JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 28, No. 6, November–December 2005

Integrating Fly-by-Wire Controls with Perspective Flight-Path Displays

M. Mulder,* A. R. Veldhuijzen,† M. M. van Paassen,‡ and J. A. Mulder§
Delft University of Technology, 2629 HS Delft, The Netherlands

To further improve the pilot manual tracking performance and to reduce workload while operating with a perspective flight-path display, the approach has generally been to augment the display with guidance symbology such as a flight-path predictor. An alternative approach would be to augment the controls. That is, through the use of fly-by-wire control technology, the aircraft flight controls can be tailored in such a way that they become compatible with the display. The design and experimental evaluation of two flight control systems to be used in conjunction with a perspective flight-path display are discussed. The first system aims at automating the innermost loop of the aircraft attitude, attitude-oriented fly by wire. The second system aims at automating the aircraft middle loop of flight path as well, namely, flight-path-oriented fly by wire. Both of the designs are evaluated in two pilot-in-the-loop experiments, one conducted in a fixed-base simulator and one in a moving-base flight simulator. These experiments confirm that control augmentation can reduce pilot workload considerably, while at the same time improving path-following performance. The flight-path oriented control augmentation outperforms the other design, with superior path-following performance achieved with the lowest pilot control activity and workload. The benefits of the flight-path-oriented flight control systems become more apparent when the difficulty of the pilot task increases.

Nomenclature

n_z	=	normal acceleration
x_e, v_e, t_e	=	lateral, vertical, and total position error, m
γ_e	=	climb angle error, deg
$\delta_{a_c}, \delta_{e_c}$	=	aileron and elevator control surface deflections, deg
$\delta_{a_s}, \delta_{e_s}$	=	aileron and elevator stick displacements, deg
δ_{r_c}	=	rudder control surface deflection, deg
δ_{r_s}	=	rudder pedal displacement, deg
θ, φ	=	pitch and roll attitude angle, deg
$\dot\theta, \dot\varphi$	=	pitch and roll attitude angle rates, deg/s
χ_e	=	track angle error, deg

Introduction

PERSPECTIVE flight-path displays such as the "tunnel-in-the-sky" or the "highway-in-the-sky" are widely recognized for their potential to help pilots manually control their aircraft along complex curved trajectories.[1–9] By the presentation of the pilot with the trajectory to follow in an intuitive three-dimensional fashion, while at the same time including the guidance constraints, the display directly portrays the pilot's primary aircraft guidance and control task. Through increasing pilot situation awareness the flight safety improves, in particular for more complex and, therefore, more critical operations. As a result, these displays may allow such complex routings to be issued to pilots, with important potential benefits for air traffic management and for noise abatement during departure and approach.[1–10]

Although the tunnel display is generally considered to be a great step forward in terms of presenting the aircraft guidance information, the hypothesis that it will truly simplify the pilot's manual aircraft control task has yet to be proven. In the 1980s, one of the main tunnel display pioneers, Arthur J. Grunwald, reported considerable difficulty for pilots in accurately following complex curved tunnel trajectories[4] (see also Ref. 2). Based on his experience, such as with the teleoperation of unmanned aerial vehicles (see Refs. 11 and 12), he decided to augment the display by presenting additional symbology. Guidance symbols like the flight-path vector (FPV), showing the instantaneous direction of the aircraft motion with respect to Earth and, in particular, the flight-path predictor (FPP), showing the aircraft future position a couple of seconds ahead, have been shown to facilitate the pilot's task greatly.[4,5,9,13–18] For the same reason, integrating flight director-like guidance with the display was considered.[19] In either case, display augmentation effectively closes the outer loops of the pilot's guidance task, leaving the pilots with equivalent dynamics that are relatively simple to control. However, this approach puts the pilot into a role of a compensatory inner-loop controller, which can result in considerable levels of pilot workload and a suboptimal path-following performance.[8,20,21]

Another, less actively pursued way to improve the performance of pilots and to decrease workload with the tunnel display is fundamentally different. Here, the approach is to use control augmentation techniques that have become available with the introduction of fly-by-wire technology.[22–26] With fly by wire (FBW), the opposite of display augmentation can be achieved, that is, the inner loops of the pilot's guidance task become automatically controlled, leaving the pilot with the opportunity to manipulate directly aircraft states higher in the control hierarchy, for instance, the direction of the aircraft motion.

The goal of this paper is to investigate the advantages of two candidate FBW flight control systems (FCS) when used in conjunction with the tunnel display: attitude-oriented control and flight-path-oriented control. In the attitude-oriented solution, the pilot control inputs act as attitude-rate, that is, pitch-rate and roll-rate, commands: When the pilot control input is zero, the system maintains the instantaneous attitude. With the flight-path-oriented system, pilot control inputs act as flight-path vector rates, that is, climb angle rate and track angle rate, commands. In other words, the pilot commands the

Presented as Paper 2002-4928 at the AIAA Guidance, Navigation, and Control Conference, Monterey, CA, 5–8 August 2002; received 3 August 2004; revision received 19 October 2004; accepted for publication 20 October 2004.

*Assistant Professor, Control and Simulation Division, Faculty of Aerospace Engineering, Kluyverweg 1; m.mulder@lr.tudelft.nl. Member AIAA.

†Research Associate, Control and Simulation Division, Faculty of Aerospace Engineering, Kluyverweg 1; a.r.veldhuijzen@bluewin.ch.

‡Assistant Professor, Control and Simulation Division, Faculty of Aerospace Engineering, Kluyverweg 1; m.m.vanpaassen@lr.tudelft.nl. Member AIAA.

§Professor and Chairman of the Control and Simulation Division, Faculty of Aerospace Engineering, Kluyverweg 1; j.a.mulder@lr.tudelft.nl. Member AIAA.

aircraft direction of motion relative to the ground. When the control input is zero, the FCS maintains the selected inertial flight path. Earlier studies, conducted in the context of simplifying the aircraft manual control task for general aviation pilots, have shown the potential benefits of the flight-path-oriented FCS, also in conjunction with a perspective flight-path display.[27–29]

In this paper, the discussion focuses on the design and experimental evaluation of the two control augmentation systems just introduced. It is structured as follows: First, the fundamental differences between display and control augmentation are discussed, followed by a description of the main principles in control augmentation. Second, the control law design and a handling qualities analysis of the two FCSs evaluated here are described. Third, the results of two experiments, one conducted in a fixed-base flight simulator and one in a high-fidelity motion-base simulator will be described. The first experiment is designed to evaluate the FCS designs experimentally under various levels of task complexity as defined by trajectory difficulty and atmospheric turbulence intensity.[26,30] The second experiment aims at investigating the effects of flight simulator motion on the performance of the two designs.[31]

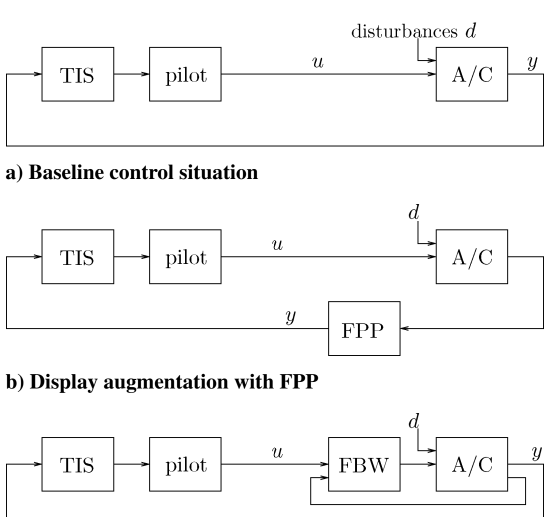
Display Augmentation and Control Augmentation

In this section, the fundamental differences between display and control augmentation will be elaborated on. To make these differences clearer, the discussion is rather broad. A more detailed discussion of the control augmentation concepts used in the present study is presented in the next section. Figure 1 shows the two augmentation concepts in relation to the baseline control situation and forms the starting point of the discussion.

Fundamentals of Display Augmentation

Irrespective of the type of cockpit displays presenting the aircraft state to the pilot, the main issues that are of concern to the pilot in the aircraft guidance task are probably those of where am I? and where am I going? The advantage of electronic displays over their (electro-)mechanical predecessors is that they can be augmented with synthetic symbology designed to help pilots in conducting their tasks in a satisfactory manner.

The synthetic enhancements are generally a form of augmenting cues, which can be defined as "a perceptual event auxiliary to the basic display that is used to enhance an important characteristic of the display."[32] In the past, numerous investigations have been conducted addressing the usefulness of synthetic symbology in two-dimensional[11,14,33] and three-dimensional[2,3,9,12,17] aircraft guidance displays.



a) Baseline control situation

b) Display augmentation with FPP

c) Control augmentation with FBW

Fig. 1 Three augmentation forms, in simplified form, for control of an aircraft with a tunnel-in-the-sky display; *u*, *y*, and *d* are pilot control input, aircraft output, and disturbances (e.g., turbulence) acting on the aircraft, respectively.

That visually presented augmenting cues have often been shown to considerably improve human performance is generally explained using two principles.[32] First, a well-designed display augmentation transforms the task at hand from a computational to a perceptual task; second, it provides a means of establishing or improving the compatibility between the display and the operator's mental model of the system and the corresponding task.

Another property of display augmentation, unfortunately one that is less commonly known beyond the control engineering domain, is that display augmentation effectively changes the equivalent dynamics of the control task itself.

This is shown, albeit in a very simplified way, in Fig. 1. In the baseline situation, Fig. 1a, the aircraft dynamics H_{ac} govern the relation between the output y and the joint effects of the pilot input u and the disturbances d acting on the aircraft, that is, $y = H_{ac}(u + d)$. The pilot control of the aircraft is based on the aircraft output shown on the display. When including an FPP symbol on the display (Fig. 1b), the pilot will alter his control strategy toward controlling this symbol on the display, with the relationship between the pilot control and the FPP output y used for control given by $H_{ac}H_{FPP}$, with H_{FPP} being the dynamics of the FPP. Hence, with a smart choice of the predictor dynamics, the equivalent dynamics that are controlled by the pilot can be modified. That is, the display augmentation dynamics can effectively cancel out part of the aircraft dynamics, reducing the order of control considerably, preferably to a single integrator over a wide frequency range.[34] The important advantages of this principle have been shown in earlier surveys on this topic.[4,9,12,13,17,34] In fact, this augmentation principle also underlies the working principle of conventional flight-director guidance systems.[7]

In terms of disturbance rejection (i.e., mitigating the effects of the disturbance d acting on the aircraft), display augmentation is less suitable. The output y of the FPP will be a joint function of the pilot input u and the disturbance d, $y = H_{ac}(u + d)$, and the pilot will have to compensate for all disturbances. Also, in the driving of the FPP motion on the display, the predictor law depends particularly heavily on the higher-order states of the aircraft (accelerations and attitude rates).[9,13] Hence, when flying through heavy turbulence, this can result in unacceptably high-frequent motions of the FPP, which reduces the usefulness of display augmentation considerably.[11,12,16] Filtering the signals suppresses the high-frequency content, but also adds a lag to the closed-loop system, reducing the phase margin of the system.

