PILOT-IN-THE-LOOP STUDIES INTO MANUAL CONTROL STRATEGIES WITH PERSPECTIVE FLIGHTPATH DISPLAYS

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Abstract. Conventional flight directors are typical command displays, requiring the pilot to apply a closed-loop compensatory control strategy. In contrast, perspective flightpath display present status information, and as a result allow a wider variety of control strategies to be applied. This paper addresses the different control strategies which are possible with perspective flightpath displays, and discusses two experiments which have been performed to gain more insight into compensatory and error-neglecting control with perspective flightpath displays.

Keywords. perspective flightpath displays, aircraft guidance, manual control.

1. INTRODUCTION

Navigation can be defined as "to direct the course of an aircraft". The guidance task comprises the control of the aircraft to keep position and velocity errors within the constraints specified by the navigation performance requirements. The conventional instrument for the guidance task is the flight director, presenting steering commands.
An alternative guidance display is the perspective flightpath display. A perspective flightpath display presents an integrated view of the desired trajectory specified in the three spatial dimensions on a two-dimensional display. Due to their spatial nature, perspective flightpath displays present navigation and guidance data in a way which is fundamentally different from conventional planar data formats used today, which in turn is likely to influence pilot control strategies. In a study into 2-D and 3-D displays for aviation, Haskell and Wickens (1993) report that the way in which a task was performed differed as a function of the displays employed. The importance of the fact that different displays can result in qualitative, strategic differences is stressed by pointing out that "when making empirical comparisons between different display types, researchers must evaluate measures other than performance on only one type of task; they must go beyond performance in any case and examine task performance strategies".

At Delft University of Technology, research into perspective flightpath displays for guidance and navigation is performed in the context of the Delft Program for Hybridized Instrumentation and Navigation Systems (DELPHINS). Figure 1 presents an example of the DELPHINS Tunnel-in-the-Sky display.

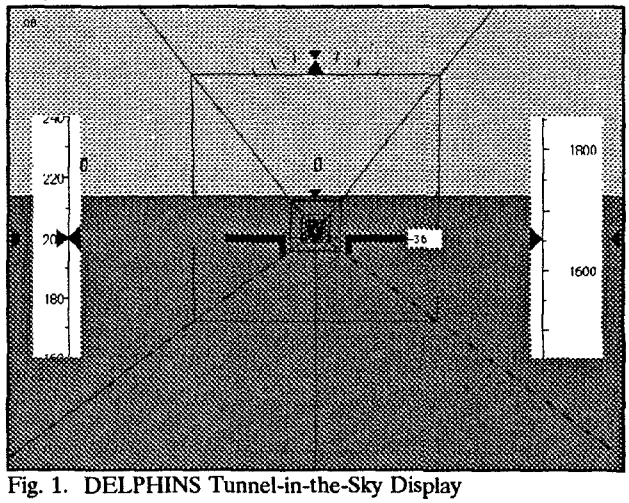

Fig. 1. DELPHINS Tunnel-in-the-Sky Display

To investigate the different control strategies and the influence of several display augmentation concepts which are possible with perspective flightpath displays, pilot-in-the-loop studies have been performed. This paper discusses the results obtained from two pilot-in-the-loop studies in the context of the specific aspects of the data presentation which allow the different control strategies to be applied.

2. GUIDANCE DISPLAYS

Flight director commands are based on a weighted combination of position and angular errors, presented in one dimension. As a result of the integration of multiple parameters into a single dimension, the pilot is unable to extract information about the specific errors from the flight director display. Furthermore, since the error-gains of the display are determined by the flight director algorithms, the possible bandwidth the pilot can apply for scanning and executing the flight director commands is very limited. Finally, the data which is required to maintain adequate spatial and navigational awareness requires the scanning of several other instruments, while the integration of this data has to be performed by the pilot. This process involves mental rotation and scaling operations, which costs time and may introduce errors.

With a perspective flightpath display, the spatial presentation of the imaginary flightpath in the three-dimensional environment can be used to combine guidance data with the data required for spatial and navigational awareness, thus alleviating the pilot from scanning several instruments and performing the mental integrations of the separately displayed position and orientation data into a spatially coherent picture.

