nxControl: Ground Mode for Manual Flight Control Laws with Longitudinal Load Factor Command

K. Schreiter, S. Müller, R. Luckner and D. Manzey

1 Introduction

Future air traffic is expected to grow and demanding requirements will intensify the needs for more complex flight trajectories (e.g., Flightpath 2050 [4]). Especially, precision requirements for flight path and speed enable a better utilisation of limited airspace. The precision requirements hold for ground operation as runway capacity is a bottleneck as well. Today, fully automated flight control systems fulfil these requirements. However, pilots should be able to take over manual control at any time. Furthermore, the Federal Aviation Administration (FAA) emphasised the loss of manual flying skills due to excessive use of full automation [5] that could be prevented by more manual flight in daily operations. As the expected requirements on future flight precision will raise pilot workload at manual flight, improved handling characteristics can counteract this trend. Modern cockpits are equipped with fly-by-wire technology and flight control computers. The underlying flight control laws improve handling qualities and stability of manual flight. Demand control laws for sidestick/yoke and pedal inputs are used to achieve precise manual flight at lower workload. But, there is a lack of control laws for manual thrust and spoiler control.

K. Schreiter (✉) · R. Luckner
Department of Flight Mechanics, Flight Control and Aeroelasticity,
Technische Universität Berlin, Berlin, Germany
e-mail: karolin.schreiter@tu-berlin.de

R. Luckner
e-mail: robert.luckner@tu-berlin.de

S. Müller · D. Manzey
Department of Work, Engineering and Organizational Psychology,
Technische Universität Berlin, Berlin, Germany
e-mail: simon.mueller@tu-berlin.de

D. Manzey
e-mail: dietrich.manzey@tu-berlin.de

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The nxControl system introduced by [11, 14] is designed as supplement for the existing manual control laws. It replaces conventional command of fan rotation speed or spoiler deflection and controls thrust and spoilers according to pilot's command of total longitudinal load factor in flight path direction $n_{xk,tot}$. Various designations are used for the total longitudinal load factor: specific excess thrust, potential flight path angle, acceleration potential, change rate of specific energy level, and total energy angle, see [2, 3, 6, 7]. To simplify the representation, $n_{xk,tot}$ will be abbreviated longitudinal load factor n_x. As derived by the longitudinal force equation of aircraft motion, $n_{xk,tot}$ is directly influenced by thrust force F and drag force D related to aircraft weight W and wind incidence angle α_W:

$$n_{xk,tot} = \frac{F - D}{W} + \sin\alpha_W \quad = \frac{\dot{V}_K}{g} + \sin\gamma \quad = \sin\gamma_E \ . \tag{1}$$

These external forces influence speed and altitude changes ($\dot{V}_K$ and γ) and therefore the change of kinetic and potential energy. The load factor n_x therefore equals the specific change of total energy represented by the total energy angle γ_E. nxControl uses these relations to control thrust via engines and drag via spoilers allocated with a hierarchical logic, as described in Sect. 3. It enables pilots to directly control the total energy state change of the aircraft instead of using the variables pitch and fan rotation speed as a proxy. This assures more precise manual flight with lower workload despite expected higher future requirements.

The impact of nxControl was tested in two evaluation studies described in [11, 13, 14] that covered three different flight scenario types: Single standard flight state changes, a standard approach with instrumented landing system (ILS), and a demanding steep approach with required navigation performance (RNP). After a short training phase with nxControl, the pilots were able to use the new system to achieve the same flight precision in standard scenarios as with their well-trained conventional manual controls but with a lower lever activity and therefore lower workload. Moreover, the results of the demanding manual RNP approaches showed significantly better precision with respect to speed control and a significant reduction of subjective physical pilot workload. As flight path precision is already supported by normal load factor control (n_z-control with sidestick), nxControl did not affect the accuracy of altitude and flight path angle.

The next step was to supplement the nxControl control laws with a ground mode to support manual control in following phases: landing (including touch-and-go), taxi, and take-off (including rejected take-off). There are existing systems that support pilots during the time critical phases of take-off and landing (e.g. autobrake). However, using the conventional control on ground in combination with nxControl in flight would require a mode change at the transitions of flight and ground motion. Such mode changes from augmented to direct controls, and therefore changes in aircraft behaviour, could disrupt the normal procedure of the pilots and may lead to a lack of situation awareness. The ground mode of nxControl therefore enables continuity in augmented manual control of thrust and spoilers. Additionally, it supports the control of wheel brakes and thrust reverser that mainly affect the longitudinal load factor at landing. With the ability to precisely control the deceleration/acceleration $\dot{V}$, it is possible to precisely influence the used runway length s. With the kinematic equations

$$s = \frac{\dot{V}}{2}t^2 + V_0\, t + s_0\ ,\ \ V = \dot{V}\, t + V_0\ , \tag{2}$$

the used runway length while landing can be calculated with initial values for runway distance s_0 and speed V_0 at touch-down, taxi speed V_T and deceleration $\dot{V}$:

$$s = \frac{V_T^2 - V_0^2}{2\,\dot{V}} + s_0\ \ . \tag{3}$$

Note that this equation is simplified with the assumption of constant mean deceleration.

The existing autobrake systems support the landing phase by controlling wheel brakes. The systems provide various fixed deceleration levels that the pilots can select, e.g., three levels at Airbus A320 aircraft [16]. This corresponds to three different landing distances. However, these landing distances do not necessarily relate to the distance between touchdown point and runway exits. Additionally, the touch down point varies for every landing. To adjust the effects of the autobrake system and to reach the appropriate runway exit, the pilots need to take over manual braking at a certain point. However, pilots neither have sufficient nor effective information about the impact of manual braking and thrust reverser. Airbus has implemented an autobrake mode, called "Brake to Vacate" into Airbus A380. This system allows for choosing a specific runway exit and the system automatically controls deceleration with wheel brakes. If the pilots use thrust reverser, the autobrake system adjusts brake force to maintain the given deceleration. However, the impact of thrust reverser is not transparent for the pilots.

The command control system for longitudinal load factor nxControl allows both precise setting and flexible adjustment of deceleration rate while getting a feedback on its impact. This enables pilots to reach predefined targets while it permits corrections if unexpected situations appear. In this way, nxControl allows a strategic use of runway length and occupation time with the pilot in-the-loop.

