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nxControl instead of pitch-and-power

A concept for enhanced manual flight control

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Abstract A command system for manual control of the longitudinal load factor in flight path direction of an aircraft is designed that completes existing flight control command systems (e.g. with sidesticks that command normal load factor). The system is called nxControl. It aims to assist pilots during manual flight by reducing the workload for monitoring flight parameters as well as for controlling thrust and airbrakes. Important for the nxControl concept is the direct flight mechanical relation between longitudinal load factor and changes of the total aircraft energy. This paper presents the system concept and a prototype realization. The nxControl system consists of the control law that combines the actuation commands for engines and airbrakes, a new input device for the longitudinal load factor command and augmented display elements informing pilots about aircraft energy states to assure situation awareness. In order to investigate the feasibility of the concept as well as to evaluate consequences on human performance, a flight simulator study with airline pilots was conducted. The nxControl prototype was used by the pilots as expected. Changes in instrument scanning behaviour and thrust lever usage confirmed this. After just a short familiarization and practice, the pilots were able to perform standard flight tasks with nxControl without exceeding given tolerance limits. So, the results provide first evidence for the feasibility of the concept.

Keywords Total energy angle · Potential flight path angle · Augmented manual flight control · Thrust control · Cockpit displays · Scanning behaviour

1 Introduction

Increasing air traffic raises the requirements for future flight trajectories coupled with the necessity to follow more complex flight paths with higher precision (e.g. Flightpath 2050 [6]). Modern commercial transport aircraft fulfil these requirements by today's automatic flight control systems. But even complex future flight trajectories must remain manually flyable with reasonable pilot workload in case of air traffic control requesting immediate adjustments of the flight path, a system failure, or for training of manual piloting skills [7].

Modern commercial aircraft are equipped with systems that assist and support the pilot in manual flight. Those systems comprise enhanced cockpit displays and augmented flight control systems. They became available in the 1980s when glass cockpits and electronic flight control systems (fly-by-wire systems) were introduced. They incorporate flight control laws to generate the control surface commands that are necessary to manoeuvre the aircraft [2, 4]. In fly-by-wire aircraft, pilots command aircraft flight parameters (typically pitch and roll rate, or angle of attack and angle of sideslip) using a control column (yoke), sidestick, or pedals instead of directly commanding control surface deflections. These control systems allow for more precise and safer manual flight at reduced pilots' work load [8].

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However, such augmentation does not yet exist for engine thrust or drag force generated by speedbrakes. Pilots still control these actuation elements in a conventional way. In order to command a desired power setting, pilots use memorized pitch-and-power values. The specific power settings depend on the aircraft's altitude, speed, mass, and configuration and vary when those parameters change. Since it is impossible to memorize proper settings for each flight situation, pilots often need to interpolate the required power setting based on values they remember. The interpolations then are optimized on a trial-and-error basis by closely monitoring and cross-checking power, pitch, speed, and altitude. This entails several performance consequences for pilots. First, pitch-and-power flying is cognitively demanding because proper combinations of values need to be memorized and, if necessary, interpolated. Second, it requires pilots to scan information that is not available on the primary flight display (PFD) and, thus, makes instrument scanning complex. Third, it often requires repeated manual adjustments of thrust based on trial-and-error.

Given this in conjunction with future air traffic requirements, it is important to look for technological developments to simplify the control and proper adjustment of thrust in manual flight, to allow flying more demanding flight paths under manual control with less workload and higher precision. This shall be accomplished by providing augmented energy-related information on the PFD and a control command system for thrust that allows a direct thrust adjustment tailored to specific flight path control targets. The paper suggests to achieve this goal by a control command system with an adapted human machine interface (called nxControl) that complements the conventional augmented manual fly-by-wire flight control concepts by a comparable concept for thrust control. For this purpose, a controller for the load factor in flight path direction (nxController) was selected.

Section 2 describes the nxControl concept and its prototype used for flight simulator investigations. The flight mechanical background is introduced briefly, the specific system components are explained, and the nxController is described. In addition, the modified elements of the cockpit interface, including an enriched PFD (nxPFD), a new status display indicating the system functionality and its limits (nxStatus), and the new functional principle of the adapted input lever (nxLever), are depicted.

Section 3 describes a first flight simulator study that had the purpose to confirm the feasibility of the nxControl concept. An experiment with eleven certified airline pilots was designed to observe if pilots easily understand the underlying concept of nxControl and if they can successfully fly standard flight tasks with the prototype implementation after only a short briefing. This concept confirmation in today's operations is seen as an essential first step before the evaluation of the nxControl concept in more demanding future flight tasks, in which it shall prove its abilities. With the aid of eye-tracking analysis, it was determined whether the participants made use of the nxControl system and the additionally displayed information. In a further step, possible benefits regarding precision of thrust control were evaluated. Additionally, it was investigated whether pilots would be able to maintain flight parameter tolerances when using nxControl compared to conventional manual flight. The detailed hypotheses, the experimental method, and the results are discussed. The final Sect. 6 includes a summary of conclusions and recommendations on further investigations of the nxControl concept.

2 System description

2.1 Flight mechanical background

The nxControl system aims at completing the augmented manual control concepts of today's sidestick controlled passenger aircraft that use vertical load factor n_z to control pitching. The longitudinal load factor n_x is not yet a primary control variable. It represents changes of the energy state. The longitudinal load factor is related to the vertical speed and flight path acceleration, which pilots use for flight path control. The fundamental flight mechanical equations that describe this relationship are well known and can be found in textbooks with differing terminology, e.g. [5, 9]. Due to its importance for the concept, a brief summary follows.

The total longitudinal load factor in flight path direction $n_{xk,\mathrm{tot}}$, as indicated by the indices *xk* for flight path direction and tot for total, is defined in [10] as the ratio between the resultant force in x_k direction, i.e. thrust force F and aerodynamic drag force D, related to weight W,

$$n_{xk,\mathrm{tot}} = \frac{F - D}{W}. \tag{1}$$

This ratio is also known as specific excess thrust. As it can be derived from the second Newtonian axiom for a rigid body mass point, $n_{xk,\mathrm{tot}}$ is equal to the sine of the flight path angle γ and the longitudinal flight path acceleration $\dot{V}_K$ divided by the gravitational constant g

$$n_{xk,\mathrm{tot}} = \frac{F - D}{W} = \sin\gamma + \frac{\dot{V}_K}{g}. \tag{2}$$

In a steady trimmed horizontal flight condition, where thrust force equals drag force, $n_{xk,\mathrm{tot}}$ is zero. Changes in thrust or drag directly affect $n_{xk,\mathrm{tot}}$, and cause either a change in flight path angle γ

$$\sin \gamma = \frac{\dot{H}}{V_K}, \tag{3}$$

if V_K is kept constant, or in flight path acceleration expressed by the ratio $\dot{V}_K/g$, if the altitude is maintained, or in both. Thus, the pilot can control $n_{xk,\mathrm{tot}}$ by setting thrust or modifying drag and distribute this difference to altitude or speed changes by using pitch control (n_z-control).