Fundamentals of Control Augmentation

The control augmentation solution to simplify the pilot's manual control task is fundamentally different. Here, an FBW control system effectively closes one or more of the aircraft feedback loops, automating parts of the aircraft control considerably (Fig. 1c). The pilot's stick input is interpreted by the computer as a command or reference, and the FBW control law will generate the appropriate control inputs.

Now, recall the disturbance rejection problem. With FBW, the output of the aircraft y remains a function of the pilot input u and the disturbance d acting on the system. However, because the FBW effectively closes (some of) the aircraft feedback loops, it also automatically reduces the effects of disturbances considerably. Assume that the FBW dynamics are given by H_{FBW}, then the effective dynamics that the pilot is controlling equal $H_{FBW}H_{ac}/(1 + H_{FBW}H_{ac})$. Now, the disturbances still act on the vehicle, but their effect on the aircraft output y are now governed by the dynamics $H_{ac}/(1 + H_{FBW}H_{ac})$. Hence, a high bandwidth of the FBW control system yields not only a desired command/response relationship ($y \approx u$), but also mitigates the effects of disturbances acting on the vehicle.

When this seemingly complex problem is reduced to its roots, the primary advantages of control augmentation vs display augmentation become clear, and that is the automatic disturbance rejection conducted by the FBW system. This is the main cause of the substantial reduction of workload that can be achieved by the control augmentation, as has been reported in several previous studies.[22–25] A detailed analytical, as well as experimental, comparison between some of the main display and control augmentation concepts is described by Lam et al.[34]

Control Augmentation Concepts

Two candidate FBW control systems, the attitude-oriented control and the flight-path-oriented control, are the subject of this study. These will be compared to the baseline situation of the direct-link, unaugmented manual flight control. Before the origins of these two FBW concepts are discussed, the direct-link manual flight control will be discussed.

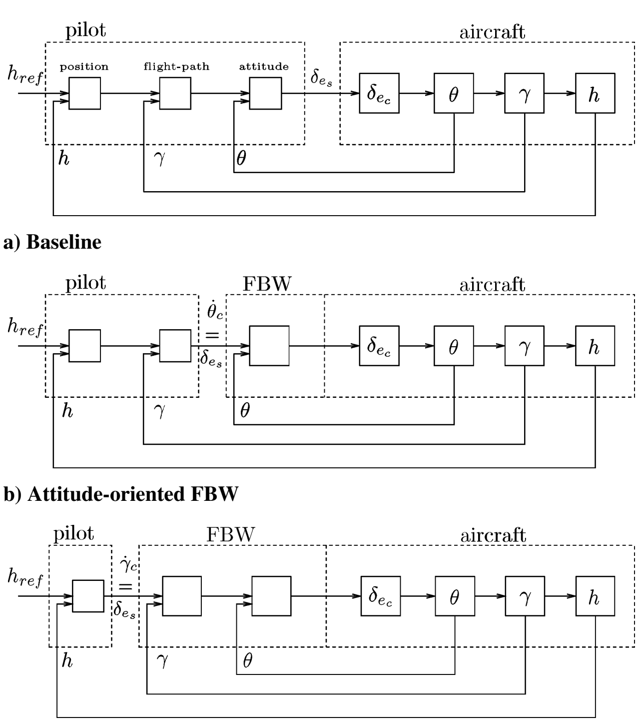
Figure 2a shows the baseline manual control of an aircraft in the task of following a trajectory in space, with the pilot closing sequentially the loops of attitude (inner loop), flight path (middle loop), and position (outer loop). The control surface deflections are directly linked to the pilot stick and rudder pedal displacements. In a perspective flight-path display, as in any artificial horizon display, the attitude can be perceived from the translation and rotation of the horizon line. The position and direction of motion relative to the tunnel trajectory is conveyed by the changing tunnel geometry.[7,21,35,36] The inner loops serve the outer loops, that is, when the aircraft has to change its lateral position relative to the tunnel, for example, it must change its lateral direction of motion, and to achieve this, the aircraft must bank. Note that, in general, the crucial part of the aircraft flight dynamics, in terms of the aircraft handling characteristics, appear in the inner loop, whereas the middle and outer loops are simply the kinematics.[21]

In the unaugmented control situation, this serial, multiloop hierarchical feedback model can effectively describe the pilot control behavior.[7,21] Although the aircraft direction of motion can be inferred from the tunnel motion perspective, the explicit presentation of the direction of flight through the FPV symbol is known to improve pilots' performance considerably.[4,7,12,16] Unlike the FPP, however, the FPV does not have any effect on the basic flight control strategy, which remains essentially the one shown in Fig. 2a (Ref. 7).

Attitude-Oriented FCSs

With an attitude-oriented FBW system (Fig. 2b), the pilot stick deflections are interpreted as attitude-rate commands. In the case of no pilot inputs, the FCS maintains the current aircraft attitude, compensating for disturbances acting on the aircraft. Thus, in comparison to the baseline control, the FCS closes the inner loop, and the pilot closes the middle and outer loops. Hence, with a proper design of the flight control laws, one can effectively reengineer the natural aircraft attitude response on stick input, crucial in aircraft handling characteristics.

A similar rate-command and attitude-hold control law has gained general acceptance and approval in the A320/330 and 340 family of transport aircraft of Airbus Industries in the low-speed regime.[24–26,37] The advantages are primarily that it results in a reduction of pilot workload, allows the implementation of flight envelope protection, and, above all, allows for the development of a family concept, that is, a range of aircraft that have quite similar handling characteristics.[38,39]



a) Baseline

b) Attitude-oriented FBW

c) Flight-path-oriented FBW

Fig. 2 Three main forms of aircraft control investigated shown here for the vertical flight dimension.

Flight-Path-Oriented FCSs

Flight-path oriented FBW systems (Fig. 2c), extend the automation of the aircraft control task one level higher. Here, pilot stick deflections are interpreted as flight-path-rate commands. In the case of no pilot input, the FCS maintains the current aircraft direction of motion, compensating for disturbances. In comparison to the baseline controller, the FCS now closes both the inner loop as well as the middle loop, and the pilot controls only the outer loop, resulting in a where-to-go command.

Flight-path-oriented control systems are not new. Since the late 1970s, NASA has done pioneering work in the design of decoupled FCSs and flight-path-rate control systems.[23,40–45]

In a decoupled FCS, the pilot is provided with independent input channels for the speed and attitude or flight-path angle. In the baseline, the pitch attitude and speed are both simultaneously effected by either pilot thrust or elevator commands. This is probably one of the more difficult aspects in learning to fly an aircraft. A decoupled FCS eliminates these cross-links between the pilot's controls and the aircraft states, in such a way that the throttle only affects the speed and the stick only affects the pitch (or the vertical speed, that is, the climb angle).[23,40–42] This simplifies the aircraft control, with obvious effects for pilot workload and performance.

In the flight-path angle rate command system, the pilot controls the aircraft velocity vector with respect to Earth.[22,43–45] This research was used in the design of the longitudinal FCS of the Boeing 7J7 (Ref. 46), as well as other aircraft.[24,25] An important outcome was that to improve pilot performance and reduce the likelihood of pilot-induced oscillations, not only the true flight-path angle should be shown on the display but also the commanded FPV. In addition, the flight-path FCS (and also the attitude-oriented FCS) require speed and attitude protection because the natural speed stability of the aircraft is missing.[26]

Task-Oriented Control/Display Systems

In the design of a task-oriented control/display concept, the main task of the pilot, that is, the control of the aircraft motion along a reference trajectory, is taken as the basis for the design of the display as well as the controls.[26] As stated earlier, the tunnel display can indeed be characterized as a task-oriented display because it allows the pilot to control the aircraft through the tunnel directly using the transformation of the tunnel image. Augmenting the aircraft with a flight-path oriented FCS would allow pilots to control the aircraft direction of motion relative to the trajectory directly. This is characterized as a task-oriented control. It takes little imagination to hypothesize that the combination of the task-oriented tunnel display, which intuitively shows the pilots where they are and where they are going, and a task-oriented automatic FCS, which allows pilots to control the direction of their locomotion directly, is an extremely powerful concept.[7,26] This has indeed been shown in several other studies that investigated the combination of a perspective flight-path display with either a flight-path-rate control system[30,34,47,48] or a decoupled control system.[27,28]

FCS Implementation

In this section the implementation of the three control system concepts of Fig. 2 is discussed, including an assessment of their handling qualities. The FCS designs were conducted for a Cessna Citation 500 (Ref. 26). All commonalities in the designs will be elaborated on first.

Aircraft Model and Common Secondary Control Systems

A detailed nonlinear flight simulation model (level-D) was available that allowed the FCS designs to be evaluated in a realistic environment.[49]

The lateral aircraft flight dynamics were augmented with a yaw damper to improve the damping of the Dutch roll mode and to stabilize the unstable spiral mode. The yaw damper provided no turn coordination; rudder inputs for a coordinated turn were negligibly small, however.

The vertical aircraft dynamics were augmented with an autothrottle system that kept the aircraft velocity at 150 kn (± 5 kn) true airspeed. All evaluations and experiments described in this paper were conducted at this speed. Hence, in the control law designs, no gain scheduling arrangements were applied.

Description of the Control Laws

Conventional, Direct-Link FCS

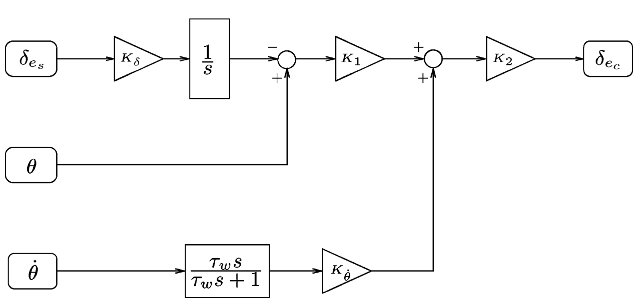
The conventional control configuration resembled the basic, unaugmented manual control of the Cessna Citation, Fig. 2a. For lateral control, the aileron and rudder control surface deflections δ_{a_c} and δ_{r_c} were proportional to the lateral stick deflection δ_{a_s} and rudder pedal deflection δ_{r_s}, respectively. For longitudinal control, the elevator control surface deflection δ_{e_c} was proportional to the vertical stick deflection δ_{e_s}.

