of a tunnel and the aircraft position indicated by a predictor at a specified time ahead. Such a display type has gained great interest since it offers the possibility to improve the guidance information for the pilot. This is because it provides the pilot with command and status information, including preview. A further improvement is possible due to the pictorial and descriptive manner in which the visual information is displayed. Thus, an intuitive access becomes feasible, yielding a reduction of the mental effort for reconstructing the spatial and temporal situation. The research on displays with a three-dimensional presentation format shows promising results [**1–11**].

This paper is concerned with a low-cost predictor-tunnel display intended for an application for small aircraft. Results from curved and steep approach flight tests are presented. The purpose is to show how efficient the pilot can be supported by such a display in demanding control tasks.

2 MANUAL CONTROL ISSUES CONCERNING PREDICTOR-TUNNEL DISPLAYS

The configuration of the predictor-tunnel display, which was used in the flight tests, is depicted in Fig. 1. It comprises a tunnel image for showing the command flight path and a predictor for indicating the position of the aircraft at an appropriately selected time ahead. They form central perceptual and cognitive constituents of the displayed visual information. With this kind of status and command information related to current and future flight states, pursuit/preview control and compensatory control are possible. Issues of these control possibilities are dealt with in the following.

The tunnel provides command information and preview. Basically, a pursuit system organization is possible. With adequate transfer characteristics of the pilot in relation to those of the aircraft, the advantages of the feedforward may become feasible for the control task.

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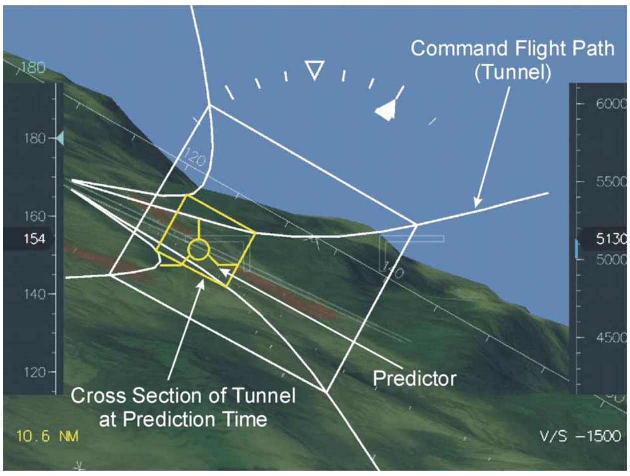

Fig. 1 Display presenting a predictor-tunnel configuration in a three-dimensional format

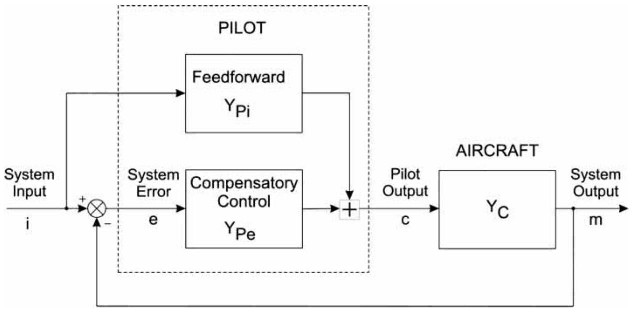

Fig. 2 Model for dual mode pilot-aircraft system

The fundamental properties of the pursuit system organization can be shown by evaluating the pilot-aircraft model presented in Fig. 2. The relations with respect to input, output, and error read

$$\frac{m(s)}{i(s)} = \frac{Y_C(Y_{Pi} + Y_{Pe})}{1 + Y_{Pe}Y_C}, \quad \frac{e(s)}{i(s)} = \frac{1 - Y_C Y_{Pi}}{1 + Y_{Pe}Y_C} \tag{1}$$

If Y_{Pi} is or can be made the inverse of the controlled element

$$Y_{Pi} = \frac{1}{Y_C} \tag{2}$$

it follows from equation (1) that

$$\frac{m(s)}{i(s)} = 1, \quad \frac{e(s)}{i(s)} = 0 \tag{3}$$

As a result, the quality of pursuit control has potential to be superior to the compensatory case. Furthermore, the stability characteristics remain basically unchanged with pursuit control.