With such a display, the pilot is required to fly through a synthetic tunnel which is a representation of his desired three-dimensional flight-path.

Perspective flightpath displays have been discussed since the early fifties, and various concepts for aircraft guidance have been evaluated in simulation (Wilckens and Schattenmann, 1968; Grunwald, 1984; Wickens et al., 1989; Theunissen, 1993), some even in actual flight (Filarsky and Hoover, 1983; Theunissen, 1995).

3. TUNNEL-IN-THE-SKY DISPLAYS

Figure 2 presents a line-drawing of the DELPHINS Tunnel-in-the-Sky display. In this display, the desired flightpath is indicated by the tunnel. In (Theunissen, 1994) it is illustrated how information about position and orientation errors can be extracted from the distortion of the symmetrical shape of the tunnel. The moving horizon presents attitude, while heading information is presented on the horizon line. Altitude, airspeed, and bank are displayed by means of separate indicators. To avoid distortions between the perspective presentation of the three-dimensional flightpath and the attitude presentation, the visible pitch attitude range

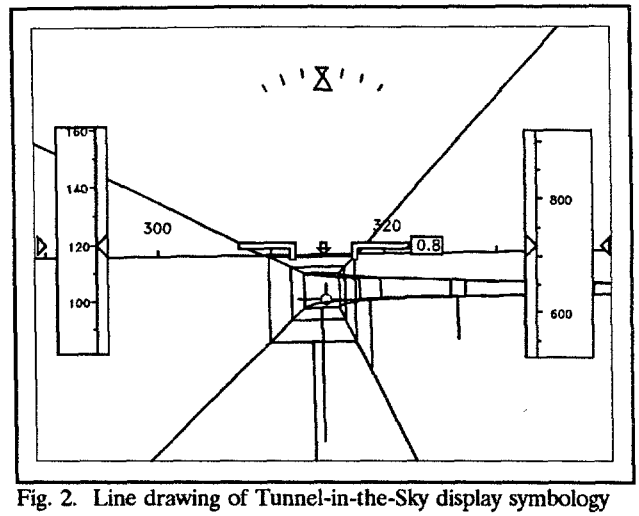

Fig. 2. Line drawing of Tunnel-in-the-Sky display symbology

corresponds to the geometric vertical field of view. To accommodate the fourth dimension, reference speed is presented by means of a bug on the speed-tape. The display also provides the possibility to present integrated speed information by means of a moving window in the tunnel.

Additional information can be presented to aid the pilot with the guidance task. This information has been divided into three levels: Unprocessed status information, processed status information, and command information.

3.1. Unprocessed status information

To aid the pilot in maintaining the correct flightpath angle, a flightpath vector can be presented (Figure 3).

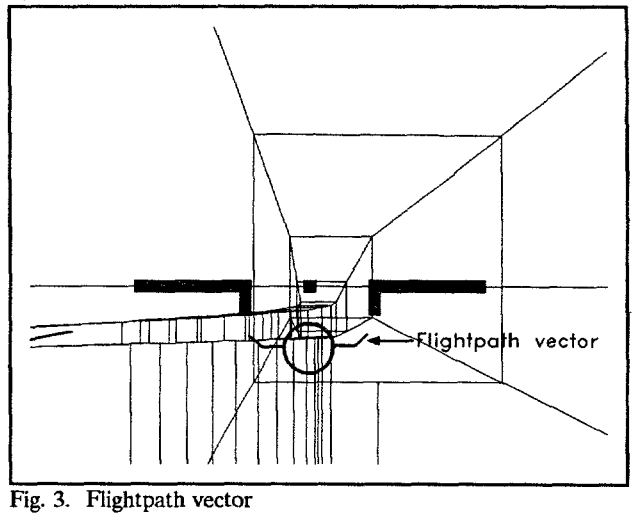

Fig. 3. Flightpath vector

This vector indicates the current direction of the velocity vector of the aircraft relative to the aircraft attitude symbol. Because a flightpath vector presents raw data, it is classified as unprocessed status information.

3.2. *Processed status information*

An airplane is a higher order dynamic system, and the pilot has to determine his control actions by predicting the future system state as a result of his actions. To aid the pilot, a predictor symbol indicating the future position and bank angle can be displayed. To resolve the position ambiguity of the predictor symbol, the cross-section of the tunnel at the position of the predictor is indicated by a transparent window (Figure 4). A predictor is classified as processed status information.

