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NXCONTROL INSTEAD OF PITCH-AND-POWER: CONCEPT AND FIRST RESULTS OF A CONTROL SYSTEM FOR MANUAL FLIGHT

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Abstract

A command system for manual control of the longitudinal load factor (n_x) of an aircraft is designed that completes existing flight control command systems (e.g. sidesticks normal load factor n_z). nxControl's aim is to assist pilots during manual flight by reducing the workload for monitoring flight parameters and the controlling of thrust and airbrakes. Important for nxControl concept is the direct relation between load factor and changes of the total aircraft energy. In the current paper a system concept and a prototype realisation are presented. The nxControl system consists of the control law that combines the actuation commands for engines and airbrakes in flight, a new input device for the longitudinal load factor command and new display elements that informs pilots about energy states to assure situation awareness. In order to investigate the feasibility of the concept as well as human performance consequences and cognitive demands, a flight simulator study with airline pilots was conducted.The results provide first evidence for the feasibility of the concept. As expected a change of scanning behaviour became apparent. For test scenarios with standard flight tasks, no impact in situation awareness and performance was observable. However, for more demanding tasks benefits are expected. Additionally, the assumed effect of a lower input device activity with the use of nxControl can be confirmed.

Nomenclature

Abbreviations

ADI	Attitude Direction Indicator
FAA	Federal Aviation Administration
FL	Flight Level
FPA	Flight Path Angle
IAS	Indicated Airspeed
TLX	Task Load Index
PFD	Primary Flight Display
SAFO	Safety Alert for Operators
SAGAT	Situation Awareness Global Assessment Technique
SMI	SensoMotoric Instruments
TEA	Total Energy Angle
TECS	Total Energy Control System

Symbols

D	Drag Force
E	Energy
F	Thrust Force
g	Acceleration of Gravity
γ	Flight Path Angle
H	Altitude
m	Mass
n	Load Factor
V	Speed
W	Weight
x	State Parameter

Indices

E	Energy
k	Path Direction
K	Inertia
n	Sample Number
t	Time Sample
tot	Total
x	Longitudinal Direction
z	Normal Direction

1 INTRODUCTION

Increasing air traffic raises the requirements on future flight trajectories coupled with the necessity to follow more complex flight paths with higher precision (e.g. Flightpath 2050 [1]). Modern commercial transport aircraft fulfil these requirements by today's automatic flight control systems. But in case of possible failures, quick adjustments of the flight path or training of manual flight (see FAA SAFO [2]), also future flight trajectories must remain manually flyable with reasonable workload. The objective of nxControl is to design a control command system together with an adapted human machine interface to fly more demanding flight paths under manual control.

There are existing systems for augmented manual control, which use the aerodynamic control surfaces at wing and tailplane of the aircraft. Pilots command the surfaces by means of control wheels, sidesticks, or pedals. In fly-by-wire aircraft they do not directly command the surface deflections, but the physical impact they shall produce. With this augmented control a more precise manual flight is possible with less workload. Such augmentation does not exist for engine thrust or drag force generated by speedbrakes. Pilots control these actuation elements in a conventional way.

To select a desired power setting, pilots use memorized pitch-and-power values nowadays. The power settings depend on the aircraft's altitude, speed, mass and configuration and are varying when those parameters change. 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 which involves considerable effort in instrument scanning. An important objective for the design of the nxControl system was the simplification of the thrust control in manual flight.

The proposed system aims to complete the augmented manual control concept for aircraft cockpits. The impact of the nxControl concept to scanning effort, flight performance and situation awareness at different flight situations were investigated in a flight simulator test campaign with 11 airline pilots. The components and the functionality of a prototype realisation are described in this paper. The objectives, experimental setup, tasks for the pilots and results of the simulator campaign are presented. The evaluation shows that the nxControl system is accepted and used by the pilots as supposed. Benefits for standard flight tasks are observed and it is expected that they will become higher when future more demanding flight paths are flown.