With regard to compensatory control, the predictor plays an essential role. The predictor indicates the position of the aircraft at a specified time ahead, the prediction time, which has to be appropriately selected. The position of the predictor symbol in the predictor-tunnel display can be related to a command reference, which is given by the cross-section of the tunnel at the prediction time ahead and specially marked (Fig. 1). Thus, a precise reference is available. The pilot can act in response to deviations of the predictor symbol from the described command reference for minimizing system errors in the presence of command and/or disturbance inputs. This is a compensatory control task for the pilot.

The predictor can be considered to have two functions:

(a) indicator of aircraft position;
(b) element of control system.

These functions are at first treated for the lateral motion, providing details on the manual control issues, and then for the longitudinal case.

The first function, which relates to the original purpose of the predictor, is based on kinematical and geometrical relationships (Fig. 3). It is also of a pictorial nature to comply with the general characteristic of the display as a device presenting visual information in a descriptive manner. The aircraft position at the prediction time ahead is determined using an appropriate mathematical model for describing the continuation of the flight path. There are various models of different complexity. A proven model is referenced to a circular continuation of the flight path. Using this model, the predictor deviation from the command flight path can

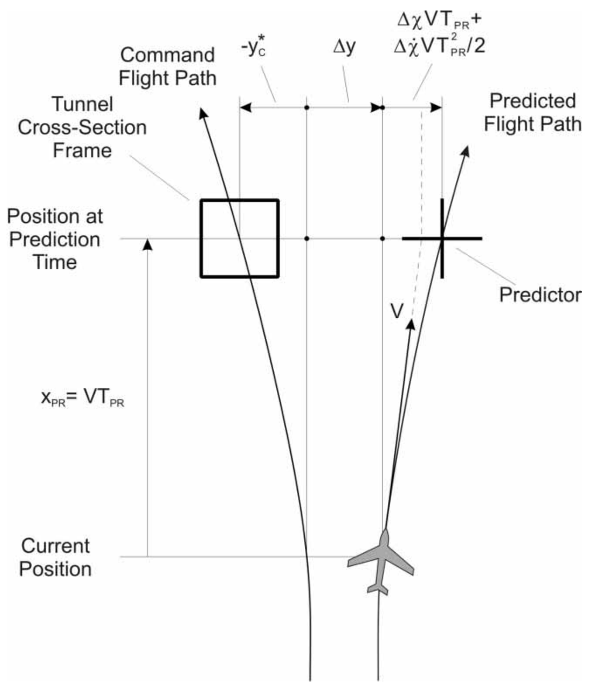

Fig. 3 Predictor indicating lateral aircraft position at prediction time ahead

be expressed as

$$\Delta y_{\mathrm{PR}} = \Delta y - y_{\mathrm{C}}^{*} + \Delta \chi V T_{\mathrm{PR}} + \frac{\dot{\chi} V T_{\mathrm{PR}}^{2}}{2} \tag{4}$$

The goal of the first function is to yield an indication of the predicted aircraft position corresponding with the motion in a realistic manner. Such a feature relates to what may be termed face validity, which concerns the correspondence between status information presented by the predictor symbol in the predictor-tunnel display and the actual situation. The presented status information has a high degree of face validity if there is a clear correspondence. This means for the predictor, which indicates the aircraft position at the prediction time ahead, that the relation between its position and the tunnel has to be realistic in a geometrical and kinematical sense. The face validity issue is considered important since the predictor is an element of a perspective flight path display which presents guidance information to the pilot in a pictorial and three-dimensional format.

The second function of the predictor concerns its role as an element of a control system, within the framework of the manual control task of the pilot. For this function, pilot-centered requirements that result from the presence of the human operator in the control loop have to be taken into account. They pertain to the effort required by the pilot for performing the control task. The goal is an overall predictive system requiring minimum pilot compensation. This goal can be achieved when the equalizations and gains are selected such that the effective transfer characteristic of the controlled element – the predictor-aircraft system – approximates a pure integration over an adequately broad region centered around the pilot-predictor-aircraft crossover [**12**, **13**]. Thus, the goal is (for the frequency region in mind)

$$Y_{\mathrm{PR,lat}} Y_{\mathrm{C,lat}} = \frac{K}{s} \tag{5}$$

where $Y_{\mathrm{PR,lat}}$ and $Y_{\mathrm{C,lat}}$ are the transfer functions of the predictor and the aircraft for the lateral motion, respectively.