The following sections give an overview of the status quo on ground operations, examine preceding considerations of pilots to nxControl ground mode, and describe the controller design as well as the human-machine interface (HMI). Additionally, a feasibility study with airline pilots was conducted to test the control law functions in different situations of landing, taxi and take-off. The results show pilots' control strategy with nxControl as well as their assessment of the nxControl system.

2 Fundamentals on Ground Operations

The nxControl design process is pilot-centred, that means the technical and procedural aspects as well as requirements of the future users are simultaneously considered. The aim of this approach is to address all relevant issues of the given human-machine-system. While designing the nxControl ground mode, ground operations as well as transitions between flight and ground had to be taken into account. Therefore, recent procedures for take-off, landing, and taxi were analysed and enriched by preceding considerations of pilots about nxControl on ground.

2.1 Typical Procedures on Ground and Transition Phases

An overview of the flight procedures is provided as collected from discussions with pilots participating in previous studies, flight crew operation manuals (FCOM), e.g., [1], as well as state-of-the-art literature, e.g., [10].

Final Approach At least 1 000 feet above ground, a stabilised flight state is required to prepare a safe landing. The aircraft must be in a steady decent on glide path (trimmed and required thrust set) with wings level and landing configuration (flaps full and gear extended). The pilots have to prepare landing by arming the spoilers for lift dump and setting the autobrake system mode. The choice of brake mode depends on runway and weather conditions and can be set to off (manual brake only), or levels between low and maximum. However, the maximum level is not recommended for landing. No autobrake may be used if the runway is long and dry as well as if the runway is very short (full manual brake required). For short and contaminated runways or at poor visual conditions, medium autobrake levels are recommended. Autobrake low is used for good weather and runway conditions.

At decision height, the pilots decide whether the landing is continued or a go-around procedure is initiated. When landing is continued, the flare phase starts shortly above ground (20–30 feet) and the pilots set the engines to idle.

Landing After touch-down the spoilers are automatically fully extended as lift dump if they were armed before. The brakes are controlled depending on the preset mode. If the autobrake system is armed, constant default deceleration rates are adjusted by the system corresponding to the level. Autobrake is disengaged if the pilots take control by manual braking. Furthermore, autobrake is turned off automatically at taxi speed. If manual braking was chosen, the pilots change incidence angle of the pedals. In addition to wheel brakes, pilots can use thrust reverser that is most effective at higher speeds. As idle forward thrust impede deceleration, idle thrust reverse is recommended but it is not mandatory. Thrust reverser are recommended to use until a minimum speed of 70 knots to prevent the suction of exhaust gas by the engines but are not limited to this speed. The pilots decelerate the aircraft until it reaches taxi speed. Spoilers are retracted at this speed.

Go-Around If pilots decide to abort landing, the go-around procedure is initiated. In first place, engines must be set to maximum (TO/GA) and the pitch angle must be increased gradually to approx. 15°. To reduce drag, flaps are retracted one step. After stabilising, a second approach is initiated at the same or an alternative airport.

Taxi After landing or before take-off, the aircraft rolls along taxi ways. The maximum taxi speed is 20–25 knots. To start taxiing, pilots set thrust slightly above idle and release wheel brakes. When taxi speed is reached, thrust is set to idle and adjusted afterwards if necessary. If the idle thrust is greater than rolling friction, pilots have to maintain speed by sequenced or continuous braking. Deceleration is initiated by setting thrust to idle and pushing the pedal brakes. Before turns, pilots set thrust to idle and reduce speed with brakes. Pilots keep brakes released and thrust in idle at the turn as long as speed is not varying to much. Otherwise, corrections of thrust and brakes are necessary.

Take-Off Pilots configure the aircraft before take-off (pitch trim, flaps). Spoilers and autobrake mode maximum are armed to be prepared for take-off rejection. Then, thrust levers are set to maximum or flexible take-off position (TO/GA or FLX) and pedal brakes are released for acceleration. Until the aircraft reaches decision speed V_1, the pilots can decide whether take-off is continued or rejected. Above V_1, the take-off must be continued. At rotation speed V_R the aircraft is ready to rotate and lifts off with a climb rate set by commanding a recommended pitch angle. After take-off, the climb phase follows, where thrust, gear, and flaps setting is adjusted.

Rejected Take-Off When a pilot decides to abort a take-off, the aircraft must be decelerated as fast as possible. The engines are set to idle and thrust reverse is activated. The autobrake system provides maximum braking force. If the braking force of the autobrake system is not sufficient, pilots shall brake manually. Therefore, deceleration during a rejected take-off procedure is similar to landing on a short runway.

2.2 Pilot Considerations Regarding nxControl Ground Mode

The eleven airline pilots, who participated in the first flight simulator study for testing the concept and the preliminary nxControl design in flight mode [11–13], were interviewed about advantages and disadvantages of extending nxControl with a ground mode. The new concept was explained for a landing procedure as example. The answers are summarised below and categorised into three topics: Overall concept, controller, and human-machine interface aspects.

The participants mentioned that the ground mode concept is a consistent extension of the flight mode. The control of the aircraft's reaction and the command of a precise value for total acceleration would be more useful than a direct control of the individual aircraft components. The control of deceleration could enable the selection of a requested runway exit by means of an optimized use of brake and thrust force.

However, the pilots were sceptical about the interpretability of the energy angle in reference to the braking distance and recommended a predictor for a selected runway exit or the end of runway. Some participants were concerned about the complexity of the system that could reduce the understanding and direct influence of the pilots. Also, one participant mentioned that existing automatic systems supporting landing procedure might be redundant with the new system.

As advantage of the demand controller, the pilots mentioned the potential of optimal allocation of the control elements, e.g., the relation of wheel brakes and thrust reverser. Additionally, the wheel brakes could be used more balanced than in the conventional manual way that could prevent brake wear. Compared to the existing autobrake system, the demand controller could also offer a more variable control of the ground velocity after touchdown without deactivation of the automation. Though, the participants showed concerns about the situation awareness, e.g., in case of failures. The detection of subsystem failures could be delayed. Also, the priority of the controlled elements should be clearly defined and authority to activate the thrust reverser should rest with the pilots.

The concept of replacing several manual control inputs by one control lever was perceived ambivalently. On the one hand, controlling just one input device with one command value could ease operations and therefore lower workload. On the other hand, the participants were worried about their situation awareness regarding which actuation element is used. Additionally, the visual head-down feedback at the displays might be difficult to use in the dynamic situation of landing and therefore interfere with a precise command.