2 SYSTEM DESCRIPTION

This section describes the prototype of the nxControl system used to determine the impact of the new flight concept to the flight performance, workload, and situation awareness. The concept and the flight mechanical background for the nxControl system were summarised in detail in [3]. The findings of a preliminary study of mental models for energy management in typical flight situations of airline pilots published in [4] and [5] were used to develop the proposed nxControl system. Following, the underlying flight mechanical basics are described and the new display concepts, called nxPFD and nxStatus, as well as the controller for nxControl are introduced.

2.1 Flight Mechanical Background

The nxControl system aims to complete the augmented manual control concepts of today's sidestick controlled passenger aircraft that use load factors to control pitching (vertical factor). The longitudinal load factor n_x is controlled manually or by autopilot.

The total longitudinal load factor in flight path direction $n_{xk,tot}$ is explained in [6] and can be derived from the second Newtonian axiom for rigid body mass point as follows:

$$(1) \qquad n_{xk,tot} = \frac{F-D}{W} = \sin\gamma + \frac{\dot{V}_K}{g} \; .$$

The equation shows, that the longitudinal load factor $n_{xk,tot}$ is dependent on thrust force F and drag force D related to the weight W. Changes in thrust or drag respectively the longitudinal load factor cause a change in flight path angle γ and/or in the ratio of flight path acceleration $\dot{V}_K$ and gravitational acceleration g. Thus, the pilot can control the longitudinal load factor by setting thrust or drag and can distribute this difference to altitude or speed changes by using pitch control (n_z-control).

Altitude relates to potential energy and speed to kinetic energy. Both are components of the total energy E_{tot} of the aircraft. Changes in the total energy can be described by the total energy angle γ_E see [7]:

$$(2) \qquad \sin\gamma_E = \frac{\dot{E}_{tot}}{mgV_K} = \frac{\dot{H}}{V_K} + \frac{\dot{V}_K}{g} \; .$$

It is defined by the derivative of the total energy related to weight and flight path velocity, which is also described by the changes in potential and kinetic energy shown right hand of equation (2). Hence, the longitudinal load factor n_x (the index xk,tot is abbreviated by to x) and the total energy angle describe the same physical behaviour.

2.2 nxPFD: Additional Symbols on the Primary Flight Display

In the nxControl concept the longitudinal load factor n_x shall be controlled by the pilots. Therefore, the knowledge of the n_x value is essential and requests showing it together with other primary flight information on the primary flight display (PFD). It is assumed that the information about n_x is intuitively visualised, when shown as the total energy angle (TEA) in degree. To recognise, how an energy change affects the flight state information on speed and/or altitude change must be gauged by the pilot. To ease this information reception, TEA and flight path angle (FPA) can be used in relationship to each other.

The concept of display FPA and TEA in relation on a PFD has been investigated e.g. by Lambregts et al. [8] and Amelink et al. [9]. However, these concepts covered 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, nxControl focuses exclusively on the integration of the parameters TEA and FPA. Therefore, a conventional PFD was used as basis and extended by two additional symbols (nxPFD, see Figure 1). It was assumed that a familiar display assures the pilot's acceptance and the use of just two additional symbols reduces clutter compared to the mentioned concepts.

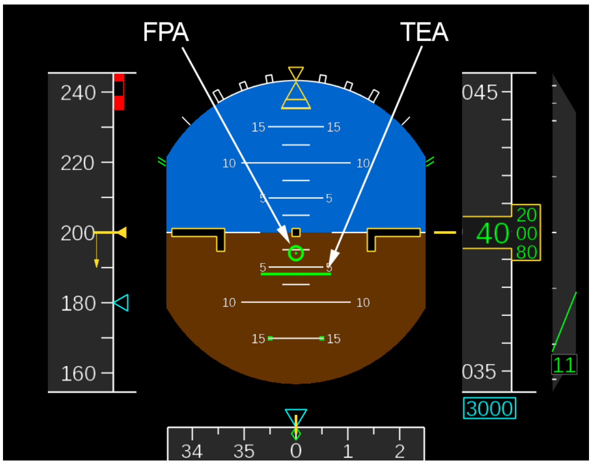

FIG 1: nxPFD in case of a -3 degree descent with an energy angle of -6 degree. FPA = flight path angle, TEA = total energy angle