For achieving this goal, an appropriate relation was developed for the transfer characteristics of the predictor (Fig. 4). As a result, the following transfer function of the predictor has been obtained

$$Y_{\mathrm{PR,lat}} = K_{\mathrm{PR,lat}}\, g \frac{(K_{\dot{\phi}}/g)s^{3} + (T_{\mathrm{PR}}^{2}/2)s^{2} + T_{\mathrm{PR}}s + 1}{s^{2}} \tag{6}$$

The relation in equation (6) accounts for a roll-rate feedback. This is an expansion when compared with a predictor based on a circular flight path continuation, which corresponds to the expression given in equation (4). Such a feature may be optionally introduced to improve the system characteristics at higher frequencies.

The dynamics of the aircraft given by its transfer function $Y_{\mathrm{C,lat}}$ can be described using the roll mode. This is because the roll mode can be considered to be the dominant mode of the aircraft for the frequency region in mind. The transfer characteristic concerning the roll mode can be expressed as

$$Y_{\mathrm{C,lat}} = \frac{\Delta\phi}{\delta_a} = \frac{L_{\delta_a}}{s(s + 1/T_{\mathrm{R}})} \tag{7}$$

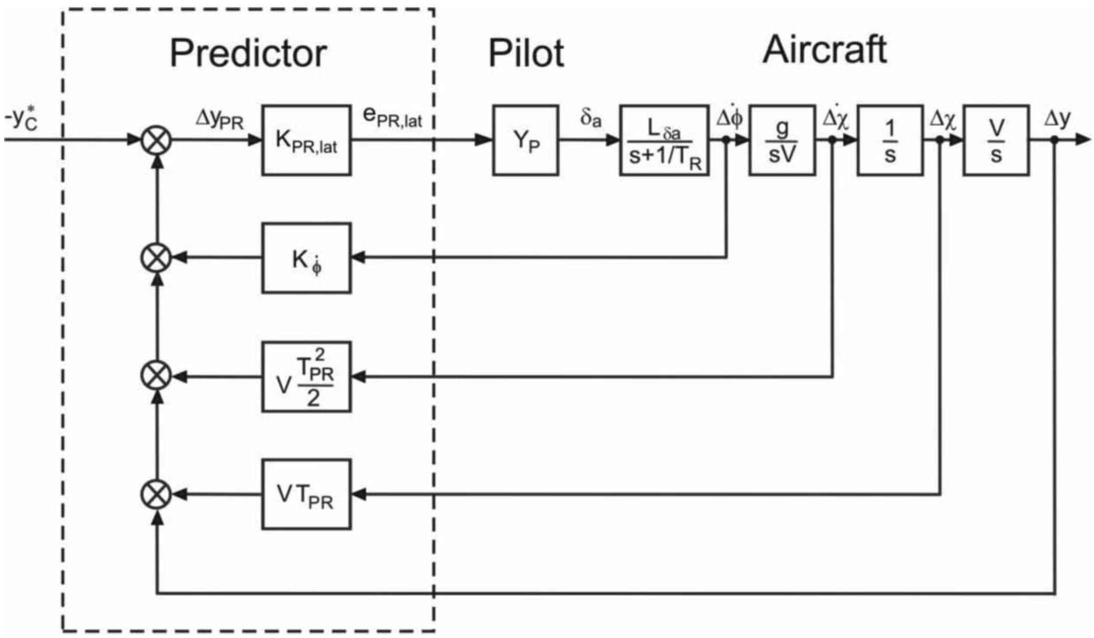

Fig. 4 Control loop with lateral predictor

Combining equations (6) and (7) and selecting

$$K_{\dot{\phi}} \approx \frac{g}{2} T_R T_{PR}^2 \quad (8)$$

yields the following transfer function for the open-loop predictor-aircraft system

$$Y_{PR,lat} Y_{C,lat} = \frac{e_{PR,lat}}{\delta_a} = K_{PR,lat} g L_{\delta_a} \frac{T_{PR}^2}{2} \frac{s^2 + (2/T_{PR})s + 2/T_{PR}^2}{s^3} \quad (9)$$