3 Functions and Architecture of the nxControl Ground Mode

The controller architecture and the benefits of nxControl flight mode were described in [14]. Recapped, the control and command variable is the longitudinal load factor defined in Eq. 1. Instead of flight path speed (inertial speed) the calibrated airspeed V_{CAS} is primarily used by the control laws, as pilots control energy state by V_{CAS}. However, to damp turbulent atmospheric influences, inertial speed and airspeed are complimentary filtered. A hierarchical allocation (daisy chain) of control laws for engines and spoilers (with additional activation button) shall yield best pilot awareness of the controller behaviour. Feedback of current flightpath angle, energy angle and power limits are given on primary and secondary displays to the pilot. Additionally, the inceptor nxLever provides haptic feedback for its neutral position (zero command). The new ground mode controller is harmonised with the flight mode, to prevent transients during mode switching. So, the ground mode is fully integrated into the entire controller structure. The ground mode adopts and extends the flight mode requirements with the considerations described in Sect. 2.2 in a human-centred design. The nxControl law comprises the control allocation logic, the single controllers for thrust, spoilers, wheel brakes, and reverser commands as well as the feedback of load factor n_x. The pilot is the higher-level controller that gives inputs and gets feedback of this control loop via the adapted human-machine interface.

3.1 Control Allocation Logic

Figure 1 shows the control law architecture of the nxController. The control allocation logic distributes the control error signal to the specific control laws. The hierarchical structure of the flight mode is extended with logics that activate and deactivate the

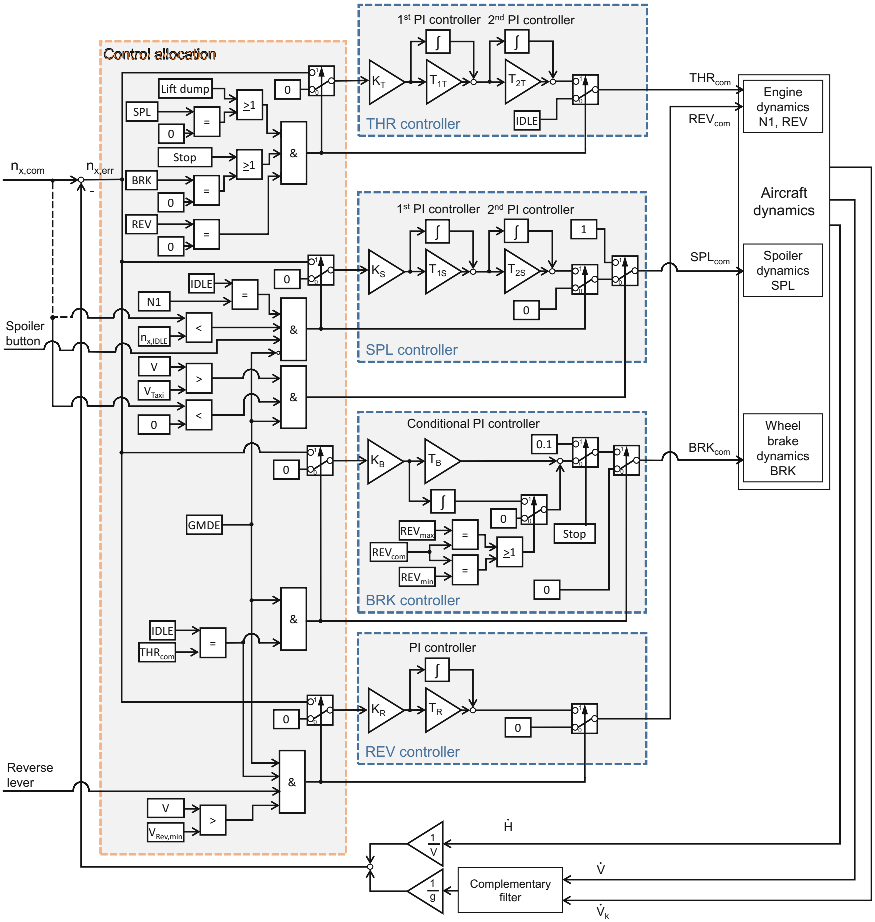

Fig. 1 Control law architecture with control allocation logic and the individual control laws for forward thrust, spoilers, wheel brakes, and thrust reverser

control elements wheel brakes and thrust reverser on ground. As in flight, the thrust controller is active as long as the spoilers (SPL) are fully retracted (except for lift dump), wheel brakes (BRK) are released (except at full stop) and thrust reverser (REV) is deactivated. Spoiler controller is active if fan rotation speed (N1) is commanded to idle and pilots allowed spoiler use by moving the spoiler switch at the nxLever. When the aircraft is on ground (flag ground mode GMDE) and faster than taxi speed, the spoilers are not controlled but fully extended for lift dump if the pilots command deceleration. Otherwise, a positive command represents cancellation of deceleration phase and therefore ground spoilers are retracted. Wheel brakes are controlled if the aircraft is on ground (GMDE) and N1 is commanded to idle. If the aircraft is slower than 0.5 knots and the command value is below zero (stop flag), wheel brakes are activated with a constant deflection to prevent unintended rolling. The use of thrust reverser is only allowed on ground and above the minimum thrust reverser speed. If engines are in idle and the pilots engage the reverser lever at the inceptor, the thrust reverser controller is active.

This allocation logic supports all phases of a turn-around and also all phase transitions, e.g., from flight to landing or take-off to rejected take-off. In addition, the alignment to the given flight procedures allows for mental awareness of the pilots. The separation of the actuation elements also allows for separate controller designs.

3.2 Controller Design

The design of the thrust (THR) and spoiler (SPL) controller is described in [14]. The controllers for wheel brakes and thrust reverser were designed with the same requirements and the same process. The structures of the control laws and the preliminary controller gains were developed with linear models and given requirements (see below). Subsequently, the controller gains were optimised using a nonlinear simulation model and additional requirements for time response of load factor n_x.

The linear models for wheel brake and thrust reverse behaviour were derived from time signals of a highly sophisticated nonlinear simulation. The step responses of the load factor induced by reverser or wheel brake inputs were analysed and modelled by linear transfer functions. A simple but sufficient approximation of the response behaviour is given by first order lag elements for both control elements:

$$F_{n_x,BRK} = \frac{k_{BRK}}{(\tau_{BRK} s + 1)} , \tag{4}$$

$$F_{n_x,REV} = \frac{k_{REV}}{(\tau_{REV} s + 1)} . \tag{5}$$

The gains k and time lags τ depend on aircraft weight and configuration.