FPA on the nxPFD is marked as a green circle with a centre dot, representing a birdy without rolling and drifting information. TEA is drawn as 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

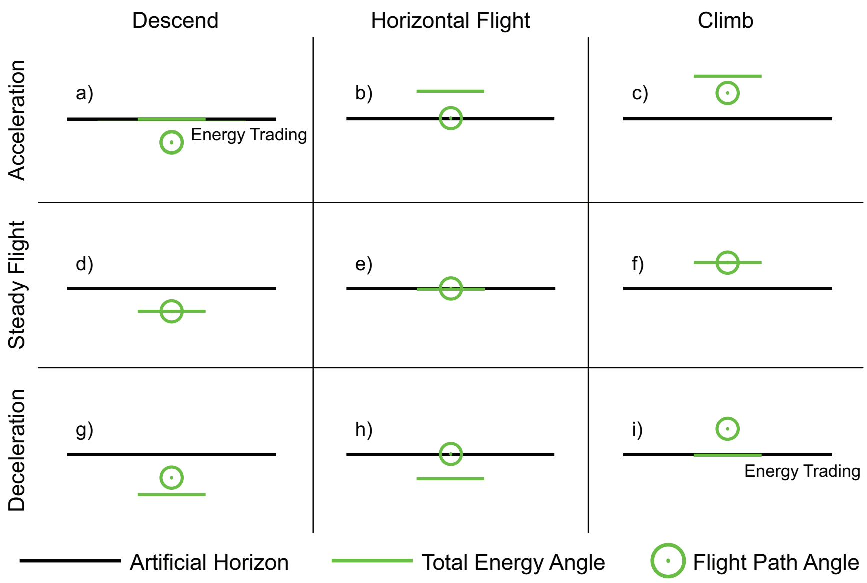

FIG 2: Relationships between total energy angle, flight path angle and artificial horizon

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

If both symbols are on the artificial horizon the energy state is not changing. Potential, kinetic, and total energy stay on a constant level and the aircraft performs a steady horizontal flight (figure 2e). If the pilot starts descending or climbing without changing the power setting, the birdy shows the current FPA over respectively under the horizon and the TEA stays on the horizon (figure 2a and 2i). The potential 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 according to the power change. If the TEA is set on the FPA birdy, the whole amount of total energy change results from a potential energy change (figure 2d and 2f). In this case, the kinetic energy and speed stay constant.

If the TEA is above the FPA, the speed is increasing (figure 2a, 2b and 2c). A decelerating flight state is shown by the TEA below the FPA (figure 2g, 2h and 2i). 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 and at one glance. Furthermore, there is now a connection to the power setting that is required for the desired flight state.

2.3 nxStatus: Scale for the Energy Angle

The additional indicators on to the PFD show how the energy state of the aircraft changes. Yet, it does not give information on the current limitations of energy gain or reduction. Thus, a second display was designed, referred to as nxStatus display (see figure 3). It shall be located near the engine parameters at the system display.

The energy angle scale of the nxStatus display is similar to the pitch scale on the PFD. The green bug shows the current energy angle of the aircraft in degree. The blue flag represents the energy angle command for the controller, which is described in section 2.4. It is solely visible, when nxControll is active.

The possible energy angle depends on the present flight situation, 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 energy angle γ_E when applying maximum thrust, the lower yellow limit indicates γ_E when flying with idle thrust and the lower orange limit indicates γ_E when flying with idle thrust and additionally airbrakes, deployed in maximum position.

The limitations can be understood as maximal sink or climb rate without changing speed. So, the pilots can assess if the aircraft is able to achieve a required energy change. This information gives awareness on available manoeuvre capabilities for example to check if a steep approach is possible without additional drag or if a go around is possible in the current configuration.

[1] This is true regarding short time periods. In long term the lift to drag ratio that changes with speed 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.