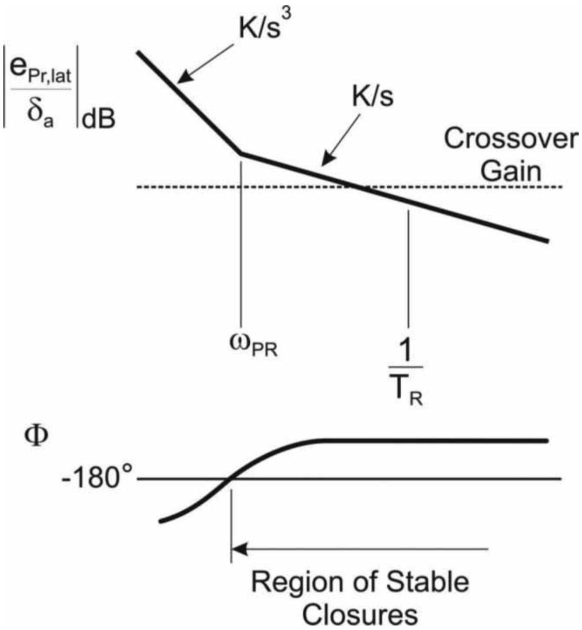

Fig. 5 Asymptotic Bode plot for lateral predictor-aircraft system

This relation describes the transfer characteristic of the controlled element. Proper selection of the prediction time yields a transfer characteristic such that

$$Y_{PR,lat} Y_{C,lat} = \frac{K}{s}$$

in the frequency region around the pilot system crossover (Fig. 5). Thus, a controlled element that requires minimum pilot compensation is achieved.

For the longitudinal motion, basically similar considerations hold for the predictor-tunnel display. Therefore, the treatment of the longitudinal motion can be kept short, with its main aspects described in the following.

The goal is again to achieve a K/s transfer characteristic of the predictor-aircraft system over an adequately broad region centred around the pilot system crossover frequency. For this purpose, an appropriate relation was developed for the longitudinal transfer characteristics of the predictor. The resulting transfer function of the open-loop predictor-aircraft system can be written as (with the aircraft transfer function $Y_{C,long}$ related to the short-term dynamics)

$$Y_{PR,long} Y_{C,long} = \frac{e_{PR,long}(s)}{\delta_e(s)} = -K_{PR,long} \frac{Z_\alpha M_{\delta_e} K_q}{V} \frac{(s + 1/T_1)(s + 1/T_2)}{s^2(s^2 + 2\zeta_{SP}\omega_{SP} s + \omega_{SP}^2)} \quad (10)$$

The associated block diagram is depicted in Fig. 6, which shows the quantities used for presenting the aircraft position at the prediction time ahead in the predictor-tunnel display.