Altitude H and flight path velocity V_K are important parameters for flight path control. They relate to potential and kinetic energy and therefore to the total energy E_{tot} of the aircraft. As explained in [5] changes in total energy can be described by the total energy angle γ_E (also known as total flight path angle)

$$\sin \gamma_E = \frac{\dot{E}_{\mathrm{tot}}}{W V_K} = \frac{\dot{H}}{V_K} + \frac{\dot{V}_K}{g}, \tag{4}$$

that is defined by the derivative of the total energy $\dot{E}_{\mathrm{tot}}$ related to weight W and flight path velocity V_K and is the sum of the changes in potential and kinetic energy as Eq. (4) shows. By comparing Eqs. (2) and (3) with Eq. (4) it becomes obvious that the longitudinal load factor in flight path direction n_x (from here, the index xk, tot is abbreviated by x) and the sine of the total energy angle are equal. Both can be controlled by setting thrust and drag of the aircraft. These principles led to the nxControl concept.

Reference [16] describes the flight mechanics relevant for the nxControl concept in more detail. A precursor study described in [13, 14] investigated how airline pilots manage energy in typical flight tasks.

2.2 nxPFD

In the nxControl concept, the longitudinal load factor n_x is directly controlled by the pilots. Therefore, the n_x value needs to be indicated in a suited combination with other information on the PFD. Instead of the load factor n_x, the total energy angle (TEA) γ_E (see Eq. (4)), which is also called potential flight path angle, is visualized instead, as it has the dimension of an angle and perfectly fits to the pitch angle scale. On a conventional PFD, pilots have to gauge how energy change affects the flight state, by evaluating the airspeed and vertical speed scale. To ease this task, the relationship between TEA and the flight path angle (FPA) can be used.

The concept of displaying FPA and TEA together on a PFD is not new. It has been introduced by Klopfstein [11] and is also suggested by other authors e.g. Lambregts et al. [12] and Amelink et al. [1]. Moreover, this combination has been proposed and implemented in head-up-displays [3]. However, these earlier concepts included several fundamental changes to the common PFD, like rescaling speed and altitude tapes or using a pathway in the sky. In contrast to the above-mentioned concepts, the approach of presenting augmented energy information as part of the nxControl concept focuses exclusively on the integration of the parameters TEA and FPA into a conventional Airbus-like head-down PFD (nxPFD). It was assumed that a familiar display assures the pilot's acceptance and the addition of only one new symbol (i.e. TEA) might reduce possible clutter problems compared to the mentioned concepts.

Displaying the FPA on the PFD is common nowadays, e.g. Airbus pilots can activate a flight path symbol by enabling the track and flight path mode on the autopilot control unit. The FPA on the nxPFD is indicated as a green circle with a centre dot, representing a FPA symbol without bank angle and drifting information. TEA is a green line parallel to the artificial horizon. Both symbols are centralized in the PFD related to the pitch scale at the attitude direction indicator (ADI) and specify the corresponding angles in degree. The green colour fits to the Airbus colour code of indicators. Figure 1 shows an example of the nxPFD during a decelerated descent, indicated by TEA below FPA.

The spatial relationship between the two symbols gives the pilots the possibility to rapidly capture a change of the energy state and of the flight state parameters altitude and speed. Figure 2 shows the relationship between TEA and FPA for different flight situations.

If both symbols are on the artificial horizon the energy state is not changing. Potential, kinetic, and total energy stay constant and the aircraft performs a steady horizontal flight (Fig. 2e). If the pilot starts descending or climbing without changing the power setting, the green circle shows the current FPA over, respectively, under the horizon and the TEA stays on the horizon (Fig. 2a, i). The potential

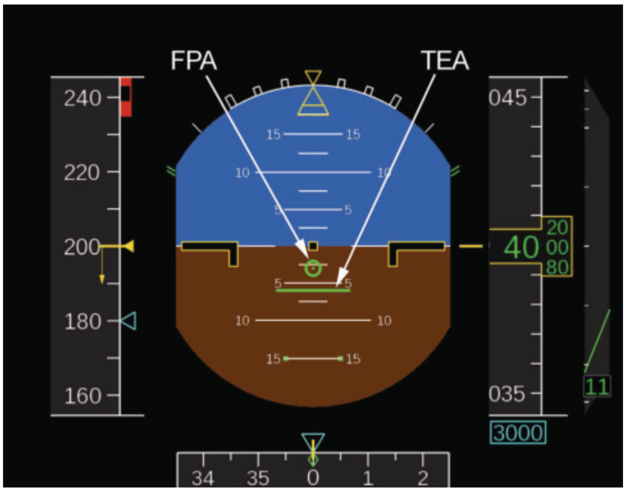

Fig. 1 nxPFD in case of a $-3°$ descent with a total energy angle of $-6°$. *FPA* flight path angle, *TEA* total energy angle

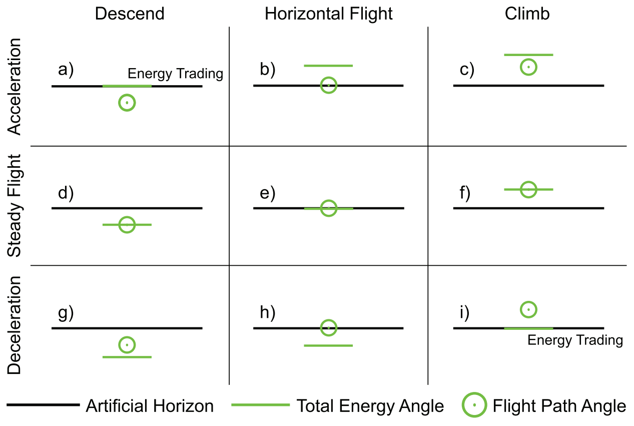

Fig. 2 Relationship between total energy angle, flight path angle and artificial horizon

energy changes while the total energy is not changing because of the constant power setting.[1] Thus, the decreasing/increasing potential energy causes an increasing/decreasing kinetic energy—an energy exchange is taking place (energy trading).[2]

If the pilot changes the power setting, the TEA is moving accordingly. If the TEA is on the FPA, the whole amount of total energy change results from a potential energy change (Fig. 2d, f). In this case, the kinetic energy and speed stay constant.

