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NLR-TP-2017-497 | February 2018

Use of Touch Screen Display Applications for Aircraft Flight Control

CUSTOMER: European Commission

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Netherlands Aerospace Centre

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EXECUTIVE SUMMARY

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Use of Touch Screen Display Applications for Aircraft Flight Control

Problem area

In the context of the European Union's 7th Framework and co-funded project Advanced Cockpit for Reduction of Stress and workload (ACROSS) an investigation was performed by the Netherlands Aerospace Centre (NLR) under the Aviate Work Package towards novel cockpit technologies and applications to contribute in reducing crew's peak workload and in improving crew's situation awareness. One of those technologies investigated was the use of touch screens in the forward displays of the cockpit having a novel dual touch Human Machine Interface (HMI) and cockpit applications.

Description of work

A piloted experiment was held in which ten airline crews participated on NLR's full motion-based flight simulator (GRACE). Baseline formed today's Airbus aircraft operations without touch screen functionality, hence the crew operation of for instance a Flight Control Unit (FCU) and line select key use with a Control Display Unit (CDU) of the Flight Management System (FMS). The experiment focused on the use of three novel touch screen applications in the cockpit of civil transport

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KNOWLEDGE AREA(S)
Cockpit
Flight Operations
Training, Mission Simulation and Operator Performance

DESCRIPTOR(S)
Situation Awareness and Workload Assessment
Aircraft Flight Control
Alternate Airport Selection
Late Runway Change
Touch Screen Application Technology

aircraft and investigated the potential for (peak-) workload reduction. Firstly there was the use of the so-called tactical flight control application. A new crew-interface performing aircraft autopilot functional control, like changing its speed, heading and altitude. Secondly a novel late runway change application was set up to be used outside the CDU for supporting the crew decision to accept a new landing runway late in the approach while still allowing safely and easily configuring the aircraft cockpit systems. Similarly the third new application allowed for a fast and easy alternate airport selection process and subsequently a new route creation and selection towards the alternate airport (again outside the CDU). Subjective workload and situation awareness ratings were used, as well as objective eye-tracking measurements and time-analysis. Also the effect of turbulence (intensity) was investigated.

Results and conclusions

The results of the piloted experiment on GRACE showed that the late runway change and alternate airport selection applications were highly appreciated by the flight crews. Both applications significantly reduced workload and improved crew situation awareness. Task execution was much faster and easier compared to the baseline. The tactical flight control application was regarded sensitive to turbulence s and showed further room for improvement especially related to the bezel design for the touch screen.

Applicability

The results can be applied in the development of new cockpit systems by industrial parties like avionic industries, by aircraft manufacturers and by small and medium avionic enterprises, especially those producing touch screen functionalities. A strong field of applications will be the R&D community and the developments in the field of single pilot operations.

GENERAL NOTE

This report is based on a paper for and a presentation held at the combined 36th IEEE /IAAA - Digital Aviation System Conference (DASC) 2017, St. Petersburg, Florida, USA, September 17 – 21, 2017.

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Contents

Abbreviations

ACRONYM	DESCRIPTION
AAS	Alternate Airport Selection, or Amsterdam Airport Schiphol
ACROSS	Advanced Cockpit for Reduction Of StreSs and workload
ALT	ALTitude
ANOVA	ANalysis Of Variances
AP	Auto Pilot
APERO	Avionics Prototyping Environment for Research and Operations
ARC	ARC-mode of ND
ATC	Air Traffic Control
CARS	Crew Awareness Rating Scale
CDU	Control Display Unit
CP	Control Panel
CRT	Cathode Ray Tube
DEST	DESTination
EFB	Electronic Flight Bag
EFIS	Electronic Flight Instrument System
EHAM	ICAO code for Amsterdam Airport Schiphol
EU	European Union
F	F-test
FCU	Flight Control Unit
FL	Flight Level
FMS	Flight Management System
FP	Framework Program
ft	Feet
GRACE	Generic Research Aircraft Cockpit Environment
HD	High Definition
HDG	HeaDinG
HMI	Human Machine Interface
ILS	Instrument Landing System
KIAS	Knots Indicated Air Speed
kts	Speed unit knots
LCD	Liquid Crystal Display
LRC	Late Runway Change
M	Mean value
MCP	Mode Control Panel

ACRONYM	DESCRIPTION
MTS	Multi Touch Screen
N	Number
NASA	National Aeronautical and Space Administration
NAV	NAVigation
ND	Navigation Display
NLR	Netherlands Aerospace Centre
p	Probability level (significance)
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
QNH	Altimeter setting: Q-code indicating the atmospheric pressure adjusted to sea
RSME	Rating Scale Mental Effort
s	Seconds
SA	Situation Awareness
SD	Standard Deviation
SPD	SPeeD
STD	STanDard altimeter setting
t	t-test
TFC	Tactical Flight Control
TLX	Task Load indeX
V/S	Vertical Speed
VSD	Vertical Situation Display
XWB	X-program WideBody

Use of Touch Screen Display Applications for Aircraft Flight Control

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***Abstract*—Touch screen technology is rapidly and progressively entering the world of commercial avionics and being introduced inside the cockpit.**

This paper presents the main results of a piloted experiment conducted by the Netherlands Aerospace Centre (NLR) as part of the ACROSS (Advanced Cockpit for Reduction Of StreSs and workload) project of the EU's 7th FrameWork Programme, see www.across-fp7.eu. The experiment focused on the use of novel touch screen applications in the cockpit of civil transport aircraft and investigated the potential for (peak-) workload reduction. Three different touch screen applications and associated experimental results will be discussed. Firstly the so-called *tactical flight control* operations of an aircraft is addressed, like changing the aircraft's speed, heading, altitude, flight level or vertical speed. Secondly a novel *late runway change* functionality was set up for supporting the crew decision to accept a new landing runway late in the approach while still allowing safely and easily configuring the aircraft cockpit systems. Similarly the third new application allowed for a fast and easy *alternate airport selection* process and subsequently a new route creation and selection towards the alternate airport.

A piloted experiment was held in which ten airline crews participated on NLR's full motion flight simulator (GRACE). Baseline formed today's aircraft operations without touch screen functionality. Subjective workload and situation awareness ratings were used, as well as objective eye-tracking measurements and time-analysis. Also the effect of turbulence (intensity) was investigated.