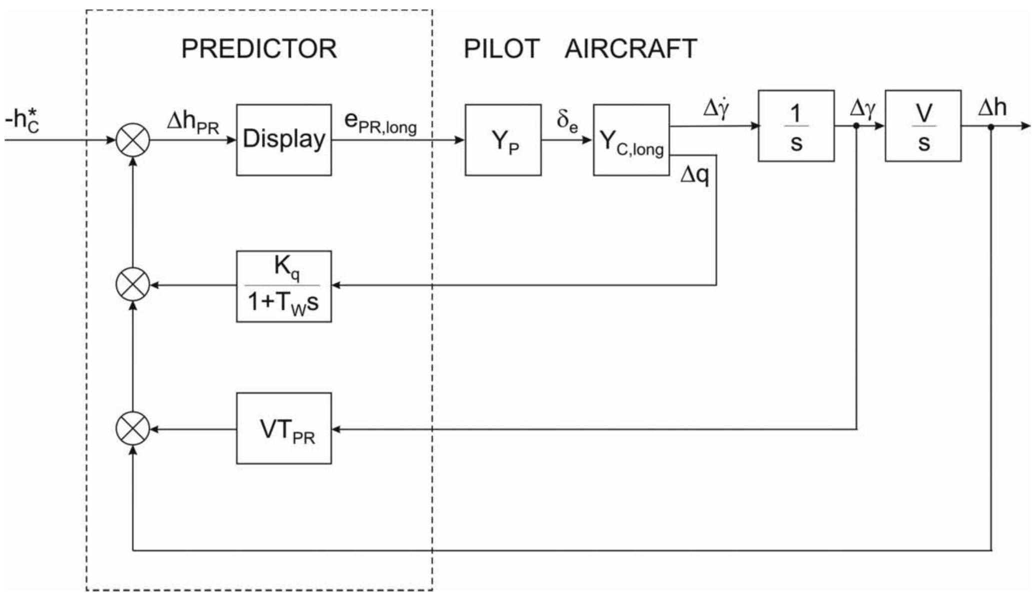

Fig. 6 Control loop with longitudinal predictor

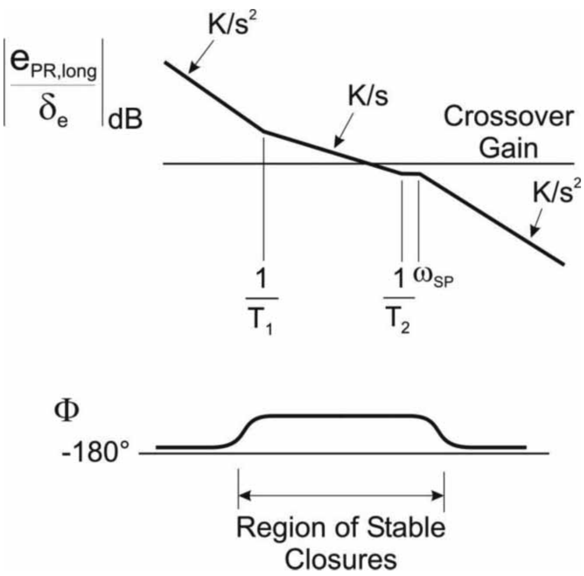

Fig. 7 Asymptotic Bode plot for longitudinal predictor-aircraft system

With a proper selection of the gains, it is possible to achieve a transfer characteristic of the open-loop predictor-aircraft system such that

$$Y_{\mathrm{PR,long}} Y_{\mathrm{C,long}} = \frac{K}{s} \tag{11}$$

for the frequency region related to pilot system crossover (Fig. 7).

With regard to the model describing the flight path continuation, there is a difference in the predictor control law for the longitudinal case when compared with that of the lateral motion. While the lateral motion is referenced to a circular flight path continuation, the model for the longitudinal flight path continuation does not show this feature. This is due to the use of the pitch rate instead of the flight path angle rate (Fig. 6). Thus it was possible to obtain the favourable K/s transfer characteristic for the open-loop predictor-aircraft system in order to achieve a controlled element requiring minimum pilot compensation.

3 RESEARCH AIRCRAFT AND TEST EQUIPMENT

The predictor-tunnel display is installed in the research aircraft of the Institute of Flight Mechanics and Flight Control of the Technische Universität München (Fig. 8). The following components are used to operate the predictor-tunnel display and to generate the three-dimensional imagery:

(a) LCD display;
(b) three-dimensional display computer;
(c) navigation system.

The LCD display presents the three-dimensional guidance information. As shown in Fig. 9, it is mounted at the right side of the cockpit instrumentation panel for the test pilot. The LCD display has a screen size of 10.4", a resolution of 640 × 480 pixels and a brightness of 1600 cd/m^2, with a refresh rate of 60 Hz. The predictor-tunnel configuration corresponds to the one shown in more detail in Fig. 1. The original instrumentation is at the left side of the panel for the safety pilot (Fig. 9).