If the TEA is above the FPA, the speed is increasing (Fig. 2a–c). During deceleration the TEA is below the FPA (Fig. 2g–i). As explained, the integration of TEA and FPA on the pitch scale shows speed and altitude trends, which makes this information redundantly available on the nxPFD, but here it is possible to capture it centralized at one glance. Furthermore, there is now a relation to the power setting that is required for the desired flight state.

2.3 nxStatus

The additional indicators on the PFD show how the energy state of the aircraft changes. Yet, it does not provide information on the current limitations of maximum possible energy gain or reduction. Thus, a second display was designed, referred to as nxStatus display (see Fig. 3). In our prototype it is located near the engine parameter (EP) on the system display.

The nxStatus display shows the current total energy angle of the aircraft as green bug on a vertical angle scale in degree. The blue flag represents the energy angle command for the controller, which is described in Sect. 2.4. It is only visible when nxControl is active.

The possible energy angle for full thrust depends on the flight condition, especially on speed, altitude and configuration of the aircraft, and the performance parameters of the aircraft. Orange and yellow tapes represent the limitations of the flight envelope: the upper limit is the possible TEA, when applying maximum thrust, the lower yellow limit indicates the TEA when flying with idle thrust and the lower orange limit indicates the TEA when flying with idle thrust plus airbrakes deployed to maximum deflection.

The limitations can be understood as maximum and minimum flight path angle without changing speed. Thus, the pilots can assess if the aircraft is able to achieve a required energy change. This information makes aware of available manoeuvre capabilities, for example, to assess if a steep approach is possible without additional drag or which climb angle is possible in a go around with the current configuration. An alternative approach of displaying such information can be found in the vertical speed tape within the experimental vertical situation display proposed by Rijneveld et al. [15].

For the example aircraft VFW614-ATD (see Sect. 3.2), Fig. 3 shows the nxStatus display in different flight situations and configurations. Situations (a) and (b) show the influence of the airspeed at constant altitude and configuration: At higher speed, the aerodynamic drag increases for speeds above minimum drag speed, which lowers the possible maximum TEA but raises the possibility to reduce the current energy state with a lower minimum TEA.

Situations (c)–(e) show the impact of different slat/flap configurations: with higher configuration, the aerodynamic drag is rising and with this the flight envelope is moving to a lower maximum and minimum achievable TEA. In case (e), the full configuration, the airbrakes are not usable. That is why there is no difference between the yellow and the orange lower limit. Additionally, it is observable that a horizontal flight in this configuration would not be possible without losing speed, since the maximum TEA is negative.

2.4 nxController and nxLever

Both, nxPFD and nxStatus display show the current state of the aircraft and can be used without the nxController. In that case, the pilot has to control the TEA with the thrust by commanding the fan rotation speed of the engines (N1) with the thrust levers or by setting the airbrakes for increased drag. As the TEA reaction after a change in N1 or an airbrake deflection depends on the current flight state, the pilot has to adjust the input for a steady TEA according to the changing flight state. To relieve the pilot from this control effort and to enable a more precise flight along highly demanding flight trajectories, the control command

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[1] This is true for short time periods. In the long term, the lift to drag ratio that changes with airspeed will affect the energy rate.

[2] This is similar to the information of a total energy compensated variometer in sailplanes, where the pilot is able to determine whether the climb rate is a result of thermal lift or steering input.

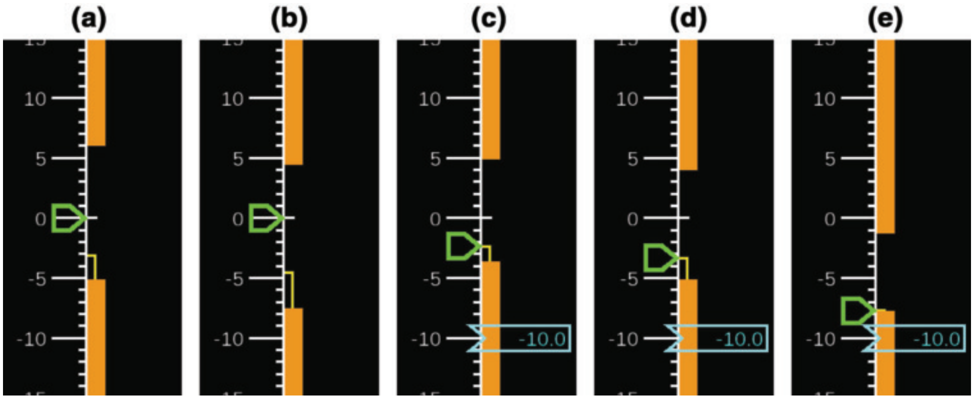

Fig. 3 nxStatus display at different flight situations with (**c**–**e**) and without (**a**, **b**) command flag; **a** FL160, IAS 200 knots, **b** FL160, IAS 250 knots, **c** FL20, IAS 170 knots, **d** FL20, IAS 170 knots, flaps 2, **e** FL20, IAS 170 knots, flaps 4 (full)

system nxControl was designed. The command and control variable of the nxController is the TEA, which is controlled by using engines and airbrakes. The control variable TEA is calculated by the sensor data of airspeed acceleration and flight path angle and is feedback to the nxController.

The TEA command value for nxController is selected by the nxLever that is used similar to the thrust lever. Its position is linearly converted into a TEA command and is indicated on the nxStatus display as a blue flag (see Fig. 3). The selected value is digitally displayed in the blue flag. The nxLever has a detent at the middle position, representing a command of zero degrees of TEA.

In this case, the nxController sets the thrust to compensate the current drag force so that the aircraft is neither losing nor gaining total energy.

Depending on the TEA command, the nxController uses the engines or the airbrakes. If the pilot's command is between the upper orange and lower yellow limit of the nxStatus display, the nxController uses the whole range of engine thrust from idle to maximum thrust. If the command is below the yellow limit, the pilot can activate the airbrakes by pushing an extra button. This allows the nxController using the airbrakes to reduce energy at a higher rate, if the engines are operating in idle thrust. If the pilot does not push the button, a command below this limit always implies idle thrust. In Fig. 3c–e, the green bug, corresponding to the current TEA of the aircraft, always stays at the yellow limit. Accordingly, a command above the upper limits always means maximum thrust (maximum take off thrust at take off, maximum continuous thrust in all other flight phases).