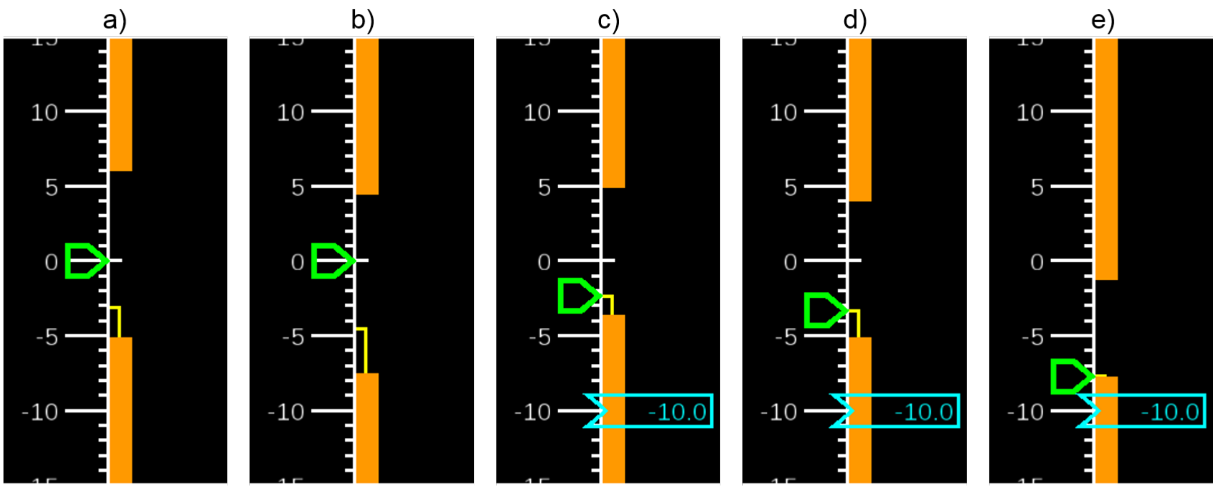

FIG 3: nxStatus display at different flight situations with and without command flag; a) FL 160, IAS 200 knots, b) FL 160, IAS 250 knots, c) FL 20, IAS 170kt, d) FL 20, IAS 170 knots, Flaps 2, e) FL 20, IAS 170 knots, Flaps 4 (full)

Figure 3 shows the nxStatus display in different flight situations and aircraft configurations. Situation 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 rises the possibility to reduce the current energy state with a lower minimum TEA.

The situations c) to 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) of the highest 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 is not possible without losing speed, since the maximum TEA is negative.

2.4 nxControl: Controller for the Energy Angle

Both, nxPFD and nxStatus display show the current state of the aircraft and can be used without nxControl. The pilot has to control the TEA with the engines thrust by commanding the fan rotation speed of the engines (N1) with the thrust levers or the additional drag by setting the airbrakes deflection. As the TEA reaction after a change in N1 or airbrake deflection is 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 control effort and to enable a more precise flight along highly demanding flight trajectories, the control command system nxControl was designed. The command and control variable of nxControl is the TEA, which is controlled by using engines and airbrakes as actuation variables in flight.

The command value for nxControl is selected by a nxLever similar to the thrust lever. Its position is linearly converted into a TEA command and is shown in the nxStatus display as a blue flag (see figure 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 degree of TEA. In this case, the controller sets the engines' thrust to compensate the current drag force so that the aircraft is neither losing nor gaining total energy.

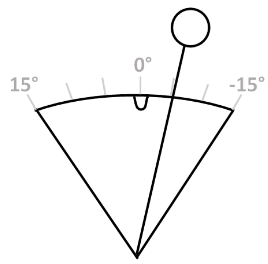

FIG 4: nxLever with three mechanical marks at $0°$, $15°$ and $-15°$

Dependent on the TEA command, the controller 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 controller uses the whole range of engine thrust from idle to maximum thrust. If the command is below the yellow limit and the pilot activates the airbrakes by pushing an extra button, the controller uses the airbrakes to reduce energy at a higher rate. Engines then are already operating in idle thrust. If the pilot does not push the button, a command below this limit always implies idle thrust. In figures 3 c) to 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.