As for the flight mode, the main requirement for the controller design is steady state accuracy. For the systems given by (4) and (5), a PI controller with the controller transfer function F_C

$$F_C = K_C \, \frac{T_C s + 1}{s} \tag{6}$$

is sufficient and leads to the closed loop transfer function F_{CL}

$$F_{CL} = \frac{k K_C}{\tau} \; \frac{T_C s + 1}{s^2 + \underbrace{\frac{1}{\tau}(k K_C T_C + 1)}_{2\zeta\omega_n} s + \underbrace{\frac{k K_C}{\tau}}_{\omega_n^2}} \; . \tag{7}$$

Equation (7) shows that the controller influences both zeroes and poles of the closed control loop. The controller gains can be calculated by setting damping ratio ζ and natural frequency ω_n and therefore the poles. To avoid all-pass behaviour, the controller gain T_C must be positive. Additionally, overshooting actuation signals after step inputs should be avoided. Therefore, the product $|K_C T_C|$ needs to be lower than the reciprocal system gain $1/|k|$. These two demands limit the pole placements, e.g., by minimum and maximum natural frequency depending on damping ratio:

$$\omega_{n,min} \;=\; \frac{1}{2\zeta T_C} < \omega_n < \frac{1}{\zeta T_C} \;=\; \omega_{n,max} \tag{8}$$

These limitations in the frequency domain were the basis for the time response design of the closed loop system. This was performed with the software tool MOPS (Multi-Objective Parameter Synthesis) of the German Aerospace Centre [9]. The described linear model as well as the sophisticated nonlinear model were implemented to generate time responses to predefined step inputs. Requirements for damping ratio, rise time, overshoot, time delay margin, actuation signal damping, and steady state error were defined as so called bad/good criteria. Depending on aircraft configuration and weight, sets of controller gains for wheel brakes and thrust reverser were calculated.

The described controller design regards the control element dynamics separately. As wheel brakes and thrust reverser act in the same direction, a distribution function for the actuation signals is necessary. The distribution function can be freely selected respecting given limitations, e.g., using less reverser to reduce noise emissions. The designed controller architecture shown in Fig. 1 respects two cases, braking on the runway with or without thrust reverser. If the pilots do not activate thrust reverser at the inceptor device, the main actuation elements are the wheel brakes with the given PI controller. If the pilots activate thrust reverser, wheel brakes become supportive elements and the thrust reverser becomes the main control element. Therefore, the integrative part of the wheel brake controller is cut off as the thrust reverse controller takes over the integrative behaviour. If the thrust reverser reaches maximum deflection, the integrator of the wheel brake controller is switched on again to achieve the commanded value by the pilot. Possible noise restrictions can be respected by lower maximum deflections for thrust reverse controller (not depicted). For emergency brake, e.g., at rejected take-off, the brake and reverser controllers are bypassed with full deflection commands (not depicted).

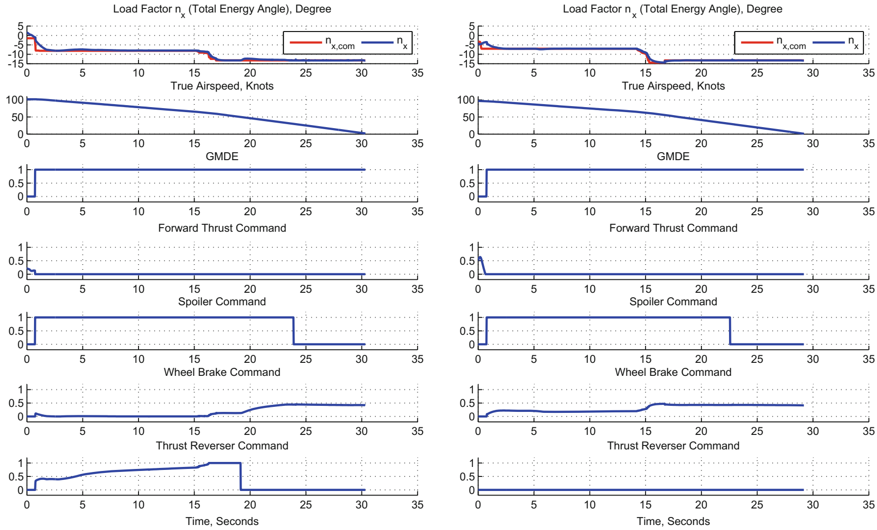

Fig. 2 Longitudinal load factor, speed, and actuation signals by nxController during a simulated manual landing with (*left*) and without (*right*) thrust reverser activation

Figure 2 shows the result of this controller design for two manually flown landing procedures, one with thrust reverser allowed (left) and one without thrust reverser (right). In both cases the initial command value for longitudinal load factor (in the form of total energy angle) of approx. −7.5° after touch down with landing speed of 108 knots was reduced after around 15 s to approx. −13°. Independent of wheel brake and thrust reverser, forward thrust command is set to its minimum. Additionally, the spoiler command is set to its maximum as the spoilers are used for lift dump until the aircraft reaches taxi speed of 20 knots. In the left figure, it can be seen that the reverser command gradually rises with time until it reaches the maximum deflection. At this point the wheel brake controller takes over the integrative behaviour and rises the wheel brake command. After around 19 s the thrust reverser is switched off because the aircraft reached 50 knots minimum thrust reverser speed. This disturbance is balanced by the wheel brakes. The right figure shows that the wheel brakes are the only control element and the command for thrust reverser is zero. Both cases show an accurate longitudinal load factor response and therefore a similar speed reduction and duration of the procedure.