Main results for the tactical flight control application showed further room for design improvements in the field of workload reduction, especially under more severe turbulence. For the other two cockpit touchscreen applications the results supported the conclusions that pilot workload decreased, situation awareness improved and task execution was much faster and easier compared to the baseline.

***Keywords*—Aircraft flight control; alternate airport selection; eye-tracking; late runway change; situation awareness; tactical flight control; touchscreen application technology; workload assessment; HMI design.**

I. INTRODUCTION

Today's modern civil commercial transport aircraft cockpits are heavily automated and require relatively little amounts of physical activities from the crews. Still "flight crew error" is known to be the single most common probable cause or contributing factor that is cited in aircraft accident investigation reports. Various reasons can be given for this like: over-reliance in automation, lack of confidence in automation, automation complexity and complacency, automation bias, non-apparent automation behavior and lack of mode awareness, see [1,2].These explanations all shift the blame somewhat into the direction of the automation, meaning towards logic and behavior of crew-system interfaces, and puts a bit less blame on the human operators, opposite to what is generally stated in the public media and perceived in the eyes of the general public. Another, but still suspected cause may however lie in the fact that there remain instances where the workload level rises to the point where even within the commonly operated two-pilot crew configuration the flight crew comes under stress. Such as during complicated arrivals, approaches and landings, especially at heavy traffic airports combined with bad weather situations or with unusual conditions; or even during challenging departures.

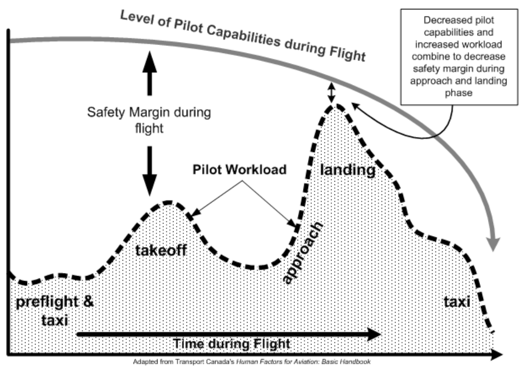

Fig. 1. Pilot Workload versus Phases of Flight [3].

A generic workload-over- flight phase-characteristic is given in Fig.1. Increased crew workload or stress levels experienced during the flight may allow normal cockpit automation behavior no longer to be comprehended properly anymore. The crew enters into a kind of tunnel-vision, or is mentally just blocked for additional information. In those situations the "blame" is somewhat more directed to the crew not receiving, or understanding the properties of the automation logic that are perfectly well understood without stress. The "what is it doing?" expression is a well-known example of that situation. Notwithstanding who or what to criticize, it is very clear that life of a human operator under high workload or stress should be made as easy as possible; hence automation logic should assist the crews to the maximum possible always. For this reason it was considered that the level of cockpit automation and state-of-the-art operational flight equipment and software logic could potentially be improved further to provide the flight crew with the support required under crew peak workload conditions while achieving the desired level of situation awareness to assure safety.

As part of the Seventh Frame Work Research Program (FP7) of the European Commission, the ACROSS (Advanced Cockpit for Reduction Of StreSs and workload) project (2010-2016), in which 36 parties participated and that was led by Thales Avionics (of Toulouse) France, aimed to research novel technologies that should improve the workload levels for the flight crews. The technical domains consisted among other of: Aviate; Navigate & Manage Mission; Communicate and Manage Systems. The proficient reader notices from the first four technical domains the way Airbus teaches flight crew to divide attention and how to operate their aircraft in a generic sense. The following describes technical innovations that formed part of the Aviate technology domain.

II. Touch Screen Operations in the Cockpit

Today touchscreen displays are already a common good in the operation of the cabin systems and passenger entertainment devices but are less well progressed into the cockpit. Even the most recent Airbus aircraft product, i.e. the A350-XWB series, does not currently have touchscreens available on the flight deck for primary operational purposes. If present at all inside an aircraft's cockpit, the touch screens are generally fitted on the outside parts, like for operation of the Electronic Flight Bag (EFB) as shown for example by Dassault's Falcon 8X, see [4]. Also in the retrofit aircraft market the old CRTs displays are not yet being replaced by touch screens but mostly by LCDs due to the required avionics infrastructure adaptations.

However, recent publications [5,6,7], news items on the most modern Gulfstream 500/600 series as well as around the upcoming Boeing B777X aircraft [8,9], reveal that touch screen technology for use in operation of primary aircraft avionics is gradually entering the cockpit of business and civil transport aircraft. This transition will thereby slowly bridge the gap with the military field, for example with the F35 Lighting II.

One of the topics developed and researched by NLR was the aspect of reducing crew workload by applying a touch screen for tactical aircraft control matters in a civil cockpit. Initial assessment took place by using NLR's fixed based-flight simulator APERO and using a first Human Machine Interface (HMI)-prototype. This consisted of a tablet multi-touchscreen put in front of the pilot for direct aircraft operations. See Fig.2. A piloted experiment was set up around this concept to identify main design issues and improve the concept.

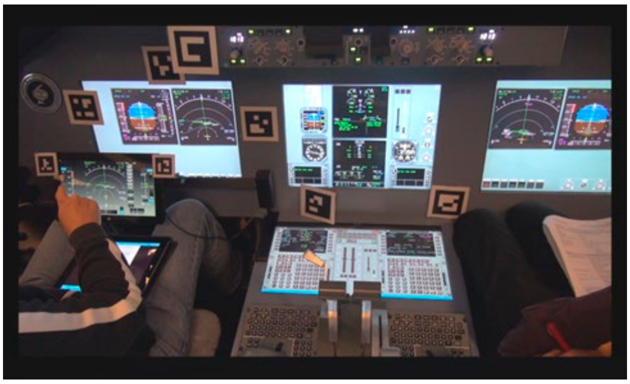

Fig. 2. Tablet touch screen with first HMI-prototype in use inside NLR's fixed-based flight simulator (APERO). Also eye-tracking reference markers are shown.