The defined priority for using engines and airbrakes is necessary to assure the pilot's situation awareness. Without the active initiation by the pilot, the airbrakes are not used. By pushing the button, the pilot can decide if the maximum decrease of energy shall exclusively be achieved by thrust reduction or additionally by drag force. Anyhow, a pilot would not increase engine thrust and extend airbrakes at the same time, as this would be energy inefficient.

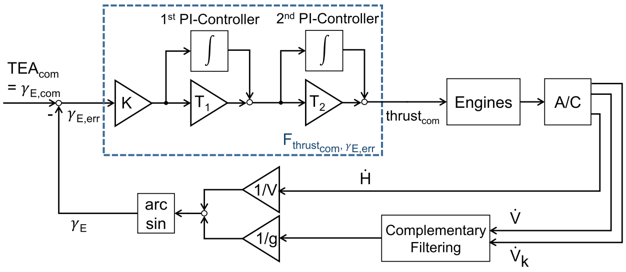

Fig. 4 Control loop for thrust controller

The nxController, therefore, comprises two control laws, one for thrust and one for airbrakes. Both control laws have the same structure and consist of two sequent PI controllers. The thrust control law (see Fig. 4) is described by the transfer function

$$F_{\mathrm{thrust_{com}};\gamma_{E,\mathrm{err}}} = K \frac{T_1 s + 1}{s} \frac{T_2 s + 1}{s}. \tag{5}$$

The gain K and the time constants T_1 and T_2 (both approx. 1.5 s) are designed to cause a thrust response to a TEA command that imitates the conventional aircraft reaction. The control law eliminates the error $\gamma_{E,\mathrm{err}}$ with steady-state accuracy by using the first integrator. The second integrator eliminates the influence of drag variation s caused by changing speeds. Thus, the pilot does not need to readjust a command input, once the value was correctly set.

In case of an external disturbance of the aircraft's energy state, nxController compensates the error with engines or airbrakes (corresponding to the selected control law). Disturbances are, for example, wind gusts, varying aerodynamic drag due to aircraft speed or configuration changes and engine thrust differences due to air density variation in climb and descend. Additionally, the complementary filter assures smooth thrust commands in turbulence. Thus, nxController will decrease the pilot's workload by eliminating the necessity of readjustments after such disturbances.

3 Experiment

An experimental study was conducted to investigate the feasibility of the nxControl concept with the overall objective to examine whether pilots were able to fly standard tasks with this system, while maintaining the given flight parameter tolerances. In order to assess whether the pilots used the additional energy information as alternative to the common pitch-and-power strategy, eye movements of the participants were analysed.

3.1 Participants

Eleven certified airline pilots, all male, participated in the experiment. Two of them were captains. All pilots had an Airbus A320 type rating. Their flight experience was between 770 and 14560 flight hours (mean $M = 4371.1$, standard deviation $\mathrm{SD} = 4558.6$). Their age ranged from 27 to 55 years ($M = 33.6$, $\mathrm{SD} = 9.2$). All pilots had normal or corrected to normal vision. The pilots volunteered their time to participate in the study.

3.2 Apparatus

3.2.1 Simulation

The experiment was conducted in the fixed-base flight simulator SEPHIR (Simulator for Educational Projects and Highly Innovative Research) at the Chair of Flight Mechanics, Flight Control and Aeroelasticity of Technische Universität Berlin. The modularly constructed simulator is configured as VFW614-ATD, which contains a manual flight control system with sidesticks similar to modern commercial aircraft. Despite minor differences (e.g. the VFW614-ATD's higher aerodynamic drag), the flight characteristics and handling as well as the cockpit configuration closely resemble those of an Airbus A320. The simulator is equipped with a collimated, high-quality visual system.

The simulation of the VFW614-ATD was supplemented by the nxControl prototype as described in Sect. 2. Figure 5 shows the cockpit and display arrangement used in the tests. The 10 in. displays, used as primary flight displays, navigation displays, and engine display, have a resolution of 1280 × 1024 pixels. The nxStatus was displayed on a separate 7 in. portrait screen, with a resolution of 480 × 800 pixels.

3.2.2 Eye tracker

The participants' eye movements were recorded with the SMI (SensoMotoric Instruments) Eye Tracking Glasses 1.9 and the software SMI iView ETG$^{\mathrm{TM}}$ in version 2.1 beta. The scene video was recorded in 24 Hz with a resolution of 1280 × 960 pixels. The eye-tracking data rely on binocular infrared tracking technology with a sampling rate of 30 Hz.

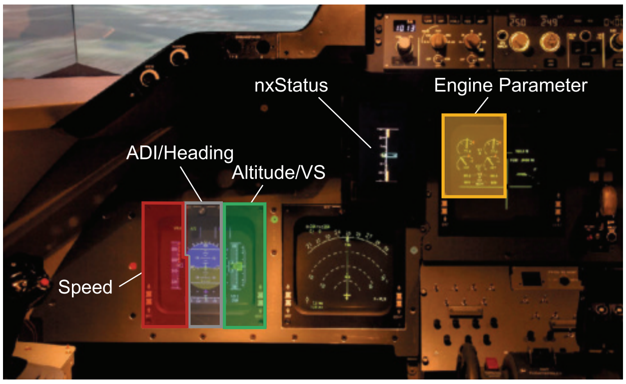

Fig. 5 Flight simulator cockpit with nxStatus display and areas of interest

3.3 Independent variables

Three configurations were compared with a within-subjects study design. Each pilot flew repeatedly all flight tasks with each of the three different simulator configurations. The three conditions represent the independent variable in this study. In the first configuration, called nxControl, the participants flew the flight simulator with the entire prototype enabled, which comprised the nxController and the displays nxPFD and nxStatus. The second configuration called nxDisplay, consisted of a reduced prototype. The nxControl displays (nxPFD and nxStatus) were shown, but the controller was disabled; thus, thrust and speedbrake control were conventional. In the third configuration, called conventional, the entire prototype was disabled. The pilots controlled the simulator conventionally using Airbus A320-like displays as in manual raw-data flight, i.e. without flight director. The sequence of simulator configurations was counterbalanced across participants.

3.4 Procedure

Prior to their simulator session, the pilots received a detailed standardized briefing and training of functions and usage of the nxControl system. To familiarize with the functionality of the prototype, the pilots had the opportunity to practice in the simulator similar tasks as in the later experiment. All in all, the introduction and training took about 1.5 h and ended with a short break.