3.3 Human-Machine Interface

The human-machine interface includes visual outputs and a manual inceptor. The HMI for the flight mode and its functionality are described in [11, 14]. The visual feedback is given by additional symbols for flight path and total energy angle at

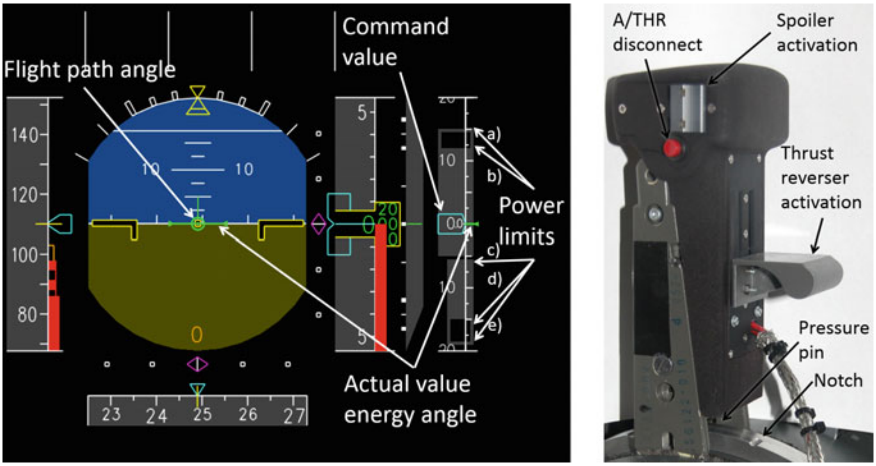

Fig. 3 HMI of the nxControl system; nxPFD: Total energy angle and flight path angle at artificial horizon, vertical degree scale for energy angle, command value and power limits next to vertical speed scale; nxLever: handle with spoiler and thrust reverser switch

the artificial horizon of the primary flight display (nxPFD) as well as an additional vertical degree scale for energy angle, command value and power limits of engines and spoilers at the engine display (nxStatus). This concept is also used for the ground mode with some improvements. Figure 3 shows the new version of the nxPFD at a situation after touch down and with a commanded energy angle of zero degree. The nxStatus scale was moved to the nxPFD at the right side of the vertical speed tape to improve scanning pattern. Also, the colours and symbols were adjusted. A functional change for the ground mode was necessary for the indication of power limitations. As the actuation elements differ on ground compared to flight, new symbols had to be introduced. On ground, power limits for forward thrust, wheel brakes and the combination of wheel brakes and thrust reverser are shown on the nxStatus scale. Both upper limits represent the maximum energy angle with (a) maximum thrust (TO/GA) and (b) flexible thrust (FLX). The first lower limit (c) indicates the energy angle with idle thrust. Commands below this value are achieved with wheel brakes limited by the lower limit of the filled tape (d). If the pilot activates thrust reverser the hollow lower limit (e) can be reached.

The concept for the inceptor of the nxControl flight mode, called nxLever (see Fig. 3), was adopted for the ground mode. One handle is used to command the target value for load factor in form of the energy angle although multiple engines are controlled. By pulling the reverser lever up, the use of reverse thrust by the controller is activated. The pressure pin on the bottom together with a grooved rail provide the mechanism for haptic feedback. The pin snaps in on predefined positions. The notch at the middle position, representing a zero command, is also used in flight mode. Two more notches are provided for typical deceleration rates on ground. One notch lies at the command value of $-10°$, as it is equal to the autobrake level *low*.

The second notch represents the command value $-15°$ that equals the autobrake level *medium* on some Airbus aircraft. These positions were freely chosen and should be adapted for particular aircraft. Commands below the last notch represent emergency brake mode. In that case, all control elements are fully deflected to minimize energy angle (thrust reverser only after activation).

4 Study with Pilots

An evaluation study was conducted with seven airline pilots in the fixed-base research 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 [15]. The simulator is based on a VFW614 ATD and the cockpit is equipped with displays and sidestick (including control laws) similar to an Airbus aircraft.

All pilots were male and in possession of Airbus type ratings (A320: 6, A380: 1). The pilots' age ranged between 25 and 64 years with a mean of 39 years (15 years standard deviation). Their experience varied widely from 330 to 25 000 total flight hours with a mean of 8 440 h (9 146 h standard deviation). Most of the pilots were ranked as First Officer, only one participating pilot was Captain.

The pilots were trained with the nxControl system, which took 1.5 h. Afterwards, the pilots had to fulfil different tasks in different scenarios with the nxControl system. The test scenarios represent the flight phases on ground: landing, taxi and take-off. All tasks were described by target values, but the procedure to fulfil the tasks lay in the hands of the pilots. Thus, the pilot strategy with the new system could be examined. There was no statistical comparison to the conventional control strategy. As part of the pilot-centred design, the study aimed at examining the feasibility of the concept, necessary changes to procedures, and exposing any issues that might have been disregarded in advance. The focus lay on the questions whether the pilots could succeed fulfilling their task, whether the pilots were aware of the system functionality, or whether *show stopper* for the ground mode concept have to be expected and how the pilots asses the system.

4.1 Test Scenarios and Interview Questionnaires

The tests were conducted at Frankfurt/Main airport former runway 25R (now 25C) shown in Fig. 4. The first scenario was a final approach with touch down and deceleration to runway exit *Ato* (*Landing Procedure Long*). In this scenario the use of the thrust reverser was not allowed. The second scenario was another final approach with touchdown and deceleration to the near runway exit *Gto* that required the use of thrust reverser. Before these two scenarios, the pilots were requested to calculate the mean deceleration rate, transformed into a total energy angle, that was necessary for

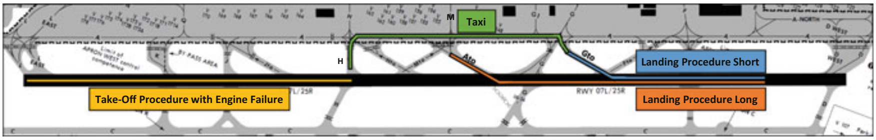

Fig. 4 Section of Frankfurt/Main (EDDF) airport chart [8] with runway 25R

the different runway lengths. The reversed Eq. (3) was provided. The objective was to build up an awareness about load factor values at landing. Both scenarios started on glide slope fully configured and with landing speed of 108 knots calibrated airspeed. After touch down, the pilots had to decelerate to 20 knots taxi speed which led to mean energy angles of $-7°$ in scenario one and $-13°$ in scenario two. The mean values were introduced as reference values but the pilots were free to perform their preferred braking strategies. After deceleration, the pilots had to leave the runway and to stop at the holding point of the runway exits.

The third scenario was taxi on ground from runway exit *Gto* to the new take-off position near runway entrance *H*. The pilots were requested to accelerate to 20 knots taxi speed, stop at the intersection *M*, and continue taxi to the holding point of runway entrance *H*.