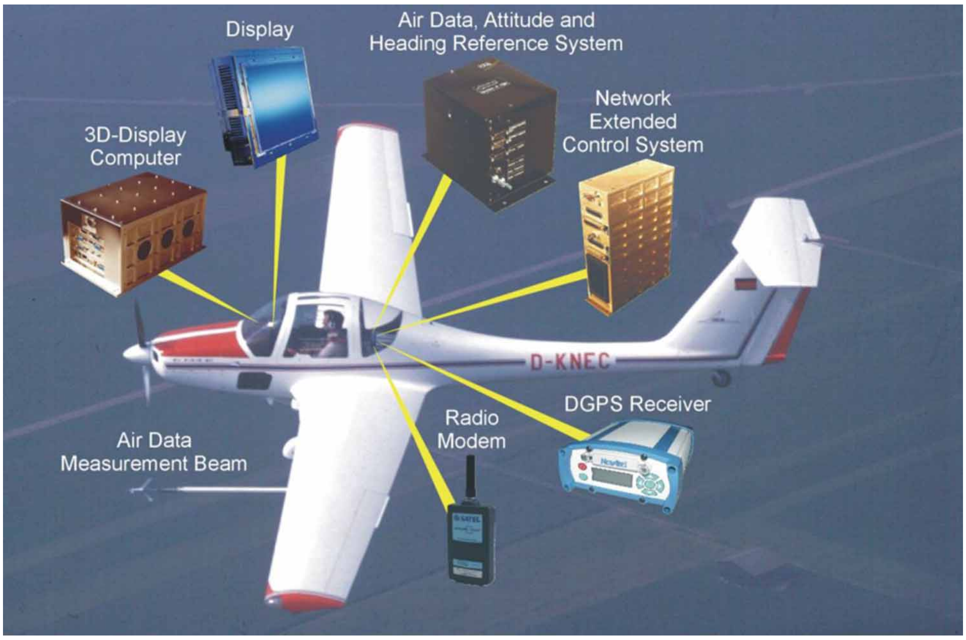

Fig. 8 Research aircraft for flight-testing of predictor-tunnel display

Fig. 9 Cockpit instrumentation with predictor-tunnel display (banked flight condition)

The three-dimensional imagery is generated using a low-cost computer which is based on slot-card PC hardware, with the following data: 1.7 GHz, Pentium IV OS Linux, 256MB. A three-dimensional accelerated graphics-card is applied (*n*VIDIA GeForce4 MX420 PCI), capable of a performance of about 30 million polygons per second.

The low-cost navigation system comprises the following components:

(a) attitude and heading reference unit;
(b) air data measurement unit;
(c) magnetic heading sensor;
(d) D/GPS receiver.

The D/GPS receiver (with a satellite-based augmentation system signal, a differential code and real-time kinematic capability) shows the following performance data for position accuracy: 1.8 m CEP for stand-alone operation, 0.8 m CEP for EGNOS and 0.45 m CEP for differential.

A CAN bus connection is used to exchange data between the predictor-tunnel display computer and the navigation system. It is a two-wire multi-transmitter serial data bus for real-time data transmission. Position data is exchanged via a RS-232 connection between the predictor-tunnel display computer and the GPS receiver.

A substantial contribution for achieving the low-cost goal is due to an efficient computer software for generating and displaying the three-dimensional imagery presented in the predictor-tunnel display. Such a software has been developed at the Institute of Flight Mechanics and Flight Control, and is implemented in the three-dimensional display computer. It provides a real-time capability and a high update rate (30 frames per second).

4 FLIGHT TEST RESULTS

The predictor-tunnel display is subject to a comprehensive flight test program, concerning demanding guidance and control tasks to exploit its capabilities. The flight tests include basic tasks related to straight flight and curved trajectory following as well as more complex flights like curved and steep approaches. Flight test results on curved and steep approaches are presented in the following, providing a representative insight into the performance achieved with the system.

The approach trajectory is graphically illustrated in Figs 10 and 11, which present the vertical profile and the horizontal projection of the command flight path. Markings from A to H are used in the figures to show features of the approach trajectory. Marking A denotes the beginning of the approach trajectory and H the end in terms of the touch-down condition on the runway. At points B to H, there are changes in the approach trajectory. At B and F, simultaneous changes in the vertical and lateral directions take place. The descent angle shows different values, up to 10° (Fig. 10).