After lessons learned on that first prototype, a modified and fully redesigned HMI concept was set up and finally evaluated by 10 airline crews on the Generic Research Aircraft Cockpit Environment (GRACE) full motion flight simulator of NLR, in a crew concept. Details on both HMI-concepts and assessments are provided in the next sections. Hypotheses were defined and statistically validated with a probability level for acceptance set at $p<0.05$ for all experiments.

III. First Prototypes on Aviate-Related Flight Control Support

To support the flight crew in their Aviate-related tasks, the following innovations were developed:

- **Tactical Flight Control support**
- **Short Term Flight Operations support**
    - **(Late) Runway Change support**
    - **Alternate destination Airport Selection**
    - Bad weather avoidance support
- Auto aircraft Configuration support
- Go Around support

In the following two sub-sections, only the above-listed and bolded innovations are discussed in more detail and first prototype assessment results are provided.

A. *Tactical Flight Control Support – Initial prototype*

1) Concept description

First of all it will be explained what is meant with *tactical* and *strategic flight operations.* The latter was regarded as the management of the progression of flight based on the use, guidance and control of the flight trajectory as set up via the flight management system (FMS) and flown in auto pilot coupled mode(s). More specifically it relates to flying the routes in the so-called "managed" modes (in Airbus phraseology). Contrary to this strategic flight operation, tactical flight operation consists of aircraft control that would result from either the direct manual control of the aircraft via stick, throttles and rudder, or the direct use of the auto pilot, auto flight guidance and auto throttle systems via the so-called “selected” modes (in Airbus phrasing), applying a selected heading, selected speed, selected vertical speed, selected altitude\Flight Level, or selected level change. Hence tactical flight operations were regarded to cover all the aspects in the use of the auto pilot outside the strategic management of the flight, including the transitions from selected into managed mode (and vice versa). Of course there is always a kind of overlap between tactical and strategical operation, since there is no flying without having a direction related to a kind of route.

In the context of tactical flight operations various innovative tactical flight control support functions were derived to support the flight crew. The basic idea was twofold. Firstly to let a pilot control the aircraft in a more direct and potentially more intuitive way via a touch screen positioned directly in front of him presenting a large redesigned Navigation Display (ND). And secondly to have the inputs of the autopilot selections and the output of the flight guidance system closer together: having a closer co-location of inputs and outputs so to speak. That should make the flight task easier, for example to quickly visually check if the inputted auto pilot values were actually set and used by the auto flight guidance system.The novel HMI contained functionality that was moved from the aircraft’s autopilot control to the ND.

Fig. 3. Top: Airbus Flight Control Unit (FCU) and bottom: left-side EFIS Control Panel.

In Airbus aircraft types a pilot controls the auto pilot via the so-called Flight Control Unit (FCU), see Fig.3. This is also named Mode Control Panel (MCP) in Boeing (or other) types of aircraft. Whatever is dialled-in by the pilot, can be seen on the FCU itself on the selection display. That value is the input to the auto pilot and full automatic flight guidance system. What comes out of the flight guidance system (like the auto pilot settings) can generally be noticed on the Primary Flight Display (PFD) and the ND. Crew procedures in a conventional cockpit generally mandate that values entered manually on the FCU are visually verified on the PFD and/or ND by the flight crew. But the two are rather dislocated in real aircraft thereby potentially introducing additional workload, both in a cognitive and a physical sense. Therefore, it was assumed and hypothesized that the co-location of inputs and outputs would lead to a reduction of workload and improved Situation Awareness (SA).

The FCU turning and push/pull buttons inside Fig.3, from left to right, are:

- Speed selection and speed value knob
- Heading selection and heading value knob
- Altitude selection and altitude value knob
- Vertical speed selection and its value knob

For the first HMI prototype developed, the first three selector knobs of these FCU functions have been HMI-redesigned, integrated with the PFD and ND functionality, and implemented onto a touch screen. Only interaction for speed-, heading- and altitude selection was developed. The vertical speed selection was left out for reasons of simplicity. Generally one can find the EFIS Control Panel (EFIS CP) on the left, see Fig.3, and right side of the FCU. This has a knob for ND mode and range selections and a knob for QNH/ Altimeter selection. Inside the first prototype only the ND-range selector for the left side was implemented. Other EFIS CP and FCU button functionalities were implemented in the second prototype. (See IV). Each original selector knob on the FCU has three functions:

- (Pre-)select a value
- Transit from Managed mode to Selected mode
- Transit from Selected mode to Managed mode

These three knob functions were implemented on the first prototype HMI via an interaction component consisting of 2 slide switches, a rotation wheel and a tape. In Fig.4 an abstract presentation of the interaction component is shown, as well as an implementation for the selection of a new altitude.

The interaction component has the following features:

- Rotation wheel to (pre-)select value
- Sweep wheel to accelerate rotation
- Feasible rotating direction indicated by small (white) triangles on top and bottom, disappearing when at its limit
- Preselected values are shown as blue dashed triangle
- Sliding of top (or bottom) buttons/switches allows to transit between Managed/Selected modes, i.e. magenta/cyan mode colouring
- Switches belonging to one scale (i.e. top and bottom, or left and right) are slaved, and can be operated from both
- If in Selected speed mode, Managed speed is dashed
- Press slide switch to re-enforce mode (needed in Airbus aircraft for Selected Altitude)
- Range limited by appropriate max and min values
- Selected values indicated inside the cyan or magenta coloured buttons/switches

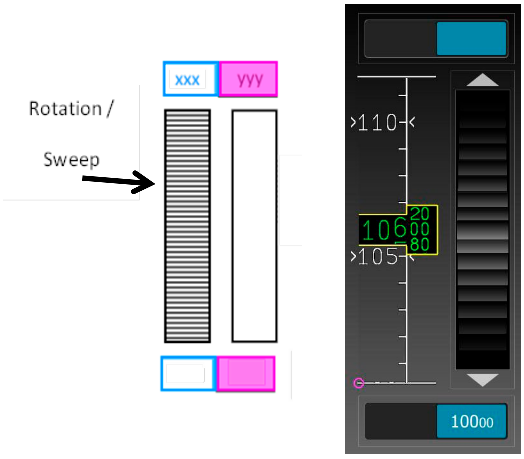

Fig. 4. Left: abstract presentation of tactical flight control interaction component of the first prototype. Right: an implemented and detailled view for the selection of the altitude.