Before performing the first configuration block, the eye tracker glasses were calibrated with a 3-point-calibration. The pilots were briefed to behave like during line operations to achieve a similar performance in the simulator as in real flight. The participants were reminded that the

Table 1 Requested tolerances for the flight tasks

Parameter	Tolerance
IAS	±5 knots
Altitude	±100 ft
Heading	±5°
Bank	±5°

experiment's objective was to analyse the handling of the prototype and not their personal performance. The tolerances were explained (see Table 1) and the pilots were told to maintain or reach the requested flight parameters as precisely as possible.

Then, each pilot performed three experimental blocks, which involved flying four scenarios that are explained below with different configurations in constant order. Each block started with a short practice flight to accommodate to the specific configuration. For each scenario, the simulator was configured with retracted speedbrakes and flaps and the thrust lever set to a position equal to a steady and horizontal flight with 250 knots, altitude FL100 and heading of 170°.

Scenario 1: idle deceleration. The pilot's task was to decelerate with idle power from 250 to 200 knots and then regain a steady horizontal flight at 10000 ft (flight level FL100) and a heading of 170°.

Scenario 2: climb and turn. The task was to perform a left turn from heading 170° to 65° with a constant bank angle of 15°, while climbing from FL100 to FL110 with a constant climb rate of 500 ft/min. In all three experimental configurations, it was mentioned, that this climb rate is corresponding to a FPA of 1.2°. The pilots were supposed to maintain the initial air speed of 250 knots.

Scenario 3: steep turn. In this task, the pilots were supposed to perform a 180° right turn with a bank angle of 45°. At a heading of 30° prior to the target heading, they should start to decrease the bank angle. During the entire task, the pilots were told to maintain a constant speed of 250 knots and altitude of FL100.

Scenario 4: descent with speedbrakes. In this scenario, a descent with a given sink rate of 3500 ft/min from FL100 to FL50 was requested. In all three experimental configurations, it was mentioned that this sink rate was corresponding to a FPA of −7°. To realize this sink rate, participants were required to make use of the speedbrakes. At 1000 ft above the target altitude, the pilots were supposed to reduce the sink rate to 1000 ft/min (FPA of −2.5°). Initial speed 250 knots and heading 170° were supposed to be constant.

The flight scenarios were designed to be short and easy to understand. All tasks involved a considerable change in energy state. Therefore, changes in speed or altitude had to be initiated by the pilot himself or were generated through disturbance by a simultaneous task-like turning to specific headings. The selected scenarios were similar to standard flight tasks in line operations or training sessions (e.g. air works).

Since a direct comparison of the four different scenarios was neither intended nor useful, the scenario type was not treated as an independent variable. Each pilot performed the scenarios with a given configuration in the same order.

During the flight task, an experiment assistant in the role of the pilot monitoring supported the participants. The assistant reacted to commands of the pilot flying and selected requested parameters, e.g. speed, altitude and heading at the autopilot control unit. The pilot monitoring also did the common callouts and pointed out if flight parameters were out of tolerance. Due to the experimental setup, all participating pilots needed to be seated on the captain seat on the left.

Subsequently to the experiment, the pilots were interviewed about their opinion about the prototype. The debriefing interview was guided by pre-assembled questions, and the participants were encouraged to comment their answers.

3.5 Dependent variables

3.5.1 Lever activity

In order to assess the objective work load in terms of control effort, the input activity at the control lever was recorded and quantified. A lever movement was detected, if a difference in lever position LP was larger than the lever threshold LT defined as 0.5 cm (one percent of the entire lever range) every $\Delta t = 2$ s:

$$\mathrm{count}_k = \begin{cases} 0, & \text{if } |\mathrm{LP}(t_k - \Delta t) - \mathrm{LP}(t_k)| < \mathrm{LT} \\ 1, & \text{if } |\mathrm{LP}(t_k - \Delta t) - \mathrm{LP}(t_k)| \geq \mathrm{LT}. \end{cases} \tag{6}$$

The lever activity *LA* is the sum of these movement counts with respect to the time sample points $N = t/\Delta t$.

$$\mathrm{LA} = \frac{\sum_{k=1}^{N} \mathrm{count}_k}{N}. \tag{7}$$

The higher the percentage, the more movements on the lever were required to fulfil the flight task.

Scenario 4 demanded additional use of speedbrakes. nxControl automatically used the speedbrakes, if the pilot activated this mode. An additional movement on the speedbrake lever as in the configurations conventional or nxDisplay was not needed. To consider the additional movements at the speedbrake lever in the configurations conventional and nxDisplay, the percentage of speedbrake lever activity was added to the thrust lever activity. The definition of the speedbrake lever activity was calculated in the same way as for the thrust lever.

3.5.2 *Eye tracking*

The eye movements of the participants were measured with eye-tracking glasses. The glasses were chosen in favour of an easier setup in the simulator and less intrusion, hence more natural behaviour of the pilots compared to remote eye tracking. The recorded eye movement data were further processed with the program SMI BeGaze$^{\text{TM}}$ version 3.5 beta. The data were manually offset corrected for each scenario, and all fixations within the scenarios were manually mapped on a fixed reference image with specified areas of interest (AOI) as Fig. 5 shows. Due to the limited resolution and precision of the eye tracker, only a limited number of AOIs could be used, and closely neighboured parameter scales had to be grouped, e.g. altitude and vertical speed (VS) scale. In addition, the display bezels, where no information is displayed, are part of the AOI to compensate for inaccuracies in eye tracking.

To detect a relative change in the scanning of the flight parameters, four AOIs were selected: Engine Parameter, Speed, Altitude/VS and ADI/Heading (see Fig. 5). Gazes on other instruments, e.g. nxStatus display, and to the outside view were neglected, since only changes concerning the relative attention to the four primary parameters allowed a direct comparison of the three experimental conditions.

The AOI Engine Parameter contains values and visual cues of the parameter fan speed N1, exhaust gas temperature, fuel flow and core speed N2 for both engines. AOI Speed contains the speed scale. Here, the indicated airspeed (IAS), selected speed, speed trend, and speed limits are displayed. The AOI Altitude/VS contains the altitude scale and VS indicator. Thus, altitude, selected altitude, VS and glide slope deviation are displayed in this area. In the centre of the PFD is the AOI ADI/Heading. In this area, the artificial horizon and the heading scale are visible, displaying the bank and pitch angle as well as the heading. In configuration nxDisplay and nxControl, the symbols for FPA and TEA are activated.

As operational definition of instrument scanning, the relative dwell time was chosen. The relative dwell time is the overall time during which gazes were placed within the boundary of a certain AOI divided by the total dwell time duration of all observed AOIs.