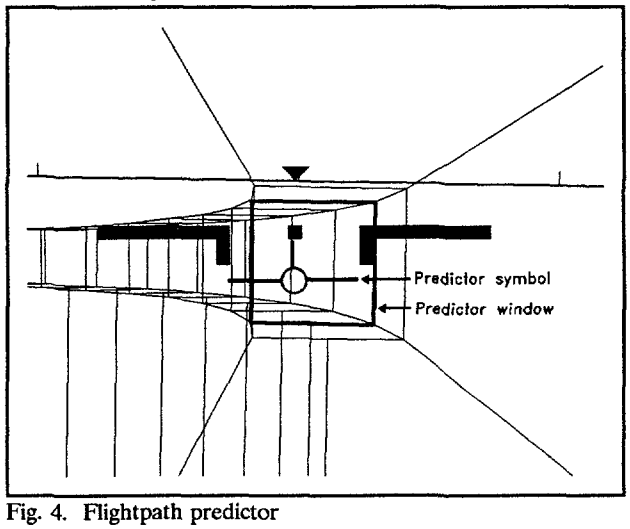

Fig. 4. Flightpath predictor

The size of the tunnel determines the size of the reference window. Thus, with decreasing tunnel size, the resolution of the reference increases. The gain of the position error data, however, is not affected. Both the predictor reference window and the predictor move. The task of keeping the predictor in the center of the reference window is a pursuit tracking task.

3.3. *Command information*

Instead of presenting status information to aid the pilot controlling the aircraft, command information can be presented, e.g. by means of a flight-director.

4. CONTROL STRATEGIES

Ample research has been performed on human control behaviour in compensatory tracking tasks (McRuer et al., 1965). Perspective flightpath displays however, present the pilot with integrated trajectory preview combined with an indication of the allowed deviations, and research into pilot control behaviour when presented with this kind of information is relatively scarce. In (Mulder, 1994) an extensive literature review about the modelling of pilot control behaviour with spatial displays is presented.

With car driving the situation is different. Various models have been proposed to describe driver control behaviour in relation with the visual environment. Since the nature of the control task (boundary control) and the visual cues are quite similar for the guidance task with a perspective flightpath display and car driving, it is expected that there also is a similarity in control strategies.

Concerning car driving, McRuer et al. (1977) present an approach in which they distinguish between compensatory, pursuit and dual mode control behaviour. With compensatory control, the driver uses lateral position and heading errors. With pursuit control the driver takes advantage of the trajectory preview to initiate an open-loop control action to follow the desired path, i.e. the driver applies feedforward control. With dual mode behaviour, the driver initiates an open-loop control action which is succeeded by closed-loop compensatory control.

Gordon (1966) states that "The behaviour involved in steering an automobile has usually been misunderstood. It is less a matter of aligning the car with the road than it is a matter of keeping the focus of expansion in the direction one must go". The velocity field provides information on the speed and direction of the vehicle's forward motion. The driver may become aware of the misalignment of the car by slewing shifts in direction, and by side-slipping sidewise movements which exceed the human visual position and movement thresholds. The driver's perceptual response is based upon an integration of these and other sources of information.

On the basis of human perception theory, it is difficult to determine which of the combinations of slew, sideslip, rate, and amplitude the driver perceives. The driver responds to a total situation, not to isolated or ranked cues. This indicates the necessity of determining a single parameter to describe and predict driver responses. Godthelp (1984) introduced the so-called Time-to-Line Crossing concept, which is based on the assumption that there is a relation between the remaining time the vehicle under control is within a certain boundary, and the moment a control action is initiated.

Most of the available vehicle control models are based on the fundamental assumption that drivers control their vehicle with permanent visual feedback. However, as it is commonly accepted, visual feedback is sometimes interrupted. Godthelp (1984) investigated the potential role of visually open-loop strategies and error-neglection in vehicle control. He assumed that the time available for a driver to

control his vehicle in an open-loop mode largely depends on the accuracy of the open-loop generated steering-wheel action and the time available for error-neglection.
The control activity indicates the amount of effort invested in the control task. For continuous closed-loop control tasks, frequency domain techniques are very useful for describing control behaviour. However, for non-continuous control behaviour encountered during error-neglection and open-loop control, time domain techniques may be more appropriate.