This functionality was implemented on a tablet driven multi-touch screen installed in front of the pilot, see Fig.2 and Fig.5. The latter shows a screen shot of this first HMI prototype in total overview. On the right side it shows the rotating wheel next to the altitude scale for operating the selected altitude. On the bottom side it shows the rotating wheel under the heading scale for inputting the selected heading values. On the left side of the speed scale it shows another rotating wheel to input selected speed values. The current figure also shows via the magenta (top and bottom) switches (or buttons), that we are actually flying the aircraft in “managed” speed mode. By sliding this button to the left side, the auto pilot speed mode is moved from “managed” into “selected” and the button colour is changed accordingly.

Left and right of the selected switches of the heading scale, two new icons can be found. From left to right this represents the icons for the Navigation Display (ND), the Primary Flight Display (PFD), as well as the gear- and flap lever status (and transition status). When touching on one of these icons it would bring the full picture in the centre part of the touch screen. It currently shows in this part the ARC-mode of the ND. Also, in the example shown of the presented ARC-mode, the ND-ranges could be changed directly on the touch screen via “pinch and zooming”.

Fig. 5. Screenshot of the first HMI prototype on a tablet Multi-Touch Screen (MTS)

It would use the same ND-range increments as present inside the ND-range selector button of the EFIS.

2) *Experimental Results*

This first novel HMI tactical flight control support interaction concept was assessed by 7 airline pilots in NLR’s APERO flight simulator, see Fig.2. Various descent scenarios where flown, eye-activity and time-recordings were made, and questionnaires were filled for workload using the RSME-scale [10], and a self-rating question: “building up and maintaining Situation Awareness was just as effortless during the related runs as during the conventional runs” for Situation Awareness (SA). The novel HMI was compared to a baseline that consisted of flying the same descent approach routes but using the conventional FCU/EFIS hardware. There was effect of winds but not of turbulence. In the simulations an Airbus A320-alike aircraft model was flown including a touch controlled Flight Management System (FMS) and Control Display Unit (CDU). Furthermore auto flight guidance, flight-director and the auto-throttles were used.

The main subjective evaluation results revealed that:

- In general, the use of a tablet as multi-touch screen device in the experimental cockpit configuration was positively received. It was found easy and satisfying to use. Furthermore, some pilots indicated that they would prefer some form of tactile feedback from the touch screen (need to ‘feel’).
- building up and maintaining SA in the cockpit with a touch screen and its tactical flight control support functions used was just as effortless, and for some pilots even less effortful than using the legacy cockpit systems.
- The first HMI-prototype on the tactical flight control function (use of touch wheels), when objectively compared to conventional operation in the fixed-based flight simulator did not lead to a faster, or more effective or more efficient operation. The time required to make tactical changes with the novel HMI, when measured and compared with the normal FCU operation, was not found to be statistically significant lower. Also the subjectively rated workload did not decrease, but seemed to increase, see red trend line see Fig.7. The reason for all this was that it was found by most pilots that the rotation wheel took rather long to set a particular value, and also that the fine-control on setting a particular value was rather difficult and took them too much time (compared to the similar FCU operation).
- Pilots really needed to get used to the rotation wheel. It was observed that for instance most pilots initially turned the altitude wheel in the “wrong” direction, meaning opposite to the intended direction. Pilots also mentioned that swiping of the rotation wheel to make numerical changes was oversensitive. That took more activity and effort to correct.
- The slide switch/button for mode transition (in and out managed/selected modes) was well received.

B. *Short Term Flight Operations support function – Initial prototype*

Furthermore, also developed and visible on the full prototyped touch screen HMI of Fig.5 is a first functionality related to the so-called *Late Runway Change (LRC)* and

Alternate Airport Selection (AAS) support functions. These are the (11) vertical buttons on left side of the altitude tape. The HMI-concept aspects of those functions are part of [11, 14] and further highlighted under section IV.B. Some results on these first prototypes will be provided directly hereafter. A few descents, approaches and go-arounds were performed per pilot to assess those two new support functions. The conventional way of performing a LRC, or selecting a new alternate airport, using the FMS and inputting new data via the CDU, was compared with these novel touch screen functionalities.

1) Some Experimental Results on the initial prototypes

The assessment results showed for:

a) Late Runway Change (LRC) function

Performing a late runway change on multi-touch screen with the novel HMI was found easier and more effective than via the CDU. Despite noticeable differences can be observed, no statistical significant difference was found between the measured times required to change a runway via the LRC function, compared to the conventional way, see Fig.6. Pilots self-rated the mental workload as lower with the touch screen function in the cockpit, see Fig.7. Measured lower eye-activity (i.e. attention ratios) confirmed this result. Pilots also indicated that this innovation was intuitive, satisfying and highly desirable to have as soon as possible on their future planes.

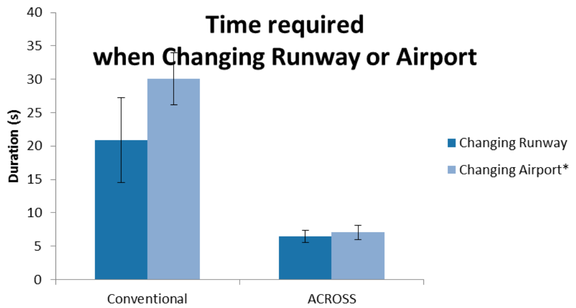

Fig. 6. Time required when changing active landing runway or destination airport (* implies $p<0.05$). Here ACROSS implies the novel functions.