Attitude-Oriented FCS

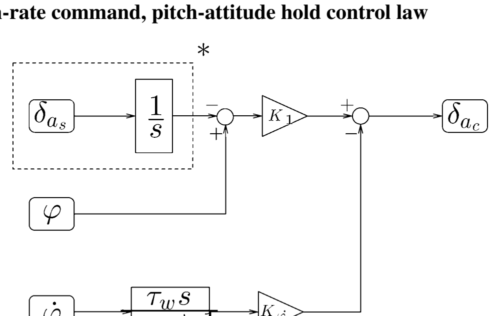
The attitude-oriented FCS consisted of a pitch-rate command, pitch-attitude hold controller for longitudinal control (Fig. 3a), and a roll-rate command, bank-angle hold controller for lateral control (Fig. 3b). The control system was decoupled: A change in bank angle required no pilot input to maintain pitch attitude.

Flight-Path-Oriented FCS

The vertical control law was a flight-path-angle rate command, flight-path-angle hold controller that was based on NASA investigations similar to those mentioned earlier (Fig. 4a). The control system

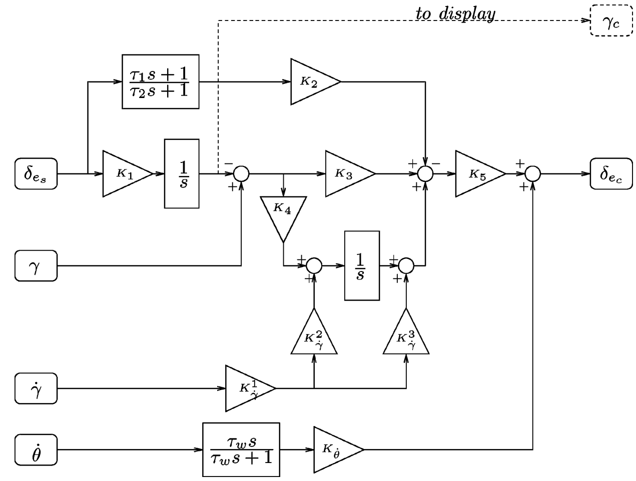


a) Pitch-rate command, pitch-attitude hold control law

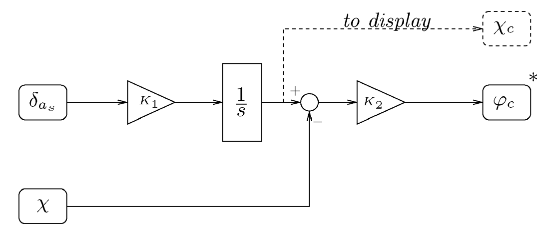


b) Roll-rate command, bank-angle hold control law

Fig. 3 Control laws for attitude-oriented FCS.



a) Flight-path-rate command, flight-path hold control law



b) Ground-track-rate command, ground-track hold control law

Fig. 4 Control laws for the flight-path-oriented FCS.

was structured as follows: An integrator transforms the flight-path rate command into a flight-path command signal. Next, a classical proportional–integral controller provides command following and error minimization. A feedforward loop would quicken the initial response of the controller. The pitch and flight-path responses were damped through a pitch-rate and flight-path-rate feedback, respectively. The control law had two outputs: the elevator deflection command δ_{e_c} and the commanded flight-path angle γ_c to drive the vertical motion of the FPV command symbol on the display.

The lateral control law was a ground-track angle-rate command, ground-track angle-hold controller (Fig. 4b). The command loop was implemented as a pure integrator that provided ease of control of the ground track angle.[25,50] The control law had two outputs: the bank angle command φ_c that is connected to the roll-rate command, roll-attitude hold control law (replacing the dashed block marked with the asterisk in Fig. 3b with φ_c, marked similarly in Fig. 4b), which, in turn, generates the aileron command δ_{a_c}, as well as the commanded ground-track angle χ_c to drive the lateral motion of the commanded FPV symbol on the display.

Note that as a result of the selection of a ground track rate control law the pilot must give a constant deflection of the side stick to the left (right) during left (right) turns, a characteristic that may be quite unnatural for pilots, unlike the accepted practice in car driving.

Note here that because there is no direct pilot control of the aircraft attitude, it is the control system that makes the necessary adjustments to attitude to maintain the commanded flight path. This may result in significant variations in the aircraft's attitude without any pilot input, for example, in turbulence. The lateral controller was limited to command a bank angle of a maximum of 45 deg.

Some final remarks on the three FCSs are needed for the sake of completeness. First, side slip is automatically minimized for the attitude-oriented and flight-path-oriented FCSs. Second, for all three FCS solutions, the stick gains in the experimental evaluations that follow were selected on the basis of achieving a compromise between a high similarity in the initial attitude responses for a stick displacement and a constant stick force per g (Ref. 26).

Handling Qualities Assessment

Only the handling characteristics of the longitudinal control laws were taken into account in the control law design cycle because these

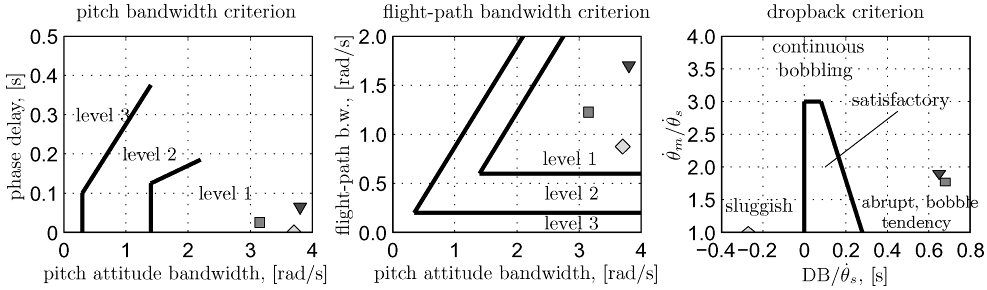


Fig. 5 Results of a handling qualities assessment: ♦, direct link; ▾, attitude; and ■, flight-path FCSs, respectively.

are generally considered to be the most critical.[50] Three criteria were used: the pitch attitude bandwidth[51] and flight-path bandwidth[52] in the frequency domain, and Gibson's dropback criterion[50] in the time domain. The results of the assessment for the three FCSs are shown in Fig. 5.

The bandwidth criteria classify all FCSs as level 1. The dropback criterion, which examines the aircraft pitch attitude response to a vertical stick deflection, is less supportive because none of the designs is classified as satisfactory. The conventional and the flight-path oriented FCSs have a dropback that is too large, whereas the attitude-oriented FCS has a negative dropback that results in a sluggish response. The dropback criterion, however, was designed for military pitch angle tracking tasks that are quite different from the path-following tasks investigated here and was, therefore, considered less important.

In summary, the handling-quality assessment did not result in unambiguous prediction of the performance of the three FCSs.

Experiment 1

The objective of experiment 1 was to compare the two FBW control augmentation concepts to the unaugmented direct-link FCS in the task of following a complex curved approach trajectory with a tunnel-in-the-sky display. The comparison is made on the basis of pilot control activity, tracking performance, and subjective workload.

Method

Apparatus

The experiment was conducted in a fixed-base, part-task flight simulator. The tunnel display was shown on a 15-in. liquid crystal display (LCD) approximately 0.80 m in front of the subject. No other information, such as a navigation display, was provided. The aircraft was flown by means of an electrohydraulic side stick (two degrees of freedom, aileron δ_{a_s} and elevator δ_{e_s}) and rudder pedals, all with normal, passive force characteristics.

Subjects and Instructions to Subjects

Five professional pilots participated in the experiment, with, on average, 5800 flying hours (Table 1). They were instructed to follow the trajectory as accurately as possible.

Independent Variables

Three independent variables were varied. First, the three FCSs as defined earlier were implemented: 1) the direct-link FCS, 2) the attitude-oriented FCS, and 3) the flight-path-oriented FCS.

The second experimental variable was the complexity of the trajectory toward the runway (Diff). The complexity was defined as the number of maneuvers per time interval that needed to be conducted, that is, the number of changes in flight-path angle plus the number of turns times two. Two levels of complexity were used: a baseline trajectory (8 maneuvers per run) and a complex trajectory (14 maneuvers per run). Both trajectories are shown in Fig. 6.

The third experimental variable was the atmospheric condition (Turb). For the stable atmospheric condition, a representative wind velocity of 8 kn (at 1000 ft) in combination with no turbulence was chosen. For the turbulent condition, a wind velocity of 15 kn (at 1000 ft) was taken combined with a moderate level of turbulence ($\sigma_{w_g} = 0.88$ m/s) (Ref. 26).

Table 1 Characteristics of pilot subjects

Pilot	Age	Hours	Types of aircraft
		Experiments 1 and 2	
A	35	1,300	Cessna Citation II (CC-II)
B	36	4,500	CC-II, Fokker 100, B767
C	36	4,000	CC-II, Fokker 100, B737
D	39	6,375	B767, MD-11
E	63	13,000	CC-II, DC3, DC8, B747-2/3/400
		Experiment 2	
F	44	7,000	Fokker 100, B767
G	34	5,500	B737
H	29	1,300	CC-II, B737
I	38	5,800	B737, B777
J	49	9,450	B737, B747-300/400
K	33	3,500	CC-II, B737
L	39	6,400	B737, MD-11

Experiment Design

A factorial within subjects design was employed, consisting of 12 conditions (3 FCSs × 2 trajectory complexities × 2 atmospheric conditions). Each pilot flew a total of 96 runs, of which the first 24 were training runs that were not used in the analysis. The runs were grouped in four blocks of 24 runs, with every block containing all experiment conditions and randomized differently for every block.

Tunnel-In-The-Sky Display

A generic tunnel-in-the-sky display was used, including in all cases a green FPV symbol. For the flight-path-oriented FCS, a second FPV symbol was presented in yellow, representing the commanded flight-path (χ_c and γ_c in Fig. 4). The tunnel width was fixed to 50 m.