5. SIMULATOR EVALUATION

As indicated in the previous section, it is expected that a similarity in control strategies between car driving and flying a tunnel-in-the-sky display exists. To evaluate pilot performance and control behaviour and obtain suitable values for the design parameters of the perspective flightpath display, several experiments have been conducted in the moving-base flight simulator at Delft University of Technology. In an experiment performed in 1993, closed-loop compensatory control was investigated. In 1994, error-neglecting control strategies were examined. The simulated aircraft was a twin-engine business jet, which is also used for the in-flight experiments.

5.1. Experiment I

In 1993 pilot performance and control behaviour when flying a Tunnel-in-the-Sky with the addition of a flightpath vector (FPV) and with a flightpath position predictor (FPP) for different error gains was investigated (Theunissen, 1993).

5.1.1. Experimental setup

Five pilots, of whom two student pilots and one none-pilot, participated in the experiment. The study consisted of a 3x2 within subject design. Pilots flew three different tunnels (22.5, 45, and 90 m width), in two different configurations (FPV, FPP). Each condition was replicated five times, resulting in a total of 30 flights for each pilot. The order in which the tunnels were presented in a certain configuration was balanced to be able to compensate for possible learning effects.
Pilots started their flight at an altitude of 1200 ft about 4 miles away from the runway threshold. The task of the pilot was to fly the curved approach as accurate as possible using the Tunnel-in-the-Sky display, and land the aircraft. Pilots were required to maintain an airspeed of 120 knots. The airspeed was indicated by a green bug on the speed-tape. No additional speed cues were presented in the display. At the beginning of the flight, the aircraft was already in the landing configuration, so no aircraft configuration changes had to be made by the pilot.
Before the experiment started, pilots were briefed on the display and the approach. After the briefing, the training sessions started. To reduce the learning effect, pilots performed eight flights in each display configuration. The standard deviation of their horizontal and vertical path error was calculated for these flights and used as a measure of performance. If performance still appeared to improve after the first eight training flights, more training flights were issued.

5.1.2. Results

Results showed that both in the FPV and the FPP configuration, tracking accuracy increased linearly with decreasing tunnel size (Figure 5).

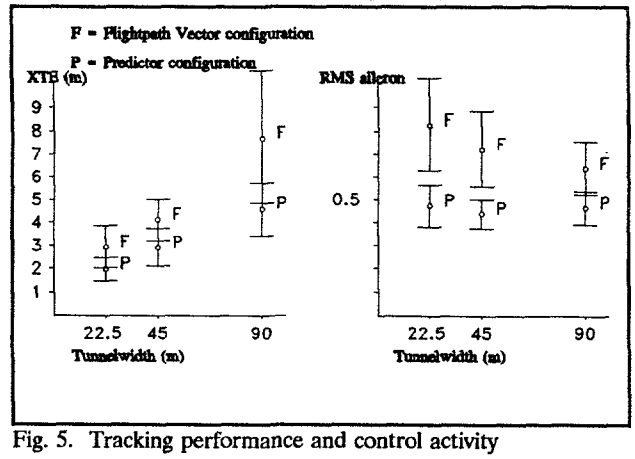

Fig. 5. Tracking performance and control activity

With the FPV, control activity was linearly related to error gain, whereas with the FPP no significant difference in control behaviour was found for the different tunnel dimensions. Figure 6 shows the average *XTE* for the five consecutive segments of the approach.