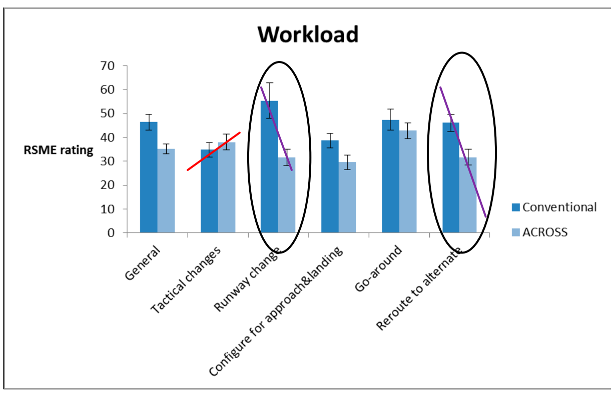

Fig. 7. Subjective workload (Rating Scale Mental Effort (RSME)) effect of TFC, LRC and AAS functions. Conventional operation versus novel touch screen function.

b) Alternative Airport Selection (AAS) function

Change of destination airport on multi-touch screen with the novel HMI was found easier and more effective than via the CDU. The time required to select and reroute to an alternate airport was statistically significant less for the novel touch screen solution compared to the conventional cockpit operation, see Fig.6. Pilots self-rated the mental workload with the touch screen in the cockpit as lower, see Fig.7. Measured lower eye-activity (i.e. attention ratios) confirmed that result. Pilots indicated that this innovation was intuitive and satisfying.

IV. Final Prototypes on Aviate-related Flight Control Support

Based on the results of the first trials with the tablet PC in the APERO flight simulator, a new ND-prototype was developed with novel types of interaction. This also was implemented on a multi-touch screen. Three Dell Precision M3800 BTX Base computers with 15.6" led-backlit touchscreens with Truelife and Full HD-resolution (1.920 x 1.080) were used and installed into NLR's full flight simulator. The concept had also to work properly in real crew operations, thereby introducing cross-crew communication aspects. To support the flight crew further in their Aviate-related tasks, the following innovation was in addition developed, based on pilot comments received during the first trials:

- **Altimeter setting (QNH/STD selections)**

In the following three sub-sections, the finally designed TFC, LRC, AAS and Altimeter selection innovations (before experiment) are discussed in more detail and final prototype assessment results are provided.

A. *Tactical Flight Control (TFC) final prototype*

From the first piloted evaluation exercise the decision was made to radically change the design on essential parts. The wheel-interaction concept was abandoned, but the aspect of the sliders (buttons) to set the "selected" or the "managed" mode for the auto-flight guidance system was retained as pilots found it easy to comprehend and intuitive to use. Furthermore, in addition to the TFC functions Speed, Heading and Altitude as set up under the initial prototype also the FCU selection modes of Vertical Speed and direct Level-Off were added and implemented.

The generic improvement idea was to have the control more direct and more intuitive in terms of a (speed) vector management in the horizontal plane, or in the vertical plane. In both planes the vector direction and its amplitude could be controlled and set to be able to directly set a new direction, altitude and speed of the aircraft. The HMI design perspective was enlarged into a crew centered design since internal prototyping design sessions revealed that the use of the FCU in real operational situations required fast information sharing between crew members. Specific FCU control functions can be accessed by first tapping the yellow aircraft symbol in the center ND part, with the ND-display and ND-selector in ARC-mode, as seen in Fig.8. This will open the touch control screen as shown in Fig.9 below. Subsequently the pilot (who actually opens this control screen) can manipulate with his/her finger the vector around the heading scale and the speed amplitude along the speed vector. More HMI-details are given next.

1) Heading Selection

To actually set a (new) heading, the heading selection button on top of the compass, see Fig.10, must be touched and slid towards the desired heading. Fig.11 shows the detail. To set a new value with the conventional FCU selection knob pilots generally turn the knob roughly and then adjust it by small increments. Similarly they can also apply this method on the touch screen by roughly sliding the selector to the desired heading and then adjusting the heading with the increment (cyan) arrows next to the actual heading value. During a selection the remaining parts shown on the MTS are slightly dimmed for improved readability on the (input) control screen.

2) Speed Selection

Similarly the Selected speed can be set by first tapping the aircraft symbol on the ND (in ARC-mode). And once the Control Panel has opened up the speed vector can be moved along and inside the grey bands, see Fig.12. By touching at the current speed value it can be moved grossly into an increased or decreased value. Subsequently with the cyan up/down arrows (seen along the left side of the speed scale in the figure) fine tuning can be performed at +/- 1 kts precise, see Fig.13.

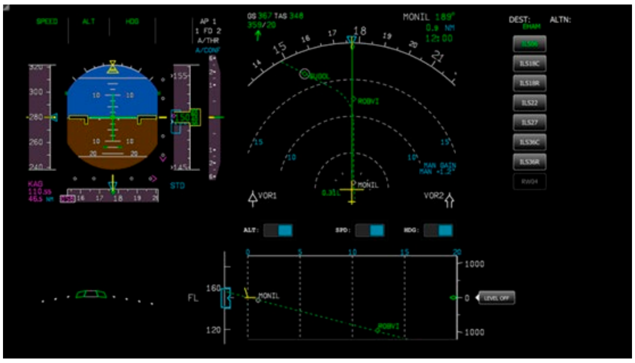

Fig. 8. Multi-Touch Screen (MTS) set up for left pilot

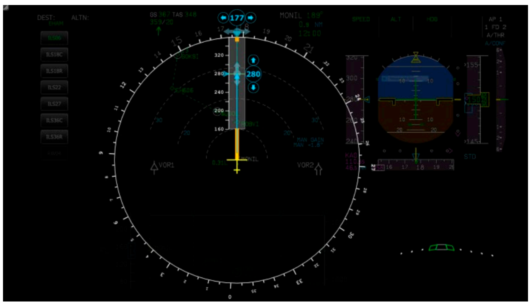

Fig. 9. Control Screen of MTS (for right-side seated pilot)

3) Altitude and Vertical Speed Selection

By tapping the yellow aircraft symbol on the Vertical Situation Display (VSD), the pop-up menu is opened, Fig.14. Then functions to adjust the altitude (or Flight Level) and the vertical speed (V/S) can be accessed. Along the borders of the VSD's pop-up menu, axes describing some units are shown.