3.5.3 *Performance*

It was investigated whether the participants could maintain the requested flight parameters altitude, IAS, heading and bank angle within the given range of tolerance (see Table 1). For each flight parameter, configuration and scenario, it was assessed when tolerances were exceeded. The mean relative duration of violations (related to the overall duration of a scenario) was taken as performance indicator.

3.6 Hypotheses

It was expected that the use of the nxControl system would amend the application of pitch-and-power knowledge and heuristics by the additional information integrated into the displays and by the controller ensuring that an input corresponds to the same aircraft reaction independent of altitude, velocity, configuration, or mass of the aircraft. At the same time, the new system should enable an easier and more intuitive way to find the required energy setting precisely and directly, i.e. with less control inputs at the thrust lever and less scanning of the engine parameters. To assess these work load and performance consequences, the study compares the frequency of thrust lever or nxLever inputs and eye movement towards the engine parameters. It was hypothesized that while flying with support of nxControl, the lever activity as well as the dwell time on traditional engine parameters would decrease, compared to conventional manual flight.

Another objective of this study was to examine whether the implementation of the TEA and FPA would alter the scanning pattern within the PFD in the expected way. By means of relative positions of TEA and FPA displayed in the centre of the ADI, the pilots receive additional and direct information about relative changes of velocity and altitude. Therefore, demands on scanning the speed and altitude scale as needed for conventional pitch-and-power flying should be reduced and scanning the centre of the ADI increased (see Sect. 2). If the expected changes in scanning pattern occur, this implies that the pilots relied on the augmented energy information for flight path and thrust control as alternative to their trained standard scanning pattern for conventional pitch-and-power flying.

Finally, it was expected that the pilots, after just a short familiarization and practice phase, would be able to maintain requested flight parameters in terms of altitude, IAS, heading, and bank angle within the given tolerances after a short training phase. The following six hypotheses were specified:

H#1: In configuration nxControl, the lever activity will decrease compared to conventional configuration.
H#2: In configuration nxControl, the relative dwell time on AOI Engine Parameter will decrease compared to conventional configuration.
H#3: In configuration nxControl, the relative dwell time on AOI Speed will decrease compared to conventional configuration.

H#4: In configuration nxControl, the relative dwell time on AOI Altitude/VS will decrease compared to conventional configuration.

H#5: In configuration nxControl, the relative dwell time on AOI ADI/Heading will increase compared to conventional configuration.

H#6: In configuration nxControl, pilots are able to perform the standard flight tasks without exceeding given tolerances for altitude, IAS, heading, and bank angle.

The experimental configuration nxDisplay was added for exploratory reasons and to better distinguish to what extend potential effects would emerge due to the individual elements of the nxControl system. nxPFD and nxStatus were activated, but the nxController was disabled.

3.7 Data analysis

A repeated measures analysis of variance (ANOVA) was used for statistic analysis of the eye tracking and performance data. The probability of the associated F-test indicates how likely it is that the observed differences in the means of the dependent variables for the different experimental conditions just reflect random variation, i.e. variation not induced by the three different simulator configurations. As usual a probability p as low as or less than 5 % was defined as level to reject the assumption of a pure chance effect (significance level). If the assumption of sphericity was violated, a Huynh-Feldt correction was performed. Due to a technical problem, lever position data were lost and only four participants in scenario 1 and five participants in scenario 2–4 could be compared. Therefore, the lever data were evaluated nonparametrically through exact Friedman test based on a χ^2-statistic by applying the same considerations as described above for the F-statistic.

4 Results

4.1 Lever activity

It was expected that the provision of nxDisplay and even more nxControl would unload the pilot from trial-and-error thrust lever adjustments by providing better guidance for proper thrust settings to reach the flight path targets. Figure 6 shows a bar chart with the average of the lever activity. The higher the value, the higher the lever activity of the pilots was. The mean values of scenario 1, 3, and 4 decreased across the configurations. Merely, in scenario 2, the thrust lever activity seems to be higher with nxDisplay than in conventional simulator configuration. The lowest relative lever movement was always observed in configuration nxControl.

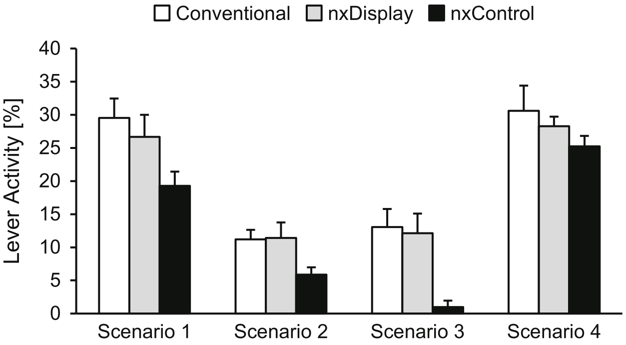

Fig. 6 Mean and standard errors of the lever activity in scenario 1–4 across all configurations (scenario 1: $N = 4$, scenario 2–4: $N = 5$)

For scenario 1 and 3, the Friedman test revealed the above-described effects as significant and confirmed H#1 [scenario 1: $\chi^2(2) = 6.500, p = 0.042$; scenario 3: $\chi^2(2) = 7.600, p = 0.024$]. Yet, the effect in scenario 2 just failed to reach the conventional level of statistical significance, $\chi^2(2) = 5.200, p = 0.093$. In scenario 4, no significant effect was found $\chi^2(2) = 2.800, p = 0.367$.

4.2 Eye tracking

4.2.1 Scenario 1: idle deceleration

The relative dwell times for the four AOI, i.e. Altitude/VS, Speed, ADI/Heading, and Engine Parameter in the three simulator configurations are displayed in Fig. 7. Note, that one participant executed the task of scenario 1 incorrectly. Therefore, his data were not used and the sample size was reduced to ten.

As becomes evident, the small percentage of dwell time on the engine display even decreased further across configurations (H#2), $F(2, 18) = 11.613, p < 0.001$. Such effect was expected because the new displays should free the pilots from traditional pitch-and-power flying.