Aircraft Model

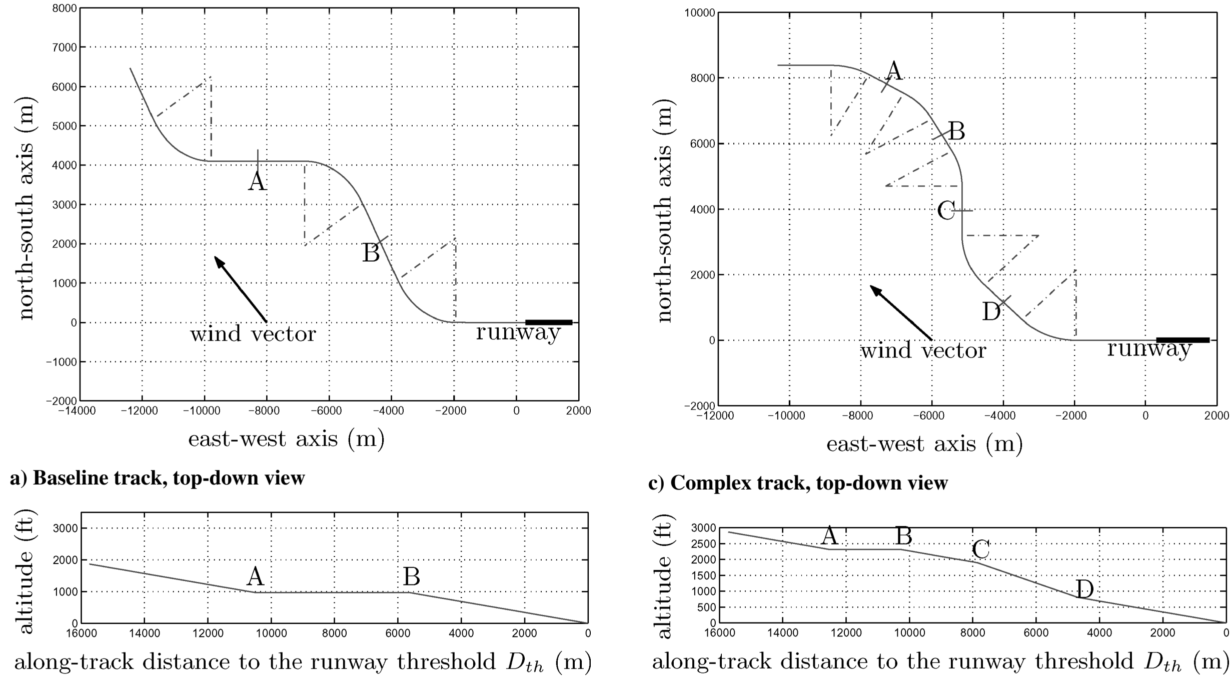
The level-D Cessna Citation 500 aircraft model[49] was extended with a yaw damper and with an autothrottle that kept the aircraft velocity constant at 150 kn true airspeed. This allowed subjects to fly the aircraft using only the side stick and rudder pedals. The aircraft was in an intermediate approach configuration, with 15 deg of flaps and the landing gear extended.

Atmosphere Model

Significant effects of turbulence models on perceived handling qualities in simulated flight have been reported in the past.[53] Hence, a fairly sophisticated atmosphere model was used, consisting of an elementary wind model and a patchy turbulence model using modified Dryden filters (see Ref. 54). The wind velocity was modeled using a logarithmic dependency of the wind velocity on the altitude. The direction of the headwind was constant with an angle of 45 deg with respect to the localizer. The gust velocities for the turbulent condition corresponded to the ICAO definition for moderate.[26]

Procedure

The pilots had to fly curved approaches to a fictitious airport. Two tunnel trajectories (Fig. 6) were mirrored relative to the runway centerline, resulting in two simple and two complex trajectories. (Note that the wind vector was mirrored as well.) A single run ended



a) Baseline track, top-down view

b) Baseline track, side view

c) Complex track, top-down view

d) Complex tract, side view

Fig. 6 Two trajectories flown in experiment 1; flight-path changes, A–D; – – –, turns and arrow, wind.

after touching down on the runway, and lasted approximately 5 min. After each run, the pilot workload was assessed using the NASA task load index (TLX).[55] When the entire experiment was finished, the pilots were asked to complete an extensive questionnaire, in which pilots were invited to comment on the experimental conditions in a structured fashion.

Dependent Measures

The dependent measures in the experiment were 1) the path-following performance, expressed in the root mean square (rms) of aircraft position errors [lateral x_e, vertical v_e, and total t_e $(= \sqrt{(x_e^2 + v_e^2)})$] and standard deviations (STD) of the flight-path angle errors χ_e and γ_e (all measured relative to the tunnel trajectory); 2) pilot control activity, that is, the STDs of the derivatives of the pilot side stick deflections ($\dot{\delta}_{e_s}$ and $\dot{\delta}_{a_s}$); 3) the ride comfort expressed by means of the STD in the normal acceleration n_z (the load factor); and 4) the pilot subjective workload (the TLX ratings).

Hypotheses

The experiment hypotheses follow logically from the experiment design and from the goals that were set out for this experiment. First, it is hypothesized that pilot workload and control activity will be lowest for the flight-path-oriented FCS, irrespective of the other independent variables and highest for the direct-link control concept. The attitude-oriented FCS is hypothesized to rate in between the other two systems. Second, it is hypothesized that the addition of atmospheric turbulence will lead to an increase in control activity for the conventional control law, whereas the control activity for the two FBW control laws is predicted to increase less. Third, the pilot performance, expressed in trajectory tracking accuracy, is hypothesized to be best for the flight-path FCS. It is expected that this will especially be the case for the short-term measure of flight-path accuracy (climb angle and ground track angle errors) and to a lesser extend for the longer-term measure (the position errors). Performance is hypothesized to be least for the direct link, and the attitude-oriented flight control is expected to rate in between. The addition of turbulence is expected to deteriorate path-following performance, especially for the flight-path-angle error measures. Again, these effects are expected to be largest for the direct-link FCS and smallest for the flight-path oriented FCS.

Results and Discussion

Time Histories

Figure 7 shows some typical time histories of the longitudinal stick input δ_{e_s} and the flight-path angle γ (one pilot, turbulent atmosphere, complex trajectory). The difference between the high-frequency input signals in the unaugmented control case as compared to the sparse and low-frequency input signals for the flight-path oriented FCS is remarkable, whereas the aircraft flight-path accurately follows the reference flight-path angle in a much smoother fashion. This is typical for the observed data in the vertical as well as in the lateral dimension and supports the hypotheses.

Representative data for the path-following performance of pilots, expressed in the total position error t_e, are shown in Fig. 8 for the three FCSs. Figure 8 indicates that the position error is generally smallest for the flight-path FCS, whereas variations are highest in the unaugmented situation.

Statistical Analysis

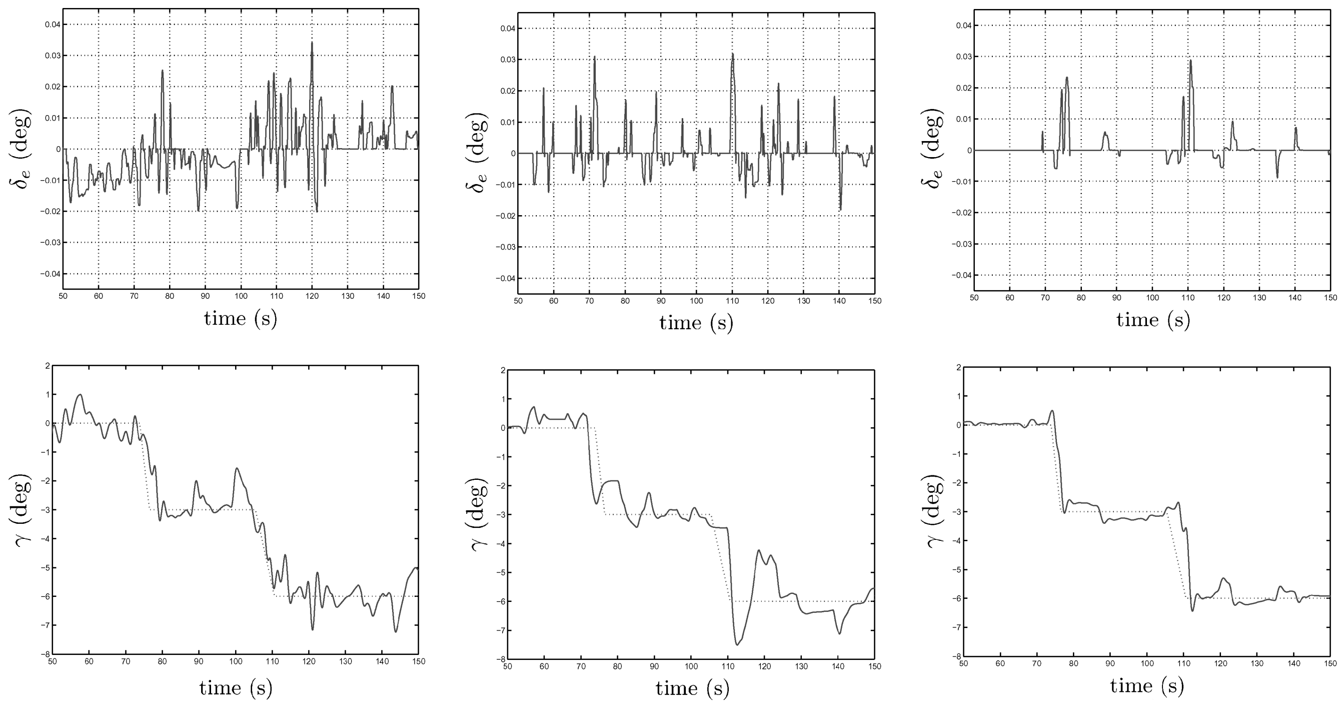
The data were analyzed using an analysis of variance (ANOVA), with pilot (five levels) as a random effect and FCS (three levels), Turb (two levels) and Diff (two levels) as fixed effects. The results of this analysis are listed in Table 2, showing the main effects and the two-way interactions. None of the three-way interactions were significant. As can be deduced from Table 2, the trajectory difficulty Diff results in hardly any statistically significant effects. Therefore, the means and the 95% confidence limits of the dependent measures are only shown as a function of the FCS and Turb independent variables (Fig. 9).