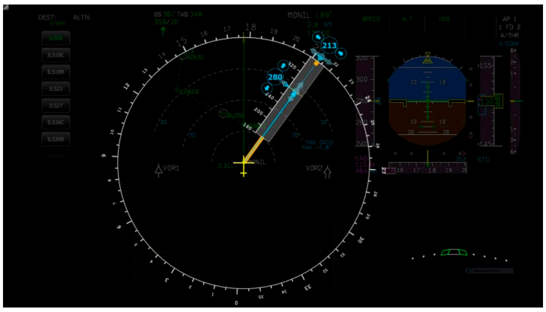

Fig. 10. Setting a new heading (by right-side seated pilot)

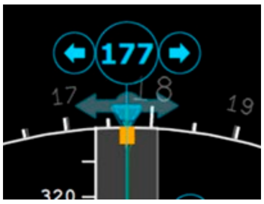

Fig. 11. Setting a new heading (by right pilot)

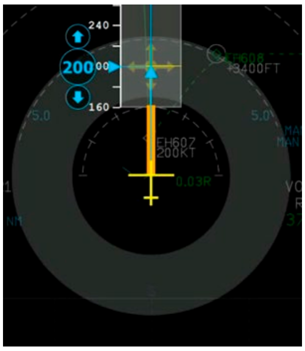

Fig. 12. Speed selection function

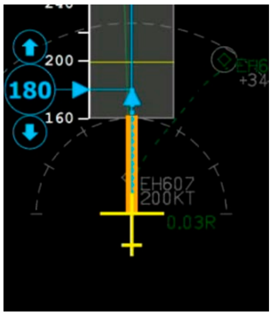

Fig. 13. Setting a speed

a) Altitude selection

To select a new altitude, the blue slider on the altitude axis has to be touched and moved along this axis (Fig. 15). The arrow symbols above and beneath the altitude value enable the pilot to change the altitude with ±100/1000ft increments. Whether the increments are 100ft or 1000ft depends on the flight phase active in the FMS (approach or other).

b) Vertical Speed (V/S) selection

In the VSD, a V/S can be set to maintain a constant vertical velocity. After pressing the yellow aircraft symbol on the VSD a yellow arrow appears, see Fig.16, which can be slid upwards or downwards in order to select a V/S (Fig.17). The arrows allow the pilot to select ±100ft/min increments for the V/S.

c) Level Off

The immediate level off to zero V/S functionality was provided via a touch button on the right side of the opened V/S control panel. See Fig.15.

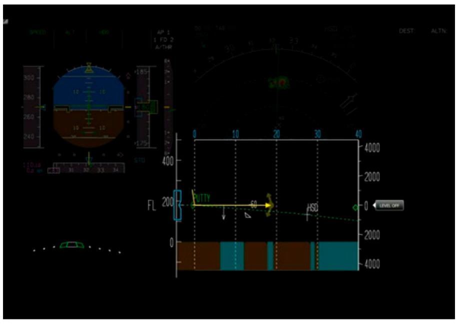

Fig. 14. VSD pop-up

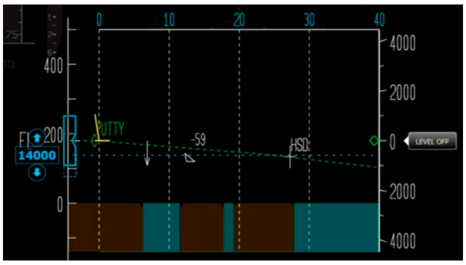

Fig. 15. Setting an altitude

d) Managed and Selected modes

Between the ND and the VSD, three slider buttons are situated. Each button can be in one of two states; managed mode or selected mode. The selected mode is displayed as a cyan button in the right position. In Fig.18 heading is managed (magenta and switched to the left) while altitude and speed are in selected mode. In selected mode the AP is directly followed

B. Short Term Flight Operational support

Based on the first prototype results, two similar touch screen functions were further improved and developed that aimed to support the flight crew in a fast way when time criticality matters most.

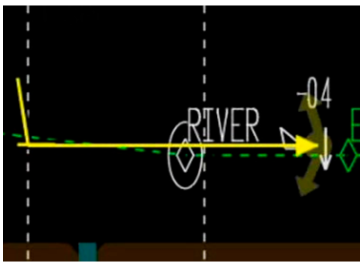

Fig. 16. V/S selection function

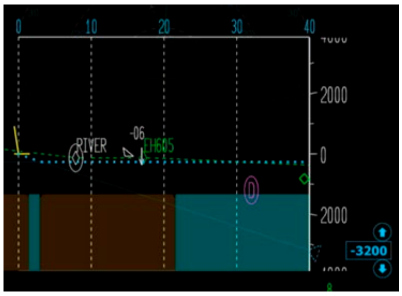

Fig. 17. Setting a particularVertical Speed (V/S).

Fig. 18. Managed heading and selected altitude+speed

1) Late Runway Change (LRC) and Alternate Airport Selection (AAS) support

Before landing, one of the runways might suddenly become unavailable for landing, and the aircraft has to be diverted to another runway by ATC. In present-day operation the pilot has to reprogram the FMS for this new runway, which takes a lot of head down time in a very demanding flight phase. The Late Runway Change (LRC) functionality developed to assist could be found on the side of the MTS, where a selection pane displays a set of selectable runways for the destination (DEST) airport. Fig.8 shows the eight buttons example for EHAM (Schiphol Amsterdam Airport). With the new function the crew can easily accept and select the new proposed runway on the MTS and a temporary flight plan is created, taking into account local ATC constraints. When the new runway is selected, the NAV-aids / ILS radio for that runway is tuned automatically. The buttons indicate which of the runways are all active (coloured white) and when greyed-out the runway is not open. The colour of the runway is green when actually selected. Another developed crew support functionality, was rather similar to the LRC in its HMI, but was devoted to the selection of an Alternate Airport. Similarly to the LRC selection pane, a list with Alternate Airports to choose from is displayed. It was positioned to the right side of the LRC function. Selecting a runway generates a new route, which is calculated from the present position to the selected airport and runway. [11,14] elaborate more on the LRC and AAS support functions' HMI.

C. Altimeter Setting (QNH/STD)

On the MTS a small area underneath the altitude tape, is dedicated to the QNH/STD value presentation. By pressing this

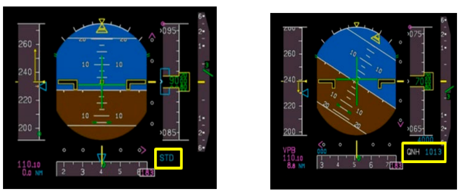

Fig. 19. Altimeter STD/QNH setting

area, STD and QNH are toggled between, see Fig.19. However in the current prototype no other inputs means was set up yet.