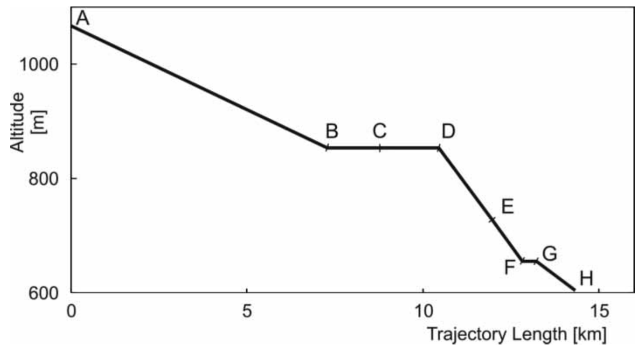

Fig. 10 Vertical profile of the approach trajectory

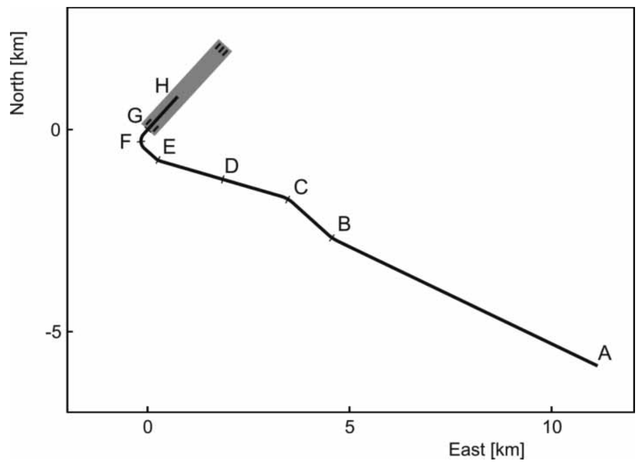

Fig. 11 Horizontal projection of the approach trajectory

The command flight path was presented to the pilot in the predictor-tunnel display in the form of a tunnel which corresponds to the configuration depicted in Figs 1 and 9. The tunnel is 40 m in width and 30 m in height. The predictor symbol and the related command reference given by the cross-section of the tunnel at the prediction time ahead also correspond to the configuration shown in Figs 1 and 9.

Results from the flight tests are presented in Figs 12 and 13, which give the time histories of the vertical and lateral deviations from the command approach trajectory. The results show that the pilots closely followed the command trajectory. There are only small deviations from the command flight path in both the vertical and lateral directions. The aircraft stayed within the tunnel boundaries, which are also indicated in Figs 12 and 13 using an area with a grey shading (±15 m distance from the centre line in the vertical and ±20 m in the lateral direction).

Precise control of the command flight path was also achieved in those segments in which changes in the approach trajectory occur, as well as in the segment with a high descent angle (10°). The segments showing changes in the trajectory relate to points B to H, the positions of which are indicated in Figs 12 and 13. Particularly, the preciseness of the trajectory control also holds for the segments at points B and F where simultaneous changes in the vertical and lateral directions take place (Figs 9 and 10).

The results on the control of the predictor symbol are presented in Figs 14 and 15. In these figures, the vertical and lateral deviations of the predictor symbol position from the command flight path at the prediction time ahead are depicted. The results show that the deviations from the command reference, which is the centre of the tunnel cross-section at the prediction time, are small. However, there are larger deviations when compared with the actual deviations from the command flight path (as shown in Figs 12 and 13). Such a behaviour can be considered as a general feature of predictor-tunnel displays of the kind dealt with in this paper [**11**]. This means that the current position of the aircraft is controlled with higher accuracy.