Pilot control activity. The control activity was measured in two ways that were both considered equally suitable for comparing the different FCSs. First, the STDs of the side stick deflection rates were taken ($\dot{\delta}_{e_s}$ and $\dot{\delta}_{a_s}$ for the longitudinal and lateral control activity, respectively). Second, the number of absolute changes in stick velocity per second were counted (decnt and dacnt). Note that the more commonly used variations in the stick deflections themselves are not very suitable for comparing the different control laws. In particular, a comparison of the lateral stick deflection δ_{a_s} is difficult because with the flight-path-oriented FCS, pilots maintained a constant lateral stick deflection when making a turn. Therefore, the stick deflection rates were considered to be more relevant.

Table 2 Results of full-factorial ANOVA on dependent measures of experiment 1

Factor	Control activity $\dot{\delta}_{a_s}$	Control activity $\dot{\delta}_{e_s}$	Control activity dacnt	Control activity decnt	Inner-loop measure n_z	Path-following performance x_e	Path-following performance v_e	Path-following performance t_e	Path-following performance χ_e	Path-following performance γ_e
Main effects										
FCS	★★[a]	★★	★★	★★	★★	★	★	★★	★★	★★
Turb	★★	★[a]	★★	★★	★★	★★	·	★	★	★★
Diff	○[a]	·	·	★	·	○	·	·	·	○
Two-way interactions										
FCS × turb	★★	★★	○	★★	★★	○	·	★	★★	★★
FCS × diff	·	·	·	·	·	·	·	·	·	·
Turb × diff	·	·	·	·	★	·	·	·	·	·

[a]★★, ★, and ○, chance levels of $p \leq 0.01$, $0.01 < p \leq 0.05$, and $0.05 < p \leq 0.10$, respectively.



a) Conventional (unaugmented) FCS **b) Attitude-oriented FCS** **c) Flight-path-oriented FCS**

Fig. 7 Longitudinal pilot stick inputs δ_{e_s} (top row) and aircraft flight-path angle γ (bottom row) for the three FCSs. In the bottom row, the reference flight-path angle (tunnel trajectory downslope) is shown using the dotted line.

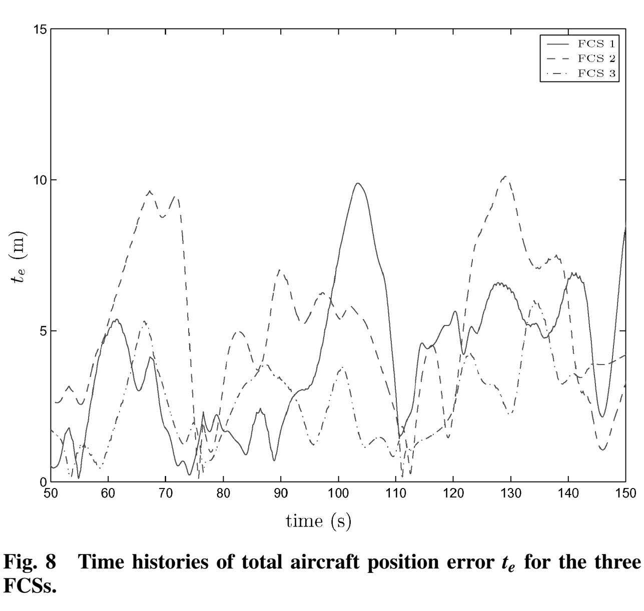
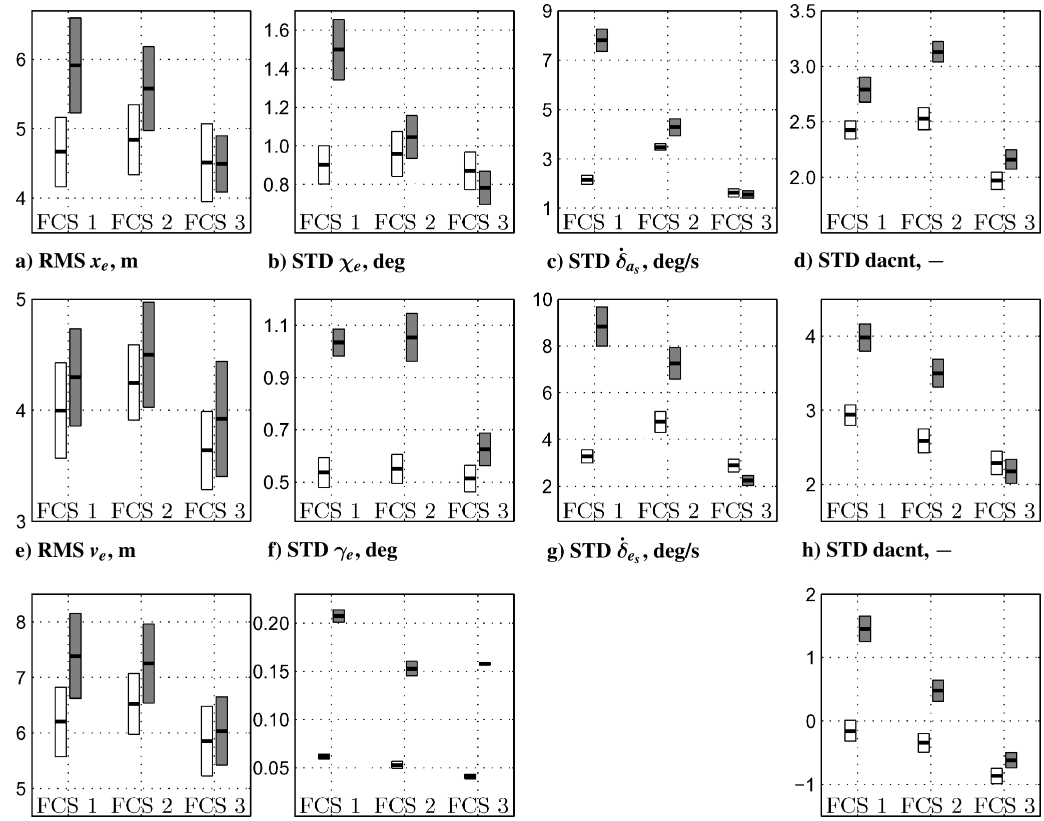


Fig. 8 Time histories of total aircraft position error t_e for the three FCSs.

Highly significant effects were found for the FCS on both the longitudinal as well as the lateral control activity measures ($\dot{\delta}_{e_s}$, $F_{2,8} = 15.551$ and $p < 0.01$; decnt, $F_{2,8} = 40.577$ and $p < 0.01$; $\dot{\delta}_{a_s}$, $F_{2,8} = 43.449$ and $p < 0.01$; and dacnt, $F_{2,8} = 88.499$ and $p < 0.01$). Post hoc analyses [Student Newman–Keuls (SNK), $\alpha = 0.05$] revealed that the differences between the three FCSs were indeed all significant for all control activity measures. The lowest control activity was found for the flight-path FCS, followed by the attitude-oriented FCS, and the highest activity for the direct-link (Fig. 9). For the highest control activity the results for $\dot{\delta}_{a_s}$ and dacnt diverged: The attitude-oriented control law showed the highest control activity according to dacnt and the conventional control law according to $\dot{\delta}_{a_s}$. Apparently, when flying with the attitude-oriented FCS, subjects made a larger number of control inputs with smaller amplitudes as compared to the direct-link FCS.

The atmospheric condition Turb significantly affected the pilot longitudinal and lateral control activity ($\dot{\delta}_{e_s}$, $F_{1,4} = 16.018$ and $p = 0.016$; decnt, $F_{1,4} = 70.679$ and $p < 0.01$; $\dot{\delta}_{a_s}$, $F_{1,4} = 34.169$ and $p < 0.01$; and dacnt, $F_{1,4} = 49.785$ and $p < 0.01$). In line with the hypotheses, the addition of the moderate turbulence led to a strong increase in control activity, although this was only the case for the



a) RMS x_e, m b) STD χ_e, deg c) STD $\dot{\delta}_{a_s}$, deg/s d) STD dacnt, —

e) RMS v_e, m f) STD γ_e, deg g) STD $\dot{\delta}_{e_s}$, deg/s h) STD dacnt, —

i) RMS t_e, m j) STD n_z, — k) zTLX, —

Fig. 9 Means and 95% confidence limits of main dependent measures of experiment 1 (data for all five subjects); for the three FCSs and the two turbulence conditions: white, stable atmosphere and gray, turbulent atmosphere; k) normalized TLX workload ratings.

direct-link and attitude-oriented FCS. For the flight-path FCS, a small decrease in control activity was found (Fig. 9). As hypothesized, the advantages of using more advanced FBW control laws become more apparent in turbulent atmospheric conditions.

The trajectory difficulty Diff resulted in only marginal effects. A higher number of longitudinal stick velocity changes are found (decnt, $F_{1,4} = 9.214$ and $p = 0.039$), but this is not accompanied by a significant increase in $\dot{\delta}_{e_s}$. Hence, the more difficult trajectory resulted in an increasing number of small stick changes. For the lateral stick deflections, no significant effects were found, except for a marginal increase in $\dot{\delta}_{a_s}$ ($F_{1,4} = 4.611$ and $p = 0.098$).

Path-following performance: position. Figure 9 shows that the flight-path FCS has the best performance in terms of the rms total, vertical, and horizontal position error, a result that was indeed significant (t_e, $F_{2,8} = 17.423$, and $p < 0.01$; v_e, $F_{2,8} = 4.901$ and $p = 0.041$; and x_e, $F_{2,8} = 6.033$ and $p = 0.025$). Post hoc analysis (SNK, $\alpha = 0.05$) showed that this effect is only because the flight-path FCS yielded significantly better performance, whereas the direct-link FCS and the attitude FCS did not result in a difference in performance at all. The addition of moderate turbulence generally led to an increasing position error (t_e, $F_{1,4} = 10.812$ and $p = 0.030$; v_e, not significant; and x_e, $F_{1,4} = 33.165$ and $p < 0.01$), but this effect was much smaller for the flight-path FCS, resulting in significant FCS × Turb interactions for t_e ($F_{2,8} = 4.774$ and $p = 0.043$) and x_e ($F_{2,8} = 3.868$ and $p = 0.067$). Note, however, that the absolute size of the differences in position tracking performance was relatively small (approximately 1.5 m).

Surprisingly, the rms lateral (and total) position errors were smaller for the complex trajectory as compared to the baseline track (x_e, $F_{1,4} = 7.398$ and $p = 0.053$ and t_e, not significant). This effect did not depend on the other independent variables. Tentatively, this can be explained as follows: Whereas in the complex trajectory more turns had to be made, the turns themselves were smaller (30 deg as compared to 60 deg). Earlier research showed that flying curved sections of the trajectory result in a considerably worse performance as compared to flying straight sections, but only in terms of the lateral position error x_e (Ref. 36).