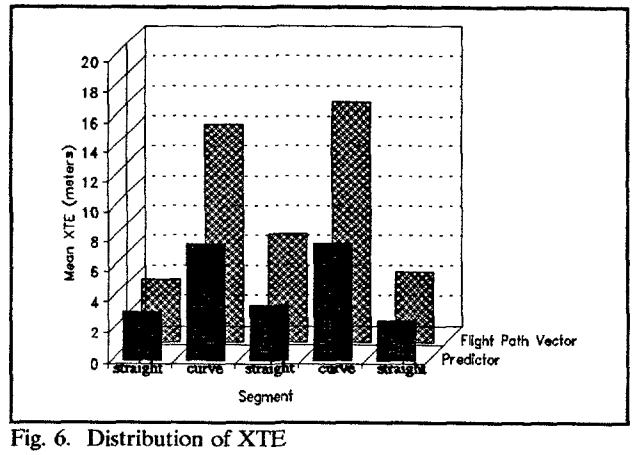

Fig. 6. Distribution of XTE

The second and fourth bar present the results for the curved sections, and show a decrease in tracking accuracy. This can partly be contributed to the increasing difficulty of the control task, and the fact that it is impossible to perfectly transition from a straight segment to a circular one. Since in a curve a FPV presents no adequate lateral guidance cues, this will also decrease tracking accuracy.

To illustrate the difference between control activity with the FPV and with the FPP, Figure 7 presents a cumulative distribution of the aileron deflections.

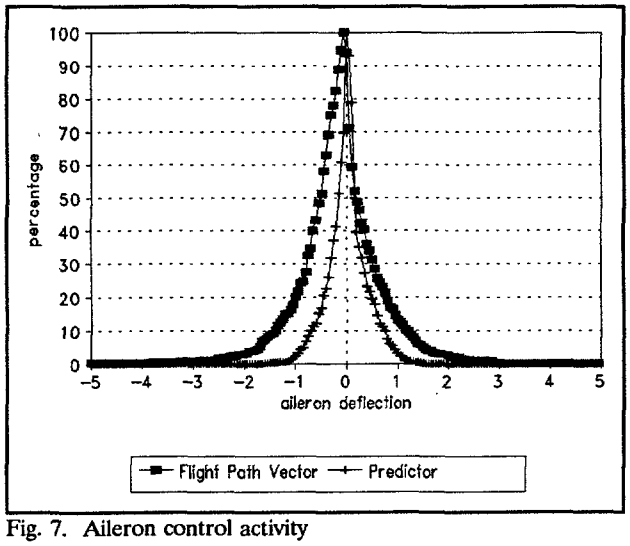

Fig. 7. Aileron control activity

As can be seen from this Figure, approximately 20% of the deflections made in the FPV configuration exceeds the maximum deflections made in the FPP configuration. The fact that in the FPP configuration control activity does not significantly increase with an increase in position error gain, suggests that in the presence of an adequate prediction of the future position and attitude, the pilot does not use the error information presented by the tunnel, but only the error presented by the predictor for the control task. Thus, when the pilot is told to fly as accurate as possible, he is likely to use the information with the highest error gain he can process to perform this task. In case of an additional flight director or predictor, the pilot will mainly concentrate on the data presented by this indicator, and control behaviour will be dominated by closed-loop compensatory and pursuit control respectively. The perspective presentation of the flightpath provides the information which allows the pilot to anticipate changes in the trajectory. When the task relaxes to maintaining the position error below the thresholds indicated by the walls of the tunnel, a shift towards more open-loop control strategies is possible.

5.2. *Experiment II*

In a follow-on study, error-neglecting control strategies were investigated (Theunissen and Mulder, 1994). The goal of this study was to determine what causes the pilot to initiate error-corrective actions. It was hypothesized that the moment an error-corrective action is initiated is strongly related to the time remaining before the aircraft crosses one of the boundaries indicated by the tunnel walls, and that the pilot uses temporal range information from the display for his decision to intervene.

5.2.1. Experimental setup

Five subjects, all airline pilots, were instructed to fly an approach to landing. After several training sessions, each pilot performed thirty approaches. To prevent the pilots from becoming accustomed to a particular approach, six different approaches were presented in a random order. To prevent them from applying a dominantly closed-loop compensatory control strategy, they were explicitly instructed that the goal was not to fly as accurate as possible, but to remain inside the tunnel using minimal control effort. A relatively low error gain was used by presenting tunnels with a width of 135m.