The defined hierarchy of the use of engines and airbrakes is necessary to assure the pilot's situation awareness. Without the active initiation of the pilot, the airbrakes are not used and the pilot can decide by pushing the button, if the maximum decrease of energy shall be exclusively achieved by thrust reduction or additionally by drag force. Besides, a pilot would not use engine thrust and airbrakes at the same time, due to the inefficiency.

nxControl is therefore split in two control laws, one for thrust and one for airbrakes. Both control laws cause the same reaction in TEA after a command change. This reaction is similar to the typical reaction of engines and airbrakes after a conventional command without the controller. The controller sets the control value to the commanded value with steady state accuracy. Thus, the pilot does not need to readjust its input, when the value once was set correctly.

In case of an external disturbance of the aircraft's energy state, the controller compensates the error with engines or airbrakes (corresponding to the selected control law). Disturbances are for example wind gusts, changes in aerodynamic drag by changing speed, additional drag caused by contamination like ice, loss of engine power, and also additional drag due to aircraft configuration. So, the pilot's workload can be decreased by eliminating the necessity of readjustments after such disturbances.

3 EXPERIMENTAL STUDY

3.1 Study Objectives

This section describes the experimental study that was conducted to investigate a prototype realisation of the presented nxControl system and the main findings of this feasibility study – for a detailed report see [10].

The overall objective of this study is to examine, whether pilots were able to fly standard tasks with the system and would (easily) understand the function of the controller and the relations between TEA and FPA. Moreover, it was expected that the use of the nxControl system supersedes the application of pitch-and-power knowledge by the additional integrated information in the displays as well as the controller that ensures that an input corresponds to the same aircraft reaction independently of altitude, velocity, configuration, or mass of the aircraft. At the same time, it enables an easier and intuitive way to find the required energy setting precisely and directly and thereby it reduces the pilot's workload.

The study compares the frequency of thrust lever or nxLever inputs and eye movement towards the engine parameters. It was hypothesized that the lever movements as well as the fixations on engine parameters decrease, while flying with nxControl.

Another objective of this study is to examine, whether the implementation of the TEA and FPA would alter the scanning pattern within the PFD. Pilots receive additional information about relative changes of velocity and altitude on the TEA and FPA displayed in the centre of the ADI. For example in flight phases where velocity and/or altitude should be steady the steady state is directly indicated by the relationship of TEA, FPA and horizon (see section 2. Therefore the demand of scanning these parameters is lowered. Hence, it was assumed that gazes on speed or altitude scale are reduced for flight tasks with constant velocity or altitude.

Due to the additional visual cues for horizontal or stationary flights and the assistive controller, it was expected that the system would further provide a better flight performance, in terms of the ability to fly more precisely at requested parameters e.g. altitude or speed. Additionally it was stated that the subjectively measured workload would decrease likewise. The differences in workload were conducted via NASA Task Load Index (TLX) [11].

Whether the expected change in the scanning pattern influences the situation awareness of pilots, was examined via Situation Awareness Global Assessment Technique (SAGAT) [12].

3.2 Experimental Design

Eleven male certified pilots from commercial airlines with an Airbus A320 type rating participated in this experimental study. The experiment was conducted in the fixed-base side-stick controlled 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 [13]. The simulation was extended by the nxControl prototype (control law and display modifications) as described in section 2. The participants' eye movements were recorded with the SMI (SensoMotoric Instruments) Eye Tracking Glasses 1.9 [14].

To examine the above described assumptions four standard flight tasks were selected that requested changes of the energy state. The selected scenarios were similar to flight tasks in line operations or training sessions. The pilots had to perform decelerations, climbs, turns, steep turns and idle descends supported by speedbrake. As a more complex scenario a landing procedure was part of the experiments. This scenario was exclusively used to test the assumptions on workload and situation awareness.

To differentiate which element of the presented concept had an effect on the experimental objectives, three configurations of the simulator were compared. They represented the independent variable of this study.