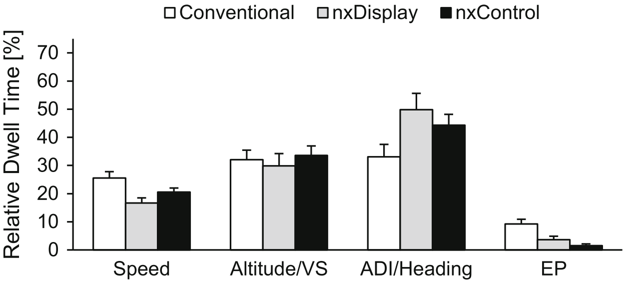

Fig. 7 Average relative dwell time of all AOI across every configuration in scenario 1 ($N = 10$)

With respect to the scanning of PFD parameters, the expected changes along with the introduction of the augmented indicators TEA and FPA were supported by the data for AOI Speed but not for AOI Altitude/VS. The relative dwell time on the speed scale decreased from the conventional configuration to the nxDisplay and nxControl configurations (H#3), $F(2, 18) = 11.523, p < 0.001$. This effect was expected, since the relative change of speed (e.g. while stabilizing the target speed) can directly be derived from the augmented display elements TEA and FPA. In contrast, the dwell times on the ADI increased significantly (H#5), $F(1.658, 14.925) = 16.735, p < 0.001$. However, contrary to expectations (H#4), no significant effect was found for relative dwell times on the altitude scale and VS indicator, $F(2, 18) = 0.813, p = 0.459$.

4.2.2 *Scenario 2: climb and turn*

Eye-tracking results for scenario 2 are shown in Fig. 8. It shows a similar shift of relative dwell time for scenario 2 as seen in scenario 1. Again, the relative dwell times on the engine parameter decreased significantly across configurations [$F(1.521, 15.211) = 10.406, p = 0.003$].

For changes of scanning behaviour within the PFD, essentially, the same pattern of statistical effect as in scenario 1 was found. The relative dwell time on the speed scale decreased significantly from conventional configuration to nxDisplay and nxControl configuration, $F(1.473, 14.681) = 8.998, p = 0.005$. As expected, a reverse effect was found for the scanning of the centre of PFD, $F(1.503, 15.032) = 11.478, p = 0.002$, due to the additional speed, altitude, and energy information presented by the augmented elements. Again, no changes of scanning behaviour emerged for the altitude/VS display section, $F(1.473, 14.732) = 0.092, p = 0.857$.

4.2.3 *Scenario 3: steep turn*

The same pattern of statistical effects for changes of scanning behaviour as in the first two scenarios was found in scenario 3 (see Fig. 9). While the relative dwell time on engine parameters decreased across configurations, $F(1.296, 12.959) = 5.116, p = 0.034$.

For the scanning pattern on the speed scale and ADI, again opposing trends were found, with a significant decrease of relative dwell times on speed, $F(1.504, 15.036) = 21.618, p < 0.001$, and an increase on ADI, $F(2, 20) = 4.735, p = 0.021$. However, also in this scenario, no effect of configuration was found for dwell times on the altitude and/or VS display, $F(2, 20) = 1.119, p = 0.346$.

4.2.4 *Scenario 4: descent with speedbrakes*

The results of scenario 4 are visualized in Fig. 10. As becomes evident, the changes of scanning behaviour induced by the different configurations closely resemble the effects in the other scenarios. The relative dwell time on engine parameters was reduced when flying in nxDisplay and nxControl configuration, compared to flying with conventional instrumentation, $F(1.373, 13.729) = 10.401, p = 0.004$.

The effects for scanning the PFD information replicates the findings in the other scenarios, with decreased scanning of the speed scale from conventional to nxDisplay and nxControl configurations, $F(2, 20) = 6.396, p = 0.007$, and a mirror effect for the scanning of the centre of the PFD, $F(2, 20) = 9.701, p = 0.001$. In this scenario, also a decrease of scanning the altitude/VS information became evident in configuration nxDisplay, $F(2, 20) = 6.981, p = 0.005$.

4.3 Performance

In scenario 1–3, all mean relative deviations of tolerance for altitude, IAS, heading, and bank angle were less or equal to 1.0 % relative duration as expected in H#6. This was also true for altitude, heading, and bank angle in scenario 4 (descend with speedbrakes). Only with respect to IAS, pilots generally were less able to fly within the given tolerance in this latter scenario. The mean relative

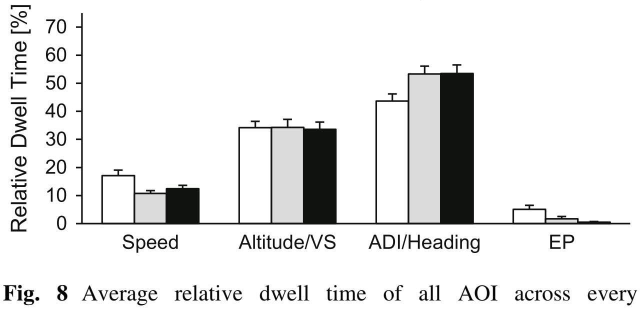

Fig. 8 Average relative dwell time of all AOI across every configuration in scenario 2 ($N = 11$)

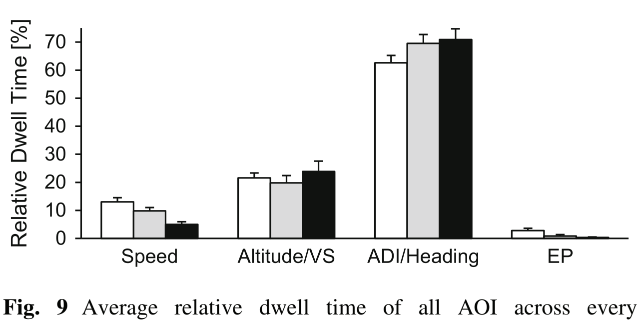

Fig. 9 Average relative dwell time of all AOI across every configuration in scenario 3 ($N = 11$)

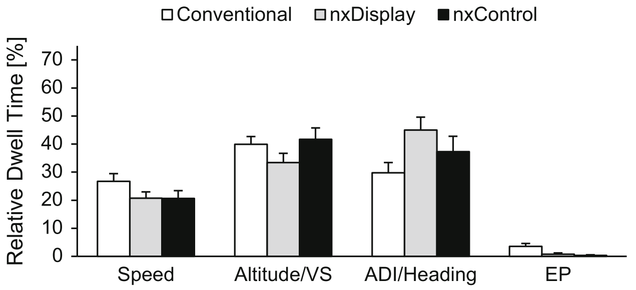

Fig. 10 Average relative dwell time of all AOI across every configuration in scenario 4 ($N = 11$)

duration of exceeded tolerances was $M = 8.4\,\%$ (conventional), $M = 6.6\,\%$ (nxDisplay), and $M = 11.2\,\%$ (nxControl). However, these differences were not significant based on a one-factorial ANOVA, $F(1.229, 12.293) = 0.255, p = 0.671$.