Scenario four and five were take-off procedures beginning near runway entrance *H* with engine failures. In scenario four, the pilots had to accelerate with TO/GA thrust setting. The engine failure appeared shortly before 100 knots decision speed V_1 that induced take-off rejection. In scenario five, thrust setting FLX was requested to accelerate and the engine failure appeared after V_1. Therefore, the pilots had to continue take-off procedure with reduced climb performance at 120 knots speed. All scenarios were performed twice and only the second trial was evaluated.

After each scenario, the pilots were asked about their opinion on the nxControl system. The interview covered the topics procedure, steering strategy, HMI, and controller/aircraft behaviour. The topic procedure included questions about potential conflicts with existing procedures as well as safety aspects. Also, the pilots were asked how they used the system and what kind of steering strategy they had in mind. As the HMI changes the standard cockpit layout, the questions addressed the scanning and input behaviour as well. Especially, the use of the added information on the primary flight display as well as the haptic feedback of the nxLever were investigated. The last topic addressed controller logic and aircraft response. The pilots were asked if the aircraft behaviour was as expected, if they could anticipate the actuation element behaviour, and if they could successfully fulfil their task.

4.2 Results and Discussion

The simulation data of commanded total energy angle, resulting calibrated airspeed, state of ground mode (GMDE), activation of thrust reverser by the pilots, and the

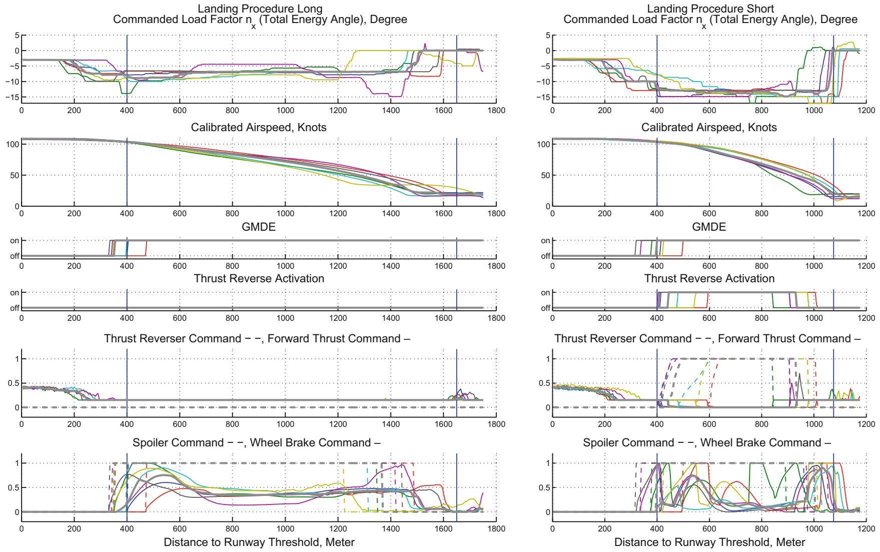

Fig. 5 Longitudinal load factor command, speed, and actuation signals by nxController of all participants and median values (*bold grey line*) against distance from runway threshold at manual landing procedures without (*left*) and with (*right*) thrust reverser activation by the pilot

commands by the nxController to forward and reverse thrust, spoiler, and wheel brakes is presented in the Figs. 5, 6 and 7. The results of all participants are shown in the background and were averaged with the median (bold grey line) that will be the basis of result description.

4.2.1 Landing Procedures

Figure 5 shows the results of both landing scenarios. The ordinates represent the distance from runway threshold. At 400 m distance, the touch down area is located. The runway exits are located at 1 650 and 1 075 m respectively. In both scenarios, the progress can be divided in the phases flare, first deceleration after touch down, main deceleration, capture taxi speed, and turn to runway exit.

In scenario one, flare phase was entered by reducing thrust setting. Therefore, the pilots changed energy angle command from −3° to averaged −7°, which corresponded to the calculated reference value. This caused forward thrust to decrease to idle (represented by the value 0.15). After touch down, the command value was further lowered for the first speed reduction. Consequently, the controller increased the wheel brake command and set the spoilers into lift dump position. At approx. 600 m distance, pilots' command was returned to nearly −7°, which lowered wheel brake command to the appropriate value. This resulted in constant speed reduction until taxi speed. Then, the pilots changed their command value gradually to zero

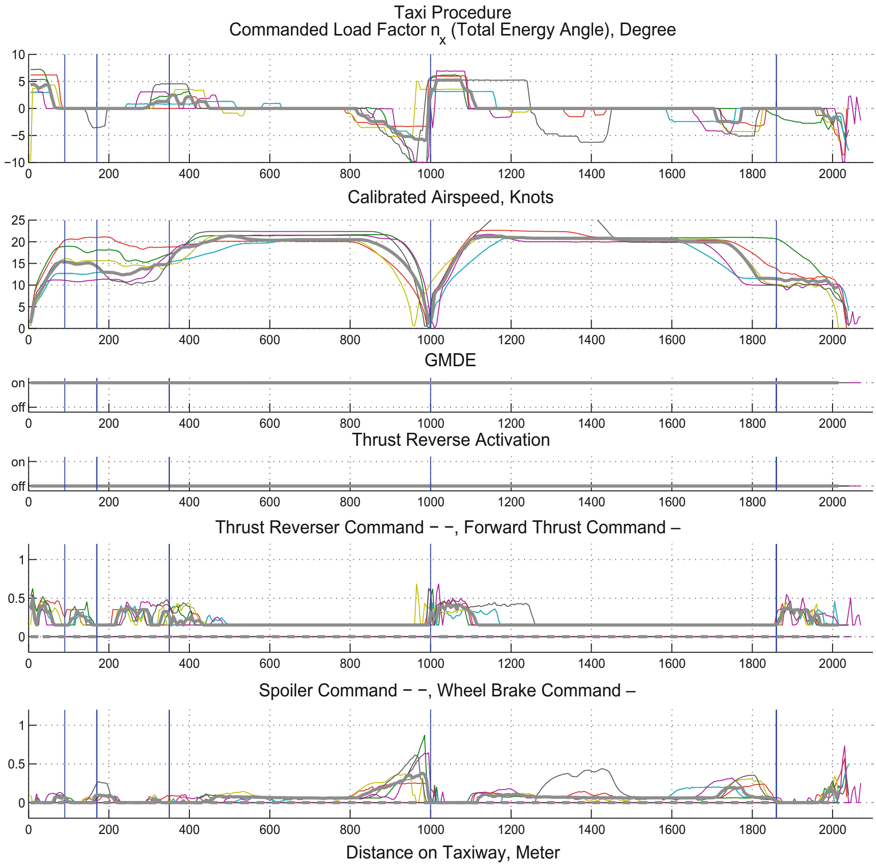

Fig. 6 Longitudinal load factor command, speed, and actuation signals by nxController of all participants and median values (*bold grey line*) against distance on taxiway at taxi procedure

(middle position of the nxLever). This released wheel brakes. As the idle thrust force of the VFW614 is higher than the rolling friction, braking is necessary to maintain speed. At turns, friction is rising and therefore energy angle would decrease. But, the nxController compensated this by rising the thrust setting.