- Configuration *conventional* is the simulation without elements of the nxControl system.
- Configuration *nxDisplays* contains the new displays, while thrust control remains conventional.
- Configuration *nxControl* covers the entire nxControl concept (control law and display modifications).

All participating pilots flew all five scenarios with each of the three different simulator configurations. Prior to the experiments, the pilots received a detailed standardised briefing and training of functions and usage of the nxControl system. After the experiment, the pilots were interviewed about their experience with the nxControl system. The debriefing interview was guided by pre-assembled questions, but participants were encouraged to comment their answers.

3.3 Results

The recorded eye tracking data showed a change in the pilots' scanning behaviour of the flight parameters at the primary and secondary flight displays (PFD and system display). Comparing the simulator configurations *conventional*, *nxDisplay* and *nxControl* a reduction of the speed tape fixations became apparent in all expected flight tasks, if the new display elements were shown. Although the assumed reduction of fixations on the altitude tape could only be observed in the deceleration flight task. In the debriefing interview around half of the pilots stated that their scanning was more often located on the TEA and FPA at the PFD, which confirms the eye tracking data.

The changing attention from the flight parameters speed and altitude to the ADI centre can be shown, where the new symbols TEA and FPA allow observing changes in those flight parameters. Thus, the most important information can be reached by less scanning effort, which eases the reception of information.

Additionally, as assumed the fixation rate on the engine parameters was reduced in all scenarios. This effect was mirrored by an increase of fixations on nxStatus. Around 80% of the pilots confirmed those results in the debriefing interview. It can be stated that all pilots recognised the additional benefits, accepted the nxControl system and used it as supposed. This speaks for an intuitive concept regarding visualisation and control.

It was expected that the lever activity decreases with use of the nxControl system. In all scenarios nxControl configuration featured the lowest amount of lever activity. The pilots' answers and comments during the debriefing supported this tendency. About 60% of the pilots stated that the input with nxControl was much more precise and goal-oriented as in the conventional setup, which hints at less required lever movement. This shows that a faster and more direct input with less effort for readjustment is possible, which is less physically demanding for the pilots.

In contrast to the assumption, comparing the configurations *nxDisplay* and *nxControl* to *conventional* no significant differences emerged in any performance variable. Thus, it can be stated that for the given flight tasks, with standard precision requirements that are relatively low, the nxControl system does not degrade the flight performance of the pilots. That means, pilots achieve the same performance when using the new nxControl system as compared to conventional flying for which they possess highly practised skills. This also proofs that the differences found in the scanning behaviour did not cause any performance degradations. It is supposed that an investigation with more complex and more demanding flight tasks might cause detectable performance differences.

Similarly, data did not support the assumption that the nxControl system would lead to noticeable reduction in subjective workload. However, in the debriefing the majority of pilots stated that the interpretation of the new display elements were unfamiliar, which explains their higher mental workload. They said that a longer training with the system would decrease this workload. Therefore, it is expected, that the mental demand will decrease, when getting used to the system.

As expected the results of the SAGAT provide an indication that the situation awareness of the pilots did not differ between the configurations of the simulator setup. Hence, it can be assumed that the changed scanning pattern does not affect the situation awareness of the pilots.

4 CONCLUSION

The presented flight simulator test campaign with eleven airline pilots revealed that pilots were able to understand and use the nxControl concept with only 1.5 hour training, which indicates an intuitive design of functionality and visualisation of the system. Neither a loss of situation awareness nor a decrease of flight performance was observed, despite a significant change of scanning and control input behaviour. The concentration on the relevant physical flight parameters (energy change and distribution) with the TEA and the FPA instead on the pitch-and-power estimation already shows a benefit of this system for the conventional flight tasks. It is expected that this might increase in case of future highly demanding flight paths.

The results of this study thus provide encouraging insight for the further development of the nxControl system. The findings of the experimental test and the debriefing interview will be integrated into design improvements. As mentioned, a future experimental study with more complex trajectories, more difficult tasks and disturbances should be conducted. The focus on the lever activity, performance, and on situation awareness is recommended.

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