5.2.2. Data analysis

Data analysis was performed for data relevant to aircraft control in the lateral-horizontal plane, both for a first and a second order *TWC* model. The assumption for the first order model is that the pilot does not use a yaw component in his estimate, and consequently assumes a straight trajectory. This is comparable to the Time-To-Contact (Lee, 1976) and Time-To-Passage (Kaiser and Mowafy, 1993) models. Equation 1 presents the second order model:

$$TWC = \frac{\cos^{-1}\left(\cos(TAE) - \frac{r\left(\frac{width}{2} - XTE\right)}{V}\right)}{r} + \frac{TAE}{r} \qquad (1)$$

In Equation 1 *width* represents the tunnel width [m], *XTE* the cross-track error [m], *TAE* the track-angle error, V the velocity [m/s] and r the yaw rate [rad/sec].

For both models, the consistency between the direction of the control actions and the prediction of the tunnel intersection (left or right) was analyzed. When the model predicts an intersection of the left tunnel wall, and the pilot initiates an error corrective action to the left, the outcome of the model is regarded as inconsistent with pilot control behaviour. At the time a control action was identified as an

error-corrective control action, all variables of interest (*XTE*, *TAE* and *TWC*) were recorded.

5.2.3. Results and discussion

Figure 8 and 9 present a distribution of the *XTE* and *TAE* variables respectively, at the moment an error-corrective control action was initiated.

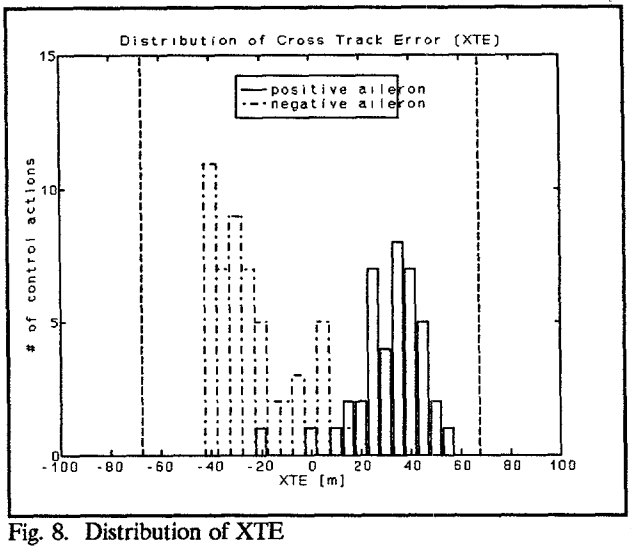

Fig. 8. Distribution of XTE

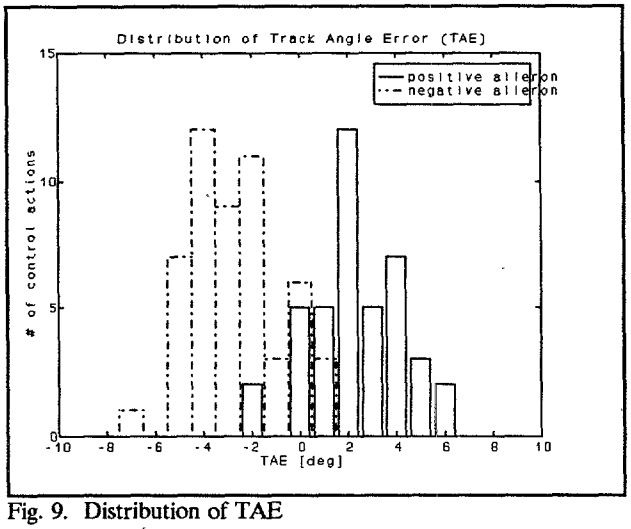

Fig. 9. Distribution of TAE

These figures indicate that there exists a large variation between the magnitudes of these variables and the number of initiated control actions. Furthermore, since no minimum threshold can be established in these distributions, it can be concluded that no individual guidance variable is solely responsible for switching from error-neglecting to error-correcting control, which strengthens the hypothesis of an integrated parameter.

In the curved segments the first order model produced completely inconsistent predictions, whereas the second order model was highly compatible with the direction of the control actions performed by the pilot. On the straight sections, both the first and the second order model predicted compatible control directions. The results showed that the *TWC* estimates of the second order model yielded a significantly smaller standard deviation as compared to the first order model. The first order model often (>50%) produced *TWC* estimates which exceeded 20 seconds, and it was concluded that the pilot does take yaw into account on the straight segments.