In the second scenario, the flare phase was entered in a similar way, but with a lower command value for the total energy angle. The pilots changed their command from $-3°$ to averaged $-10°$. This value corresponded to a notch of the nxLever (haptic feedback). After touch down, the pilots averagely commanded the reference value of $-13°$ for first deceleration and allowed thrust reverser by activation on the nxLever. Therefore, the wheel brake command increased until thrust reverse became active. Afterwards, the brake command decreased until thrust reverse reached its maximum and additional amount of braking became necessary. Around 700 m after threshold, the pilots reduced energy angle command under the reference value for a

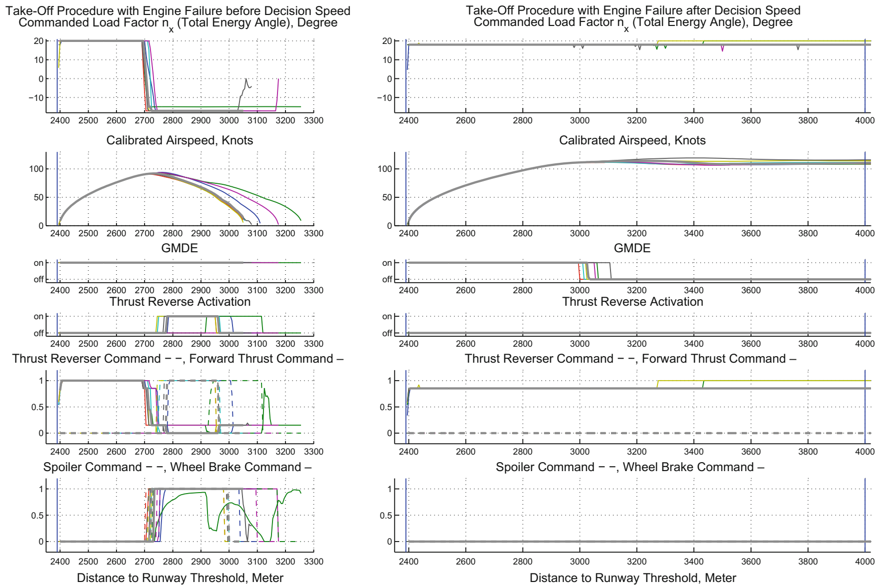

Fig. 7 Longitudinal load factor command, speed, and actuation signals by nxController of all participants and median values (*bold grey line*) against distance from runway threshold at manual take-off procedures with engine failure before (*left*) and after (*right*) decision speed

stronger speed decrease. Note that commands below −15° correspond to emergency brake mode. As speed reached 50 knots, thrust reverser was automatically deactivated and therefore wheel brake command increased again. With the beginning turn to the runway exit, the pilots commanded 0° energy angle to hold taxi speed. Therefore, brakes were released and thrust partially increased to compensate additional friction.

In the interviews, the pilots mostly recalled the steering strategies represented by the median behaviours. Four of the seven pilots stated that they used the calculated reference energy angle in favour of constant deceleration. Due to safety considerations, two pilots chose a higher deceleration rate at first and then reduced the deceleration to the reference value. One pilot's strategy was to keep runway occupation time short with a low deceleration after touch-down and increased it closer to the runway exit. Some pilots mentioned that they used emergency brake position by mistake as they tended to use the lever's end stop position while decelerating. To avoid accidentally selecting emergency brake, a harder notch prior to emergency brake or secondary inputs commanding emergency brake should be considered.

Concerning the handling of nxControl, a few pilots mentioned the extended head-down time to select a specific energy angle with nxStatus scale. In their opinion, this was very unusual and the priority in this phase should mostly remain on the outside view. However, one pilot supposed that the lengthened head-down time could be caused by missing deceleration clues in the fixed-base simulator.

Despite criticism that braking with hands is unusual, there were also comments on its advantage: The pedals would have one function and the pilots could concentrate on lateral control.

The pilots were also asked, if nxControl made these tasks more difficult or easier. For scenario one, six pilots answered with "slightly easier" or "easier", one pilot opted for "unchanged". For scenario two, five pilots stated "slightly easier" and two pilots stated "slighly more difficult".

4.2.2 Taxi on Ground

Figure 6 shows the results of taxi scenario. The ordinate represents the distance covered on taxiway. Between 90 and 170 m and between 170 and 350 m, a left turn followed by a right turn led to the main taxiway. At 1 000 m distance, intersection *M* was located. The turn to runway entrance *H* began at 1 850 m.

For acceleration at the beginning of the scenario and after the full stop at 1 000 m, the pilots commanded a positive total energy angle (averaged 4–5°, maximum 8°). Consequently, engine command for forward thrust rose above idle level and brakes were released. To overcome static friction, the initial thrust command was higher than necessary for taxiing. Before the first two turns, the pilots accelerated to approx. 13 knots and selected the zero command afterwards to maintain speed while changing the direction. As already seen at the turns after landing (Sect. 4.2.1), the additional friction in a turn is compensated by additional thrust. The following acceleration to taxi speed was again achieved by positive energy angle command – but with a lower value (averaged approx. 1.5°, maximum 3°) – which induced lower brake commands and higher thrust commands. At the straight and steady segments after acceleration, the pilots commanded 0° energy angle to maintain speed. Therefore, brake commands increased to compensate idle thrust force. The full stop at 1 000 m was initiated with a negative energy angle command. In average, the pilots chose −5° and in maximum −10° leading to an incrementally rising brake command until full stop was reached. The same sequence appeared at deceleration before the turn to runway entrance *H*, but with a lower absolute command value (averaged approx. −3°, minimum −5°). The pilots reduced taxi speed to approx. 10 knots for the following turn.