Fig. 20. Touch screens installed inside NLR's full flight simulator (GRACE). Also eye-tracker markings are shown.

D. *Experimental design and execution*

The experiment used a repeated-measures design. Baseline formed today's aircraft operations without touch screen functionality. This experiment had four independent variables as indicated in the table I below.

TABLE I Independent variables

Independent Variable (touch screen function)	**Number of Levels**	**Value Of Levels**
TFC novel HMI	2	On/Off [a]
Alternate Airport Selection (AAS)	2	On/Off [a]
Late Runway Change (LRC)	2	On/Off [a]
Turbulence	2	Low/ Severe

[a] Off is implying selections are done via FCU or CDU/FMS

Several research questions and hypothesis were defined and statistically assessed. Ten airline crews participated in the piloted assessment on NLR's GRACE; see Fig.20, flying an A320-alike aircraft model. Dependent measures used were: a) Pilots' ratings of the workload on the NASA TLX scale [12] in the post run questionnaire; b) Pilots' rating of the situational awareness on the Crew Awareness Rating Scale (CARS,[13]); c) Questions in the run questionnaire relating to acceptability of the HMI; d) Questions in the post experiment questionnaire relating to workload, situational awareness and acceptability of the HMI. An experiment matrix was set up. Three different descent and approach scenarios were flown several times with different support functions and settings, but max 10 runs per crew. ATC provided various radar vectors, hence tactical control instructions to allow the crews sufficient exposure to the new TFC function. Two levels of Turbulence were used (L)ow and (S)evere (=high).“Off” implies use of conventional FCU, or conventional CDU/FMS. During one approach also the LRC function was assessed. Generally no landings were made but go arounds, after the go-around also the AAS function was evaluated once per pilot.

V. MAIN RESULTS

A. *MTS-TFC versus FCU*

The impact of the touch input display for making speed, heading and altitude changes was compared to conventional input through the FCU.

1) *Workload, NASA-TLX , blink rate, eye activity and task duration.*

Workload was assessed with unweighted, 7-axes, averaged raw NASA-TLX scores in the post-run questionnaire. Fig.21 shows the mean results and the standard deviation (SD, generally known as the standard error) of the mean (M) per Pilot Flying (PF) and Pilot Monitoring (PM) for the low and high (=severe) turbulence situations and for both the conventional (i.e. FCU) use and the touch screen functionality (ACROSS Tactical Flight Control) use.

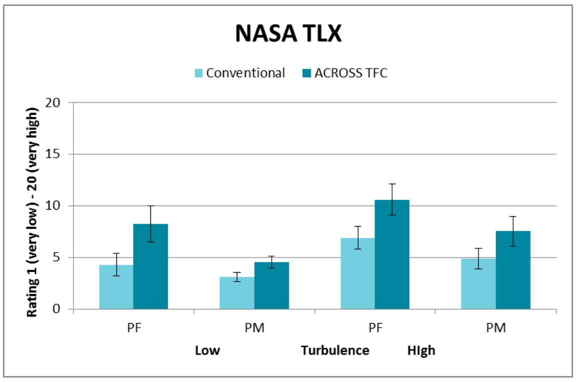

Fig. 21. Post run NASA-TLX ratings by Pilot Flying and Pilot Monitoring, with and without the touch functionality under low and high turbulence, N(PF)=8, N(PM)=7.

The differences in NASA-TLX scores between working with the conventional functionality and the new (ACROSS) TFC touch screen functionality was significant for the PF in low turbulence, and in high turbulence conditions ($t(8) = -2.394$, $p < 0.05$). The perceived workload was higher with the touch screen than without, so in conventional FCU operation. The difference was also significant for the pilot monitoring, but only under low turbulence conditions ($t(7) = -5.466$, $p < 0.01$).

The blink rate (= eye blink per minute) during the complete run was analysed. Fig.22 shows the non-significant mean results and the standard blink rate error per PF and PM for the low and high turbulence situations and for both the conventional (i.e. FCU) use and the touch screen functionality (ACROSS Tactical Flight Control) use. Generally speaking, a higher workload results in a lower blink rate, see [15,16] for more background information on these matters. The eye activity (not presented) of the PM did not differ significantly between conditions.

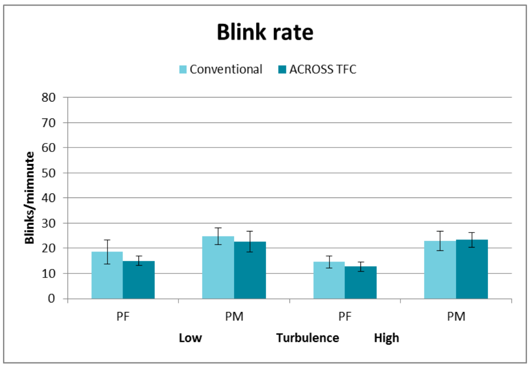

Fig. 22. Blink rate per minute for Pilot Flying and Pilot Monitoring with and without the touch functionality under low and high turbulence conditions, N(PF)=8, N(PM)=7.

Fig.23 shows a highly significant (p<0.00396) result from the main effect Analysis Of Variances (ANOVA)-analysis of the time it took by the crews (actually the PFs) to set new autopilot values based on ATC instructions. The example chosen was the first descent instruction from Flight Level 180 (and Speed 280 KIAS) down to FL140. With the FCU (=TFC being OFF) it clearly took far less (Mean M= 5.05 s) than with the TFC (=ON) (when M= 10.25 s). Also the number of inputs (TFC touches on MTS or input selections on the FCU knobs) was analysed with a main-effect ANOVA, see Fig.24. A slight increased number of input handlings when using the MTS-FTC compared to using the FCU knobs. However the result is statistically non-significant. Also no meaningful effect of turbulence level was found for both the time data and input data.

2) Situation Awareness (SA)

The CARS ratings from the PFs did not differ significantly between the functionalities, see Fig.25, but a trend was found indicating that rating was lower with the TFC touchscreen function compared to the conventional FCU (t(8) = 2.007, p = 0.085). Also the PMs rated the SA with the TFC lower than with the conventional functionality both under low turbulence conditions. In the post-experiment question analysis, PFs tended to disagree on the statement that the TFC touch input display increased SA. PMs neither agreed nor disagreed. This yields a (non-meaningful) lower SA with the touch input display compared to the conventional FCU.