5 Discussion

The overall objective of the study was to prove the feasibility of the nxControl concept, i.e. whether the display enhancements and assistive controller would be easy to understand and could be effectively used by pilots for thrust and speedbrake control in manual flight, opposed to conventional pitch-and-power flying. In addition, it was of interest to investigate how this concept would impact the instrument scanning strategies of pilots, and whether its performance consequences for pilots would meet the expectations. Expected was that the concept would enable pilots to properly adjust thrust with less workload in terms of control movements and scanning of engine parameters.

A summary of the findings regarding the six hypotheses is provided in Table 2. Hypothesis H#1 stated that the lever activity would decrease, when flying in nxControl configuration. The findings support this hypothesis to a large extent. In all scenarios, the activity was the lowest at the nxControl configuration, which confirms the hypothesis. Furthermore, this effect was only found for the configuration nxControl. Just flying with nxDisplay did not change lever activity compared to flying in conventional configuration. Evaluating these results, it must be taken into account that, due to a technical problem, they were only based on data of four to five pilots, and further investigations will be needed to substantiate this effect.

However, it is in line and gets further support by subjective comments of the participants in the debriefing. About 60 % of the pilots stated that the input with nxControl was subjectively more precise and goal-oriented than in the conventional setup which hints at less required lever activity. This shows that a faster and more direct input with less effort for readjustment is possible, which reduces control effort and pilot workload.

As expected in hypothesis H#2, the dwell time on the engine parameters was reduced in all scenarios. Around 80 % of the pilots confirmed this result during debriefing. With the nxControl system and the enhanced displays, the engine parameters are less relevant for pilots. It can be stated that all pilots recognized the benefits of FPA, TEA, and nxStatus display and used the nxControl system as supposed.

To summarize the outcomes of hypothesis H#1 and H#2, results support the basic assumption that the use of nxControl can support and ease the proper application of pitch-and-power relationships. Specifically, the new system provides a more precise and direct way to find and select proper energy settings required for control of a given flight path which, in turn, reduces the number of necessary thrust adjustments and hence the effort involved in thrust control.

Furthermore, the eye-tracking data give important insight into the question, whether the implementation of the TEA and FPA would alter the scanning pattern on flight parameters provided on the PFD. Comparing the simulator configuration conventional to nxControl a reduction of the dwell time on the speed scale (H#3) as well as an increase on ADI (H#5) became apparent in all four scenarios. Generally, the changes in configuration nxDisplay were similarly orientated as in configuration nxControl. This

Table 2 Findings compared to hypotheses

Hypothesis	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Idle deceleration		Climb and turn		Steep turn		Speedbrake descent	
H#1: lever activity	✓	(×)	✓	(×)	✓	(×)	×	(×)
H#2: AOI Engine Parameter	✓	(✓)	✓	(✓)	✓	(✓)	✓	(✓)
H#3: AOI Speed	✓	(✓)	✓	(✓)	✓	(✓)	✓	(✓)
H#4: AOI Altitude/VS	×	(×)	×	(×)	×	(×)	×	(✓)
H#5: AOI ADI/Heading	✓	(✓)	✓	(✓)	✓	(✓)	✓	(✓)
H#6: flight performance	✓	(✓)	✓	(✓)	✓	(✓)	✓	(✓)

✓ supported by significant ($p < 0.05$) or marginally significant ($p < 0.1$) effect, × not supported; marks in brackets indicate, if an effect was also found in configuration nxDisplay effect was expected since the changes on the displays were the same in both configurations.

However, in contrast to the assumptions stated in hypothesis H#4, a reduction of scanning the altitude/VS information was only found for scenario 4. Only in this scenario, the relative dwell times on the altitude and VS scales were actually lower when flying in nxDisplay or nxControl configuration, as compared to conventional flying. Why it did not lead to a reduction of scanning the AOI Altitude/VS in three of the four scenarios cannot be clearly elucidated on basis of data available. Possibly this is due to the fact that the VS indicator provides more detailed and accustomed information about the sink rate (in ft/min) than is provided by the relative positions of FPA and artificial horizon (in °). Given the fact that the pilots were not yet accustomed to the augmented elements in the ADI, they also might have used the altitude and VS indicators to cross-check these parameters. Additional data of extended and more comprehensive flight tasks could provide further insight regarding this question.

Albeit this latter result, the effects observed in the eye-tracking data clearly indicate that the pilots shifted their focus to the centre of the PFD when flying in nxDisplay and nxControl configuration. This was expected, because the most important information needed to safely aviate is available with less scanning effort in nxPFD. The integrated visual cues of the FPA and TEA ease the reception of information. These findings were supported by the pilots' answers during debriefing after the tests. About 50 % of the pilots stated that their scanning was more often located on the TEA and FPA at the PFD. The fact that this shift of attention was associated with less scanning of the speed band suggests that the pilots relied on the information provided by TEA and FPA.

As expected in H#6, after a short phase of familiarization and practice, the pilots could maintain requested flight parameters in terms of altitude, IAS, heading, and bank angle within the given tolerance range when flying with support of the nxControl system. Only in scenario 4, the mean relative duration of exceeding the IAS tolerance range was higher than expected. As this was similar in configuration nxDisplay and conventional, it is assumed that in this speedbrake descend, the pilots generally lowered the prioritization of IAS in favour of maintaining the requested sink rate. It can be concluded from the performance data that for the given flight tasks, with standard precision requirements, pilots achieve a similar and sufficient performance when using the new nxControl system. This result emerged although the pilots were not as familiar with the new system as they were with conventional configuration for which they possess highly practised skills. This also implies that the differences found in the scanning behaviour induced by nxControl did not cause any detrimental side-effects in terms of performance degradation. That is a promising result, which encourages further investigations for future more complex flight tasks like curved required navigational performance (RNP) approaches.

6 Conclusion

In summary, the present flight simulator test campaign showed that pilots were able to understand and use the new nxControl concept of flying after just 1.5 h trainings which indicates suitable design of functionality and visualization of the system. All pilots used the nxControl system as assumed with sufficient flight performance in standard airwork.

Overall, the result of the present study supports [1, 12] that suggest new formats of presenting energy-relevant information to pilots. The addition of the nxControl concept tailored to this sort of displays represents a further promising step. The findings of this research including the debriefing comments from pilots will be integrated into the next nxControl prototype. Further studies are planned to investigate the performance consequences of nxControl with more demanding flight tasks comprising more challenges in energy management. It is expected that in such scenarios the nxControl system will lead to lower pilot workload and higher flight precision at the same time.

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