The interviews revealed two main strategies while taxiing. One group determined and used reasonable reference values to accelerate and decelerate, e.g., ±5°. The other group did not utilize specific energy angle values. They used engine noise and lever position as orientation. Most pilots approved and made use of the middle notch (0° command) due to tactile feedback to comfortably hold taxi speed. However, some noted that it was unusual at first to taxi with lever not in idle position.

A few pilots disliked the high fan rotation speeds when starting to roll. Moreover, almost every pilot was initially surprised that thrust was increased in a turn to compensate for additional friction. This controller behaviour was rated differently by the participating pilots. Some of them thought that this functionality is unnecessary or disturbing. Especially the A380 pilot stated that this could be a safety issue when ground vehicles were in close proximity. Other pilots appreciated this behaviour in respect to holding taxi speed in turns and regarding the consistency of nxControl's overall concept. To resolve this issue, the commanded thrust could be restricted to moderate limits at low speeds used while taxiing. The disunity among pilot's feedback was mirrored when asked if nxControl made this taxi task easier or more difficult. Three pilots chose "slightly more difficult" or "more difficult", one pilot chose "unchanged", and three pilots chose "slightly easier".

As additional comment, it was noted that in some cases of taxi differential thrust or brake is used, e.g., in turns on slippery runways. This could be addressed by an additional function of lateral control laws that would balance thrust and brakes.

4.2.3 Take-Off Procedure

Figure 7 shows the results of both take-off scenarios. The ordinate represents the distance from runway threshold. Both scenarios started at 2 400 m. Engine failures appeared in both scenarios at 90 knots (around 2 700 m) and 105 knots (around 2 800 m) respectively. At 4 000 m distance, the end of runway is located.

The first take-off scenario was initiated by commanding the total energy angle to TO/GA setting (depicted as 20°). This caused full-thrust command for acceleration. After engine failure before V_1, the take-off was rejected by retarding the energy angle command to the emergency brake position represented by values below $-15°$ (only one participant did not use the emergency mode). Most participants (except one) then added thrust reverser to safely decelerate and to compensate the yawing moment of the failed engine. Consequently, the command for forward thrust immediately decreased to idle followed by increasing commands for thrust reverse, brakes, and ground spoilers to their full position. By reaching 50 knots speed, thrust reverse was automatically deactivated.

The beginning of the second take-off scenario was similar to the first. The commanded energy angle was at FLX position depicted by the value 18°. Therefore, the command for engines increased to 85%. With the engine failure, the acceleration rate decreased. As the failure appeared at rotation speed, this emerged to a decreased climb rate compared to the nominal case (not shown in the figure). After lift-off, the most pilots chose to maintain the FLX setting and stabilised climb with steady speed. Some participants added more thrust by setting TO/GA.

The majority of pilots stated at the interview that the take-off procedure using nxControl corresponded closely to conventional thrust control. Furthermore the deceleration phase while rejected take-off was very similar to conventional procedure. The pilots steering strategy was to push the lever in TO/GA or FLX position and pull it all the way back and enable thrust reverser to decelerate. In the case of engine failure after V_1, three pilots mentioned that they consciously used flight path angle and/or energy angle to stabilise their flight and air speed. The pilots, which did not command emergency brake or thrust reverser, stated that it happened accidentally. This may be caused by their lack of practice since some company policies only allow captains to taxi and perform take-off decisions.

Two minor conflicts with current procedures were reported. First, regarding the rejected take-off procedure, thrust reverse should be used until complete stop. This can be resolved by an adjusted controller logic. Second, it is not possible to increase fan rotation speed with brakes applied to check for synchronisation of all engines before take-off. It could be complied with this procedure by using parking brake.

Concerning the usability, two pilots thought that they could perform the first take-off scenario "easier" or "slightly easier" with nxControl, while the other five pilots answered "unchanged". For the second take-off scenario, four pilots stated "slightly easier" and three pilots chose "unchanged".

5 Conclusion

To maintain manual flight in future air traffic, supporting systems that allow commanding demand values instead of control surface deflections will become necessary. Today's cockpits provide such functions spawned by fly-by-wire technology. The nxControl system supplements these functions with a demand control law and display elements for the longitudinal load factor represented by the total energy angle. In flight, the system controls thrust and spoiler deflection according to pilot's commands and aims at supporting the manual energy management. It relieves the pilot of controlling the parameters fan rotation speed or lever deflection as proxy for energy change by means of direct control of the relevant physical parameters.

After validation of the nxControl concept during flight in a previous study, the concept was extended for operation on ground to prevent mode changes at the time critical phases of take-off and landing as well as to enable a precise but still flexible control of take-off and landing distances. Therefore, the control logic of the demand controller was supplemented by the actuation elements wheel brakes and thrust reverser. The control philosophy and the control law design process was consistently applied to the new ground mode. In addition, the HMI was improved considering the results of the previous flight mode study as well as the concept extensions for ground mode.

In a study with seven airline pilots in a research flight simulator, the presented ground concept was tested at landing, taxi, and take-off. The results showed the feasibility of the new system. The pilots used the system as it was intended in all given scenarios after a limited training phase. At two landing scenarios, the pilots reached the near and far runway exits at taxi speed with goal oriented inputs. The use of the command value as well as the thrust reverser activation was not rated as a problem. Taxi on ground was also feasible with the system despite the use of inceptor and actuation elements slightly differ from the conventional case, e.g., rising thrust at turns with zero command, taxi with lever in middle position instead of the rear position, and braking with the lever instead of the pedals. The behaviour of the participants at a rejected or continued take-off after engine failure was similar to the standard procedure. Therefore, nxControl did not affect the conventional behaviour of the pilots in this very fast take-off situation and would not lead to loss of basic skills. Moreover, some participants mentioned the good stabilisation opportunity after take-off with engine failure. As disadvantage, the pilots mentioned a longer head-down time to set the appropriate command that may have been reinforced by the missing physical loads of the fixed-base simulator. Also, some procedural details ought to be adjusted when using nxControl, e.g., using parking brake until initial engine synchronisation at take-off or introducing energy angle values as reference in briefing material.

Despite some improvement opportunities, the study showed that the extended nxControl system can be used on ground and during transition phases. Therefore, the system can provide support of manual control in all phases of an aircraft turn-around. Mode changes at the time critical transitions could therefore be avoided. In addition, the direct manual control of the aircraft reaction is possible and could provide more precise control with lower workload at future demanding trajectories.

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