B. LRC versus FMS-CDU

1) Workload,blink rates,task duration and inputs

The main HMI and evaluation results were published in [11].The PMs, who mostly operated the function, rated the NASA-TLX workload lower when the LRC functionality was used. It was found statistically significantly lower with a paired t-test (t(8) = 2.532, p < 0.05. For the PF the difference was not found to be statistically significant, as expected. Also the blink rates were not found significantly different for PFs and PMs. Task duration was found to be statistically significantly (p=0.00084) lower with the LRC function.The time it took with the LRC is also far less (M=7.37s) than with the CDU (LRC=OFF) (when M= 9.21s). The result on the number of pilot inputs made is also highly significant (p=0.00000). 8 interactions with the CDU versus 2.5 with the LRC function.

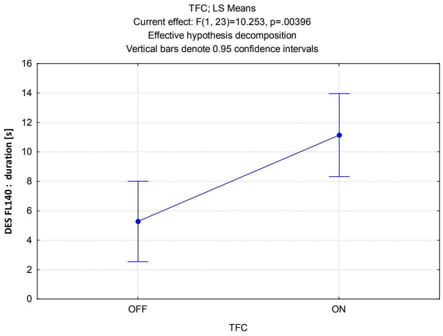

Fig. 23. Time analysis (in seconds) of TFC (=ON) versus FCU (TFC=OFF) use for all 10 crews N(PF=10).

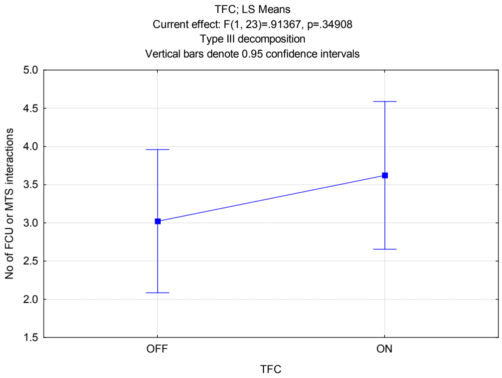

Fig. 24. Analysis of number of input selections for TFC (=ON) versus FCU (TFC=OFF) use for all 10 crews N(PF=10).

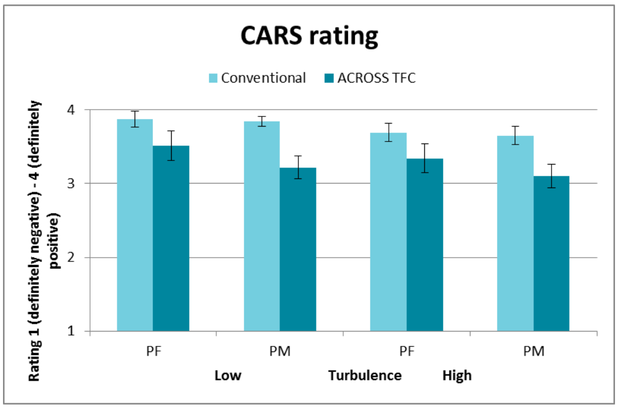

Fig. 25. Analysis of Situation Awareness (CARS-ratings, [13]) comparing FCU - versus TFC use for Pilot Flying and Pilot Monitoring under low and high turbulencee consitions

2) Situation Awareness

PF rated the Situation Awareness (post-run CARS) higher in the condition with the LRC compared to the conventional condition. For the PMs no significant difference was found. However via post-experiment questionnaire results both pilot roles agreed that the LRC increased SA.

C. AAS versus FMS/CDU

1) Workload, NASA-TLX, task duration, and inputs made

No statistically significant results in reduced perceived workload ratings via the NASA-TLX was obtained. In the post-experiment questionnaire however the pilots agreed that the AAS decreased workload (M_pilot flying = 4.8, M_pilot monitoring = 4.5), $t(9) = 9$, $p < 0.01$. A highly significant result ($p=0.00002$) for the main effect ANOVA-analysis was found. With the AAS far less time (M=11.81 s) was needed than with the use of CDU-FMS key strokes M=61.89 s). The main effect ANOVA analysis for the number of inputs made showed statistically highly significant ($p=0.00412$) results, with mean values given by M_AAS=4.2 and M_CDU-FMS = 34.85. The number of AAS inputs is much lower thereby decreasing workload.

2) Situation Awareness

CARS data results remained inconclusive. But both pilot roles agreed in the post experiment questionnaires that the Alternate Airport selection functionality increased the SA. (M_pilot flying = 4.6, M_pilot monitoring = 4.3).

VI. Conclusions and Recommendations

The use of a touch screen in the primary cockpit flight displays was in overall found easy to use and appreciated by the participating pilots.

A. Conclusions related to the specific support functions

- The final prototype of Tactical Flight Control support function, in essence a novel way of interacting with the autopilot modes did not reduce workload nor increase situation awareness in a statistically significant manner, and this worsening effect was aggravated under severe turbulence.
- The Late Runway Change (LRC) and Alternate Airport Selection (AAS) functionalities both decreased workload and situation awareness and were much faster than CDU/FMS operations. There was a pilot role difference.
- The AAS and LRC functions were appreciated a lot by the crews and are the way forward to move from CDU/FMS operations to touch screen operations. More crew-assisting features can be added to the buttons.
- The STD/QNH touch screen toggle switch on the PFD was highly appreciated, but still requires an input device to set proper values.

B. Final remarks for further improvements

Surprisingly the result differences found with the FCU were relatively small. Main causes for this all were identified: the design should allow a faster use of inputting data while not being head down too long, and also the inputting of data under severe turbulence levels should be improved. A more-optimised bessel design around the touch screen could help out to allow more precise value control. Cross-checking options should be further refined by making the two control panel inputs more intelligently slaved to be able to earlier inform the other pilot about the really selected values. With these design updates the results are expected to be improved. This should all be further investigated, as it was not expected that conventional FCU operation in use for more than 40 years would be that easily beaten. LRC and AAS can be extended with additional useful information.

Acknowledgment

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