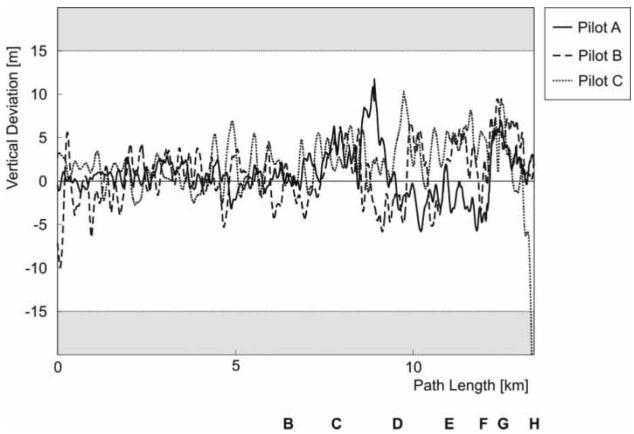

Fig. 12 Vertical deviation from the command flight path

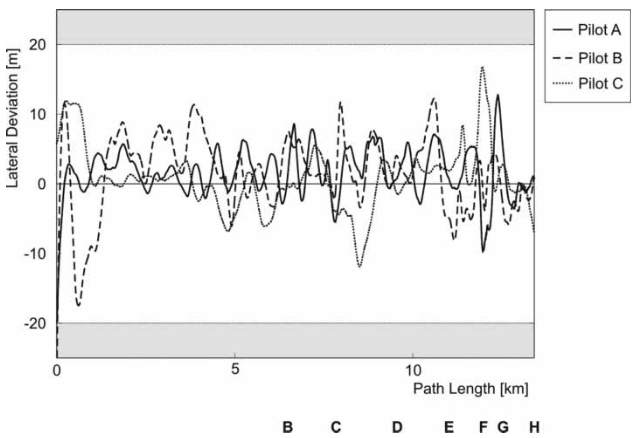

Fig. 13 Lateral deviation from the command flight path

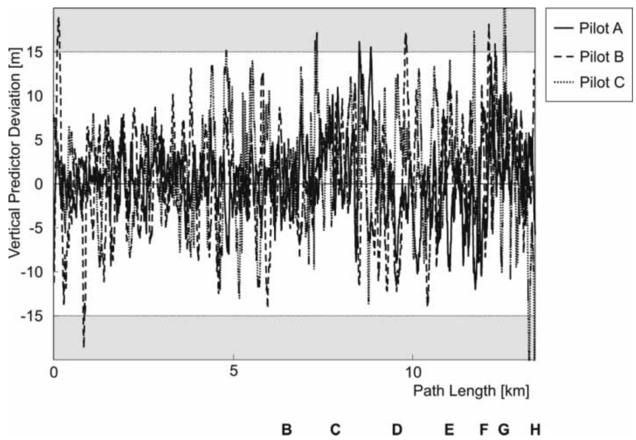

Fig. 14 Vertical predictor deviation from the command flight path

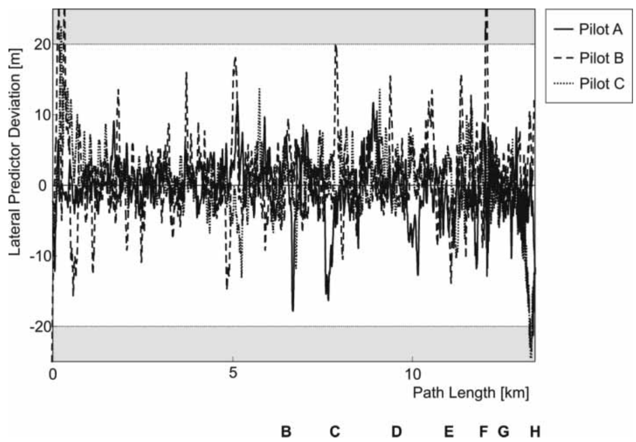

Fig. 15 Lateral predictor deviation from the command flight path

5 CONCLUSIONS

A display presenting a predictor-tunnel configuration in a three-dimensional format is considered a means to improve the visual guidance information of the pilot. The tunnel shows the command flight path and the predictor indicates the position of the aircraft at an appropriately selected time ahead. Manual control issues are dealt with that concern the command and status information as well as the preview provided by the predictor-tunnel display. Results from flight tests involving curved and steep approaches with several trajectory changes in the vertical and lateral directions are presented. They show that the pilots can closely follow the command flight path using the displayed three-dimensional guidance information.

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APPENDIX

Notation

e	system error
g	acceleration due to gravity
h	altitude
$i(s)$	system input
K	gain
L	rolling moment
$m(s)$	system output
M	pitching moment
q	pitch rate
s	Laplace operator
T	time constant
T_{PR}	prediction time
V	speed
$Y(s)$	transfer function
x	longitudinal coordinate
y	lateral coordinate
Z	vertical force
γ	flight path angle
δ	control deflection
Δ	denoting a perturbation, e.g. Δh
ζ	damping ratio
ϕ	bank angle
Φ	phase angle
χ	azimuth angle
ω	frequency