Path-following performance: flight path. The effect of the independent variables were stronger for the short-term measures for path-following performance, χ_e and γ_e (Table 2 and Fig. 9). The tracking performance is superior for the flight-path FCS (χ_e, $F_{2,8} = 9.831$ and $p < 0.01$ and γ_e, $F_{2,8} = 120.742$ and $p < 0.01$). For the other two FCSs, adding turbulence deteriorates the flight-path tracking performance (χ_e, $F_{1,4} = 15.373$ and $p = 0.017$ and γ_e, $F_{1,4} = 112.032$ and $p < 0.01$), whereas performance with the flight-path FCS remains largely unaffected by the turbulence condition. This causes the significant FCS × Turb interaction (χ_e, $F_{2,8} = 13.127$ and $p < 0.01$ and γ_e, $F_{2,8} = 85.879$ and $p < 0.01$). The trajectory difficulty Diff resulted in slightly higher flight-path angle errors for the complex trajectory for all FCSs, but with only a marginal significance for γ_e ($F_{2,8} = 7.283$ and $p = 0.054$).

Aircraft normal accelerations. The aircraft normal accelerations provide an indication of the ride comfort. The FCS had a highly significant effect ($F_{2,8} = 322.934$ and $p < 0.01$) and the addition of moderate turbulence obviously resulted in a strong and highly significant increase in the load ($F_{1,4} = 6864.310$ and $p < 0.01$). Post hoc analyses (SNK, $\alpha = 0.05$) revealed that the differences between the three FCSs were all significant for the stable atmospheric condition, with the lowest load factors for the flight-path FCS, followed by the attitude FCS, and the highest loads for the direct link. For the turbulent atmospheric condition, however, only the direct-link FCS showed a significantly higher variance of the load factor, the differences between the other two FCSs were not significant.

Subjective Workload

In Fig. 9, the normalized TLX ratings (Z scores) are shown. Workload was rated lowest for the flight-path FCS and highest for the direct-law FCS. The attitude FCS was in between, representing a highly significant effect ($F_{2,8} = 109.638$ and $p < 0.01$). When the turbulence is added, the workload increases for all FCSs except for the flight-path FCS, resulting in significant effects for Turb ($F_{1,4} = 325.218$ and $p < 0.01$) and the highly significant FCS × Turb interaction ($F_{2,8} = 25.361$ and $p < 0.01$). Post hoc analyses (SNK, $\alpha = 0.05$) revealed that the workload ratings for the flight-path FCS are indeed lower than for the other FCSs in all conditions. These results correlate well with the objective measures for workload, such as the pilot control activity, as discussed earlier. No significant differences were found for the trajectory difficulty.

Pilot Questionnaire

After the experimental trials, subjects were asked to complete an extensive questionnaire. The flight-path FCS was clearly favored by all pilots and was considered the best match for use in combination with the tunnel-in-the-sky display. The attitude FCS was considered the second best. Pilots suggested, however, that with the flight-path FCS, some visual reference should be presented in the perspective display showing them where to put the commanded FPV symbol, in particular during the (interception of) curved parts of the trajectory. This recommendation has been followed upon in later studies.[34,48]

Conclusions of Experiment 1

It can be concluded that the main advantages of using control augmentation with the tunnel display can be found in the reduction of pilot workload. The improvements in path-following performance are not spectacular, mainly because of the very good performance that is already realized with the combination of conventional manual control with the tunnel-in-the-sky display. Nonetheless, the flight-path FCS outperforms the other two control systems in all respects. Path-following performance is superior, with minimal pilot control activity and pilot workload.

An important result of this study is that it clearly shows the increasing benefits of a flight-path-oriented FCS when metrics for task difficulty, such as the presence of turbulence and the complexity of the curved approach, increase. In some cases, performance even improved with the flight-path FCS when task difficulty increased. These results correspond well with the hypotheses and also with previous research on flight-path FCSs.[14,23–25,27,28] They clearly demonstrate the strong potential for the combination of the flight-path-oriented tunnel-in-the-sky display with a flight-path-oriented FBW control system, yielding a truly task-oriented pilot interface.

Experiment 2

During the execution of experiment 1, results of a flight test with a Cessna Citation 2 aircraft showed substantial differences in pilot path-following performance and workload in tracking straight tunnel trajectories as compared to earlier experiments conducted in the same fixed-base flight simulator.[21,30] Tracking performance during a straight-in approach was reported a factor of two–three times worse when conducted in real flight as compared to performance in the fixed-base simulator, and workload was reported to be much higher in the flight tests.

These discrepancies raised the question whether results obtained in fixed-base simulators are indeed representative of (or can be extrapolated to) pilot behavior in real flight. They suggest that the task of flying a tunnel may be sensitive to simulator fidelity, including pilot-perceived motion. Extensive tests in the past have outlined the type of testing facility suitable for many piloting tasks. Tunnel displays, however, are relatively novel and appropriate methods of testing them still need to be explored.[31] Hence, the goal of experiment 2 was to investigate the impact of simulator motion on pilot performance and workload with the same three FCSs investigated in experiment 1.

Method

In the following text, the experimental design will be described. Because of the great resemblence with experiment 1, mainly the differences with experiment 1 will be emphasized.

Subjects and Instructions to Subjects

There were 12 professional pilots participating in the experiment, with on average 5660 flying hours (Table 1). They were instructed to fly the aircraft through the tunnel as accurately as possible.

Subjects were briefed in detail about all objectives of the experiment, except for one, namely, that our intention was to examine the effects of flight simulator motion. Rather, pilots were briefed with the statement that "In this experiment we will be testing different motion models." In the experimental trials, care was taken that all ancillary cues of simulator motion were consistent between runs, such as performing the motion setup procedure before each run, even when motion was then turned off at the start of the run from the control room.[31]

Apparatus and Setup

Subjects were seated in the cabin of the SIMONA flight simulator, Delft University's high-fidelity six-degree-of-freedom motion simulator. The tunnel display was shown on a 15-in. LCD display placed 0.80 m in front of the subject. To the side of the tunnel display, a standard navigation display and engine indication display were shown. The aircraft was flown through the control column; the pilots had as yet no rudder pedal at their disposal.

Independent Variables

The experiment had two independent variables. The same three FCSs were employed as in experiment 1. The second experimental variable was the flight simulator motion: Motion was either on or off.

Experiment Design

A factorial within subjects design was employed, consisting of six conditions (three FCSs × two motion states). All conditions were run three times, yielding 18 measurement runs.

Tunnel-in-the-Sky Display

The tunnel-in-the-sky display of experiment 1 was used again, except that now the tunnel width was slightly smaller at 45 m. The trajectory flown was the baseline trajectory.

Aircraft and Atmosphere Models

The aircraft model as well as the patchy turbulence model were the same as in experiment 1. However, the intensity of the turbulence was reduced to a lower level, but still represented a moderate turbulence level.

Procedure

Each pilot flew a total of 24 runs, of which 6 were training runs. The runs were blocked by FCS, that is, they were run as 3 sets of $(2 + 6)$. During the training runs the motion was always on. Each run lasted approximately 5 min. After each run the pilot workload was assessed using the NASA TLX. After the experiment was finished, all subjects were asked to complete a pilot questionnaire.

Dependent Measures

The dependent measures in experiment 2 were the same as those in experiment 1, extended with maneuvering-related variables such as the aircraft attitude rates $\dot{\theta}$ and $\dot{\varphi}$.

Hypotheses

The main experimental hypothesis was that, independent of the FCS, the presence of motion stimuli helped pilots to better control their aircraft and, therefore, improve their performance. It was expected that this positive effect of motion increased when the level of flight control automation decreased. That is, the advantage of having motion stimuli was hypothesized to be larger for the direct-link FCS than for the advanced flight-path-oriented FCS. The reason for this hypothesis is that the motion stimuli are generally believed to be useful in particular for controlling the aircraft inner loops, such as attitude and flight path.[56,57] With the attitude-oriented and flight-path-oriented FCSs, the attitude control loop is automated, and the relation between the pilot control and the aircraft attitude response is less direct than in the situation of the direct-link control.

Results and Discussion

Statistical Analysis

The experimental data were analyzed using ANOVA, with pilot (12 levels) as a random effect and FCS (3 levels) and motion (2 levels) as fixed effects. The main results, shown in Fig. 10, are listed in Table 3.

Control activity. The main effects FCS and motion are both significant for the pilot vertical stick deflections δ_{e_s} (FCS, $F_{2,22} = 71.204$ and $p < 0.01$ and motion, $F_{1,11} = 15.780$ and $p < 0.01$). The highest variations are measured for the direct-link FCS and the smallest variations with the flight-path FCS. A post hoc analysis (SNK, $\alpha = 0.05$) confirmed the significance. Simulator motion resulted in higher stick deflection rates, independent of the FCS ($\dot{\delta}_{e_s}$, $F_{1,11} = 14.645$ and $p < 0.01$ and $\dot{\delta}_{a_s}$, $F_{1,11} = 11.920$ and $p < 0.01$) (Fig. 10). They were also significantly different for the three FCSs ($\dot{\delta}_{e_s}$, $F_{2,22} = 8.301$ and $p < 0.01$ and $\dot{\delta}_{a_s}$, $F_{2,22} = 19.858$ and $p < 0.01$, then SNK with $\alpha = 0.05$), with a trend for decreasing stick rates for the increasing level of automation FCSs.

Path-following performance. The lateral, total, and vertical position errors were significantly smaller (SNK, $\alpha = 0.05$) for the flight-path FCS as compared to the other FCSs, independent of the simulator motion (x_e, $F_{2,22} = 6.779$ and $p < 0.01$; v_e, $F_{2,22} = 11.038$ and $p < 0.01$ and t_e, $F_{2,22} = 13.181$ and $p < 0.01$). The differences in performance between the other two FCSs were not significant. The flight-path performance is best for the flight-path FCS (χ_e, $F_{2,22} = 17.149$ and $p < 0.01$ and γ_e, $F_{2,22} = 11.060$ and $p < 0.01$); performance of the other two FCSs was not different (SNK, $\alpha = 0.05$). Rather surprisingly, path-following performance was not affected at all by simulator motion.