When examining the distribution of the *TWC* (Figure 10), it can be seen that no control actions were made for *TWC* values smaller than approximately 4 to 5 seconds.

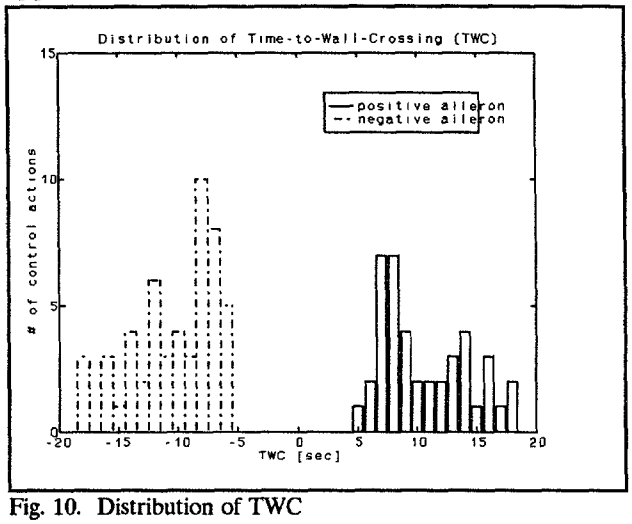

Fig. 10. Distribution of TWC

This strengthens the hypothesis that pilots maintain a certain temporal spacing from the boundaries represented by the tunnel walls, which they directly perceive from the display.

A statistical analysis (non-parametric Kolmogorov-Smirnov), showed that none of the distributions were from a normal population. Furthermore, no statistically significant differences were found between the distributions of control actions related to preventing crossing the right or left tunnel walls, allowing both distributions to be combined. As can be seen from Figure 11, showing box-plots of the combined distributions, the error-corrective control actions are initiated for a wide range of individual guidance variables.

For the *TWC* variable, however, the ratio between the standard deviation and the mean remains rather small, supporting the hypothesis that pilots maintain a certain temporal spacing from the boundaries represented by the tunnel walls, which they directly perceive from the display. The temporal spacing varies between pilots, and is believed to be determined by a self-chosen safety margin which, in turn, is largely determined by the familiarity the pilot has with the airplane and its handling qualities.

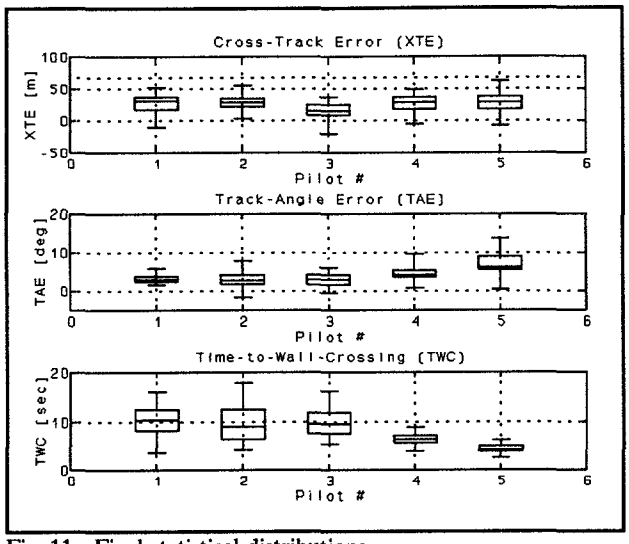

Fig. 11. Final statistical distributions

6. CONCLUSION

The first study illustrates that the size of the perspective flightpath can be used to help the pilot obtain a certain required performance. Introduction of the flightpath predictor can be used to increase the pilots' performance, while reducing control activity. Such a display combines the best properties of two concepts. It presents integrated trajectory, position and attitude information which contributes to the pilots spatial and navigational awareness and increases his level of confidence, and it presents processed status information which allows him to spend less effort to control the system.

The second study illustrates that one of the advantages of the perspective flightpath display is that, due to its integrated presentation, pilots do not have to mentally integrate the values of position and angular errors and error rates and verify whether the outcome exceeds a certain threshold, which would be required for error-neglecting control with non-integrated displays. Instead, the ego-referenced spatial presentation of guidance data allows pilots to extract temporal range information which enables them to apply an error-neglecting control strategy.

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