Aircraft attitude rates and normal accelerations. Simulator motion resulted in higher aircraft attitude rates, an effect with borderline significance ($\dot{\theta}$, $F_{1,11} = 3.331$ and $p = 0.095$ and $\dot{\varphi}$, $F_{1,11} = 3.956$ and $p = 0.072$) that was stronger for the flight-path FCS. Roll rate decreased for the attitude-oriented FCS and in particular, for the flight-path FCS in comparison to the direct-link solution, independent of the simulator motion ($F_{2,22} = 79.447$ and $p < 0.01$). Pitch rate was smallest for the attitude FCS and about the same for the other two systems ($F_{2,22} = 54.345$ and $p < 0.01$). The normal acceleration n_z showed effects similar to the pitch rate $\dot{\theta}$, except for the significantly higher g levels for the direct-link FCS.

Table 3 Results of full-factorial ANOVA on dependent measures of experiment 2

	Control activity		Inner-loop measures			Path-following performance					Workload
Factor	$\dot{\delta}_{a_s}$	$\dot{\delta}_{e_s}$	$\dot{\varphi}$	$\dot{\theta}$	n_z	x_e	v_e	t_e	χ_e	γ_e	z TLX
Main effects											
FCS	★★[a]	★★	★★	★★	★★	★★	★★	★★	★★	★★	★★
Motion	★★	★★	○[a]	○	·	·	·	·	·	·	○
Two-way interaction											
FCS × motion	★★	·	○	·	·	·	·	·	·	·	·

[a]★★ and ○, chance levels of $p \leq 0.01$ and $0.05 < p \leq 0.10$, respectively.

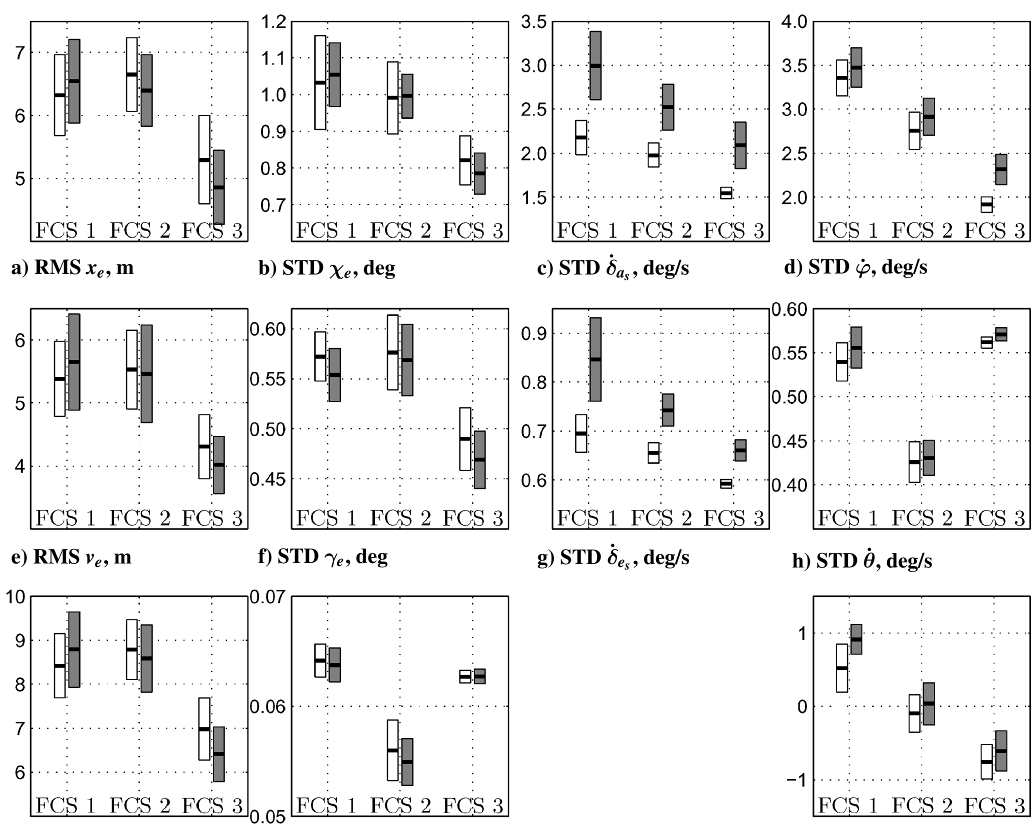


Fig. 10 Means and 95% confidence limits of main dependent measures of experiment 2 (data for all 12 subjects); for the three FCSs and the flight simulator motion conditions: white, motion off and gray, motion on; k) normalized workload ratings.

Subjective Workload

The TLX subscale ratings were all significantly influenced by the FCS (SNK, $\alpha = 0.05$), with minimal workload for the flight-path FCS, maximal workload for the direct-link FCS, and the attitude FCS rating in between. Simulator motion resulted in a significant increase ($p < 0.01$) in the mental demand and physical demand subscale ratings only, in particular for the direct-link FCS. The normalized ratings, the Z scores, are shown in Fig. 10. Workload is smallest for the flight-path FCS and largest for the direct-link FCS, with the attitude-oriented FCS in between, a significant effect [SNK ($\alpha = 0.05$) and FCS, $F_{2,22} = 13.370$ and $p < 0.01$]. The addition of simulator motion resulted in an increase in pilot workload, an effect that occurred for all three FCSs, but with only borderline statistical significance ($F_{1,11} = 4.684$ and $p = 0.053$).

Pilot Questionnaire

By the use of a nine-level progressive scale, the addition of simulator motion resulted in a statistically significant ($F_{1,11} = 6.413$ and $p = 0.018$) increase of the perceived realism of the simulation, independent of the FCS.

Conclusions of Experiment 2

The main trends in the data are found to be very similar to those of experiment 1. For several reasons, such as the different turbulence intensity, the slightly smaller tunnel size, and the use of a heavy control column rather than the light and small side stick, the data obtained are somewhat different, but the overall main trends did not change. Again, the superiority is shown of the flight-path oriented FCS, resulting in the best path-following performance, minimal pilot corrective action, and the lowest workload.

Independent of the FCS, simulator motion yields higher workload ratings, higher pilot control deflection rates, higher aircraft attitude rates, and a significantly higher pilot judgment of the flight simulation realism. Path-following performance was not affected at all by the simulator motion.

It can be concluded from this experiment that the flight simulator motion results in a more realistic task environment, in which pilots feel and act on the much more salient motion stimuli from the aircraft attitude rates and specific forces. The pilot control of the aircraft inner loops benefits from this information, resulting in a higher pilot gain for controlling attitude. However, this does not result in a higher path-following performance, a typical outer loop measure. Rather, the main result is that it leads to higher levels of pilot workload. This supports the earlier findings in flight tests with the tunnel display, where pilots commented that they had to work much harder to maintain performance as compared to their experience with the display in fixed-base simulator trials.[21,30]

When flying tunnels in real flight, or, equivalently, in a high-fidelity motion-based simulator, pilots can much better appreciate the effects caused by maneuvering through the tunnel on the aircraft attitude, attitude rates, and accelerations. That is, pilots can better judge aspects like comfort, flyability, and safety. Hence, tunnels that can be flown with some effort in a fixed-base, part-task flight simulator might prove to be impossible to fly in a comfortable or even safe manner when they are flown in real flight. In summary, when pilot behavior with tunnel displays in fixed-based flight simulators is investigated, it is recommended that care be taken with any statements about pilot workload and on the flyability of these trajectories.

Conclusions

The results show that the combination of a tunnel-in-the-sky display with a flight-path-oriented FCS outperforms other control augmentation solutions. When the task of the pilot becomes more difficult, for example, due to atmospheric turbulence or an increased complexity of the reference trajectory, the flight-path-oriented control/display system yields the best interface solution. That is, in the unaugmented situation or with attitude-oriented FCSs that are used in conjunction with the tunnel display, performance deteriorates considerably and pilot control activity as well as pilot workload increase when the task becomes more difficult. With the use of the flight-path oriented FCS, these adverse effects are not found at all. The path-following performance remains the same, as does pilot workload and control activity. These results are well in line with the fundamental philosophy behind this work and support the need for continuing research into control augmentation techniques to be used in conjunction with perspective flight-path displays.

Acknowledgments

The authors express their gratitude to the staff of Delft University's Institute for Simulation, Motion, and Navigation technologies (SIMONA), in particular to Olaf Stroosma and Adri Tak, and to graduate students Jerome Chiecchio and Mark Roeden, for their essential contributions in conducting experiment 2. The authors also wish to thank all pilots who participated in the two experiments.

References

[1]Knox, C. E., and Leavitt, J., "Description of a Path-in-the-Sky Contact Analog Piloting Display," NASA TM-74057, Oct. 1977.

[2]Grunwald, A. J., Robertson, J. B., and Hatfield, J. J., "Experimental Evaluation of a Perspective Tunnel Display for Three-Dimensional Helicopter Approaches," *Journal of Guidance and Control*, Vol. 4, No. 6, 1981, pp. 623–631.

[3]Roscoe, S. N., and Jensen, R. S., "Computer-Animated Predictive Displays for Microwave Landing Approaches," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-11, No. 11, 1981, pp. 760–765.

[4]Grunwald, A. J., "Tunnel Display for Four-Dimensional Fixed-Wing Aircraft Approaches," *Journal of Guidance, Control, and Dynamics*, Vol. 7, No. 3, 1984, pp. 369–377.

[5]Grunwald, A. J., "Improved Tunnel Display for Curved Trajectory Following: Control Considerations," *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, 1996, pp. 370–377.

[6]Theunissen, E., "Integrated Design of a Man–Machine Interface for 4-D Navigation," Ph.D. Dissertation, Faculty of Electrical Engineering, Delft Univ. of Technology, Delft, The Netherlands, Feb. 1997.

[7]Mulder, M., "Cybernetics of Tunnel-in-the-Sky Displays," Ph.D. Dissertation, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, The Netherlands, Nov. 1999.

[8]Funabiki, K., Muraoka, K., Terui, Y., Harigae, M., and Ono, T., "In-Flight Evaluation of Tunnel-in-the-Sky Display and Curved Approach Pattern," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, 1999, pp. 1–7.

[9]Sachs, G., and Sennes, U., "Perspective Flightpath and Predictor Display with Two-Axis Control Coordination," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, 2000, pp. 1–10.

[10]Parrish, R. V., Busquets, A. M., Williams, S. P., and Nold, D. E., "Spatial Awareness Comparisons Between Large-Screen, Integrated Pictorial Displays and Conventional EFIS Displays During Simulated Landing Approaches," NASA TP-3467, Oct. 1994.

[11]Merhav, S. J., and Grunwald, A. J., "Display Augmentation in Manual Control of Remotely Piloted Vehicles," *Journal of Aircraft*, Vol. 15, No. 3, 1978, pp. 182–189.

[12]Grunwald, A. J., and Merhav, S. J., "Effectiveness of Basic Display Augmentation in Vehicular Control by Visual Field Cues," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-8, No. 9, 1978, pp. 679–690.

[13]Grunwald, A. J., "Predictor Laws for Pictorial Flight Displays," *Journal of Guidance, Control, and Dynamics*, Vol. 8, No. 5, 1985, pp. 545–552.

[14]Hynes, C. S., Franklin, J. A., Hardy, G. H., Martin, J. L., and Innis, R. C., "Flight Evaluation of Pursuit Displays for Precision Approach of Powered-Lift Aircraft," *Journal of Guidance, Control, and Dynamics*, Vol. 12, No. 4, 1989, pp. 521–529.

[15]Theunissen, E., and Mulder, M., "Pilot-in-the-Loop Studies into Manual Control Strategies with Perspective Flightpath Displays," *Proceedings of the XIVth European Annual Conference on Human Decision Making and Manual Control*, Delft Univ. of Technology, Delft, The Netherlands, 1995, pp. 1.3.1–1.3.7.

[16]Mulder, M., "Flight-Path Vector Symbology in a Tunnel-in-the-Sky Display," *Proceedings of the XVIIIth European Annual Conference on Human Decision Making and Manual Control*, Loughborough Univ., Loughborough, England, U.K., 1999, pp. 250–267.

[17]Sachs, G., "Perspective Predictor/Flight-Path Display with Minimum Pilot Compensation," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 3, 2000, pp. 420–429.

[18]Sachs, G., and Sennes, U., "Total Energy Related Speed Control for Three-Dimensional Guidance Displays with Predictor," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, 2001, pp. 1–11.

[19]Funabiki, K., "Tunnel-in-the-Sky Display Enhancing Autopilot Mode Awareness," *Conference Proceedings of the 1997 CEAS Free Flight Symposium*, Delft Univ. of Technology, Delft, The Netherlands, 1997, pp. 29.1–29.11.

[20]Mulder, M., Kraeger, A. M., and Soijer, M. W., "Delft Aerospace Tunnel-in-the-Sky Flight Tests," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, 2002.

[21]Mulder, M., and Mulder, J. A., "Cybernetic Analysis of Perspective Flight-Path Display Dimensions," *Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 3, 2005, pp. 398–411.

[22]Lambregts, A. A., and Cannon, D. G., "Development of a Control Wheel Steering Mode and Suitable Displays that Reduce Pilot Workload and Improve Efficiency and Safety of Operation in the Terminal Area and in Windshear," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, New York, 1979, pp. 609–620.

[23]Stewart, E. C., Ragsdale, W. A., and Wunschel, A. J., "Evaluation of Automatic Control System Concepts for General Aviation Airplanes," *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, AIAA, Washington, DC, 1988, pp. 330–343.

[24]Van der Geest, P., Nieuwpoort, A., and Borger, J., "Simulator Evaluation of Various Manual Control Concepts for Fly-by-Wire Transport Aircraft," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Washington, DC, 1992, pp. 181–199.

[25]Verspay, J. J. L. H., de Myunck, R. J., Nibbelke, R. J., Van den Bosch, J. J., Kolstein, G., and Van Gelder, C. A. H., "Simulator Evaluation on Control and Display Issues for a Future Regional Aircraft," *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, AIAA, Reston, VA, 1996, pp. 176–189.

[26]Veldhuijzen, A. R., "Integrating Flight Path Oriented Control with the Tunnel-in-the-Sky Display—A Promising New Concept for the Primary Interface Between Pilot and Aircraft," M.S. Thesis, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, The Netherlands, Nov. 2002.

[27]Stewart, E. C., "Piloted Simulation Study of Advanced Controls and Displays for Novice General Aviation Pilots," AIAA Paper 94-0276, Jan. 1994.

[28]Beringer, D. B., "Performance-Controlled Systems, Fuzzy Logic, and Fly-by-Wire Controls: Revisiting Applications to General Aviation," *Proceedings of the 43rd Annual Meeting of the Human Factors & Ergonomics Society*, HFES, Santa Monica, CA, 1999, pp. 61–65.

[29]"NASA Small Aircraft Transportation System (SATS)—Program Planning White Paper," NASA White Paper, NASA Langley Research Center, Hampton, VA, Sept. 2000.

[30]Mulder, M., Veldhuijzen, A. R., Van Paassen, M. M., and Bennani, S., "Fly-by-Wire Control and Tunnel-in-the-Sky Displays: Toward a Task-Oriented Control/Display System," AIAA Paper 2002-4928, Aug. 2002.

[31]Mulder, M., Chiecchio, J., Pritchett, A. R., and Van Paassen, M. M., "Testing Tunnel-in-the-Sky Displays and Flight Control Systems With and Without Flight Simulator Motion," *Proceedings of the 12th International Symposium on Aviation Psychology*, Wright State Univ., Dayton, OH, 2003, pp. 839–844.

[32]Eberts, R. E., "Internal Models, Tracking Strategies, and Dual-Task Performance," *Human Factors*, Vol. 29, No. 4, 1987, pp. 407–419.

[33]Gold, T., "Quickened Manual Flight Control with External Visual Guidance," *IEEE Transactions on Aerospace and Navigational Electronics*, Vol. ANI-11, No. 9, 1965, pp. 151–156.

[34]Lam, T. M., Mulder, M., and Van Paassen, M. M., "Comparison Between Augmentation Techniques for Tunnel-in-the-Sky Displays," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, 2004, pp. 1–13.

[35]Mulder, M., "An Information-Centered Analysis of the Tunnel-in-the-Sky Display, Part One: Straight Tunnel Trajectories," *International Journal of Aviation Psychology*, Vol. 13, No. 1, 2003, pp. 49–72.

[36]Mulder, M., "An Information-Centered Analysis of the Tunnel-in-the-Sky Display, Part Two: Curved Tunnel Trajectories," *International Journal of Aviation Psychology*, Vol. 13, No. 2, 2003, pp. 131–151.

[37]Favre, C., "Fly-by-Wire for Commercial Aircraft: The Airbus Experience," *Advances in Aircraft Flight Control*, edited by M. B. Tischler, Taylor and Francis, London, 1996, pp. 211–230.

[38]"The Airbus Fly-by-Wire," Airbus Industries, Blagnac, France, Sept. 1996.

[39]Fielding, C., and Luckner, R., "Industrial Considerations for Flight Control," *Flight Control Systems*, edited by R. W. Pratt, AIAA, Reston, VA, 2000, pp. 1–53.

[40]Hamer, H. A., and Johnson, K. G., "Effects of Errors on Decoupled Control Systems," NASA TP-1184, July 1978.

[41]Miller, G. K., Jr., "Fixed-Base Simulation Study of Decoupled Longitudinal Controls During Approach and Landing of a Medium Jet Transport in the Presence of Windshear," NASA TP-1519, Oct. 1979.

[42]Miller, G. K., Jr., "Simulation Comparison of a Decoupled Longitudinal Control System and a Velocity Vector Control Wheel Steering System During Landings in Windshear," NASA TP-1734, Nov. 1980.

[43]Morello, S. A., Knox, C. E., and Steinmetz, G. G., "Flight-Test Evaluation of Two Electronic Display Formats for Approach to Landing Under Insrument Conditions," NASA TP-1085, Dec. 1977.

[44]Kelley, W. W., "Simulator Evaluation of a Flight-Path Angle Control System for a Transport Airplane with Direct Lift Control," TP-1116, March 1978.

[45]Steinmetz, G. G., "Simulation Development and Evaluation of an Improved Longitudinal Velocity Vector Control-Wheel Steering Mode and Electronic Display Format," NASA TP-1664, Aug. 1980.

[46]Sankrithi, M. K. V., and Bryant, W. F., "7J7 Manual Flight Control Functions," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, New York, 1987, pp. 905–913.

[47]Veldhuijzen, A. R., Mulder, M., Van Paassen, M. M., and Mulder, J. A., "Aircraft Task-Oriented Control/Display Interfaces," *Proceedings of the 12th International Symposium on Aviation Psychology*, Wright State Univ., Dayton, OH, 2003, pp. 1191–1196.

[48]Borst, C., Mulder, M., and Van Paassen, M. M., "Advanced Fly-by-Wire and Tunnel-in-the-Sky Displays: Development and Experimental Evaluation of a Path-Oriented Control Augmentation," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Reston, VA, 2004, pp. 1–13.

[49]Van der Linden, C. A. A. M., "DASMAT: The Delft University Aircraft Simulation Model and Analysis Tool," Faculty of Aerospace Engineering, Delft Univ. of Technology, Rept. LR-781, Delft, The Netherlands, April 1996.

[50]Gibson, J. C., "Development of a Methodology for Excellence in Handling Qualities Design for a Fly-by-Wire Aircraft," Ph.D. Dissertation, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, The Netherlands, April 1999.

[51]Hoh, R. H., Mitchell, D. G., and Hodgkinson, J., "Bandwidth, a Criterion for Highly Augmented Airplanes," Criteria for Handling Qualities of Military Aircraft, CP-333 AGARD, April 1982.

[52]Shweyk, K. M., and Rossitto, K. F., "Applicability of Pitch and Flight-Path Bandwidth Criteria to Transport Aircraft with Flight-Path-Rate Response System," *Proceedings of the AIAA Modeling and Simulation Technologies Conference*, AIAA, Reston, VA, 2000, pp. 255–265.

[53]Jacobson, I. R., and Joshi, D. S., "Investigation of the Influence of Simulated Turbulence on Handling Qualities," *Journal of Aircraft*, Vol. 14, No. 3, 1977, pp. 272–275.

[54]Van de Moesdijk, G. A. J., "The Description of Patchy Atmospheric Turbulence, Based on a Non-Gaussian Simulation Technique," Rept. LR-192, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, The Netherlands, Feb. 1975.

[55]Hart, S. G., and Staveland, L. E., "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," *Human Mental Workload*, edited by P. A. Hancock and N. Meshkati, Elsevier, Amsterdam, 1988, pp. 139–183.

[56]Van der Vaart, J. C., "Modelling of Perception and Action in Compensatory Manual Control Tasks," Ph.D. Dissertation, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, The Netherlands, Dec. 1992.

[57]Hosman, R. J. A. W., *Pilot's Perception and Control of Aircraft Motions*, Ph.D. Dissertation, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, The Netherlands, Nov. 1996.