School of Informatics

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Human Factors in Touchscreen Avionics

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Abstract

While touchscreen devices have gained popularity in consumer electronics, the technology is still in experimental stages in airplane cockpit applications. Cockpit design has seen revolutionary changes over the years, improving efficiency without sacrificing safety. Being a safety-critical field, deploying touchscreens on the flight deck is subject to regulations, but relevant ones may not always exist. As instruments conveys information between the machines and pilots, human factors considerations are at the centre stage of evaluating novel designs, while mixed responds is collected from previous studies.

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1 Introduction

Touchscreen technology has been deployed on personal consumer electronics devices since the mid-2000s'. It has the flexibility that classic keyboard design cannot provide, enabling software-driven development process [1]. It can also save space [2] and reduce mechanical components [1]. However, the trend of touchscreen did not see applications in the flight deck design until recently, in fact mainstream civil aircraft manufactures still use non-touchable screens and mechanical buttons and knobs as their primary input/output devices as of today [3]. It is normal that as a safety-critical application, the aviation industry is typically slow on adopting emerging technologies [2], which need to go through rigid certification processes before it is declared safe and robust for in-flight environments. Though there is no specific regulation for touchscreen avionics [1], there are non-mandatory designing guidelines and advisors concerning general safety of flight displays and software [4]. The DO-178, currently on version C, is a widely-accepted guidance on aviation software safety, served as a bedrock of many national standards [4]. The Federal Aviation Administration (FAA) Advisory Circular (AC) 25-11B specifies in display devices. A detailed comparison of regulations published by different authorities can be found at [5]. As two-pilot crew became standard since the 1980's [6] and will continue to be so in the foreseeable future, human factors will remain to be a central consideration in flight deck design. Several experimental systems aimed to improve pilot's situational awareness and reduce workload, either by redesigning and integrating current control and display units [7], or proposing complementary touchscreen devices to work alongside existing instruments [3] [8]. Evaluation of these devices include quantitative and qualitative parts, and often involve computer simulation and test pilot trials.

The report will start by reviewing the history of flight deck design, to understand how previous new technologies were adopted in cockpit for new applications, with evolving information representation and control logic. The report will then introduce regulations and designing considerations. Cockpit upgrades can be divided into two categories: the first type is to add new devices or functions on top of the original design, while the other method is redesigning the whole system, fundamentally changing the way that the airplane operates. Examples for both methods, concerning touchscreen avionics, will be given. After that, the report will introduce methodologies used to evaluate these designs, and show their respective findings. Finally, the report will include discussions, conclusions and suggest further works.

2 Literature Review

2.1 Evolution of Flight Deck

According to FAA AC 25-1302.1, flight deck designing is critical because the interaction behaviour of the system may affect flight crews' ability to assess situations and take appropriate actions. While touch screens can enable inputs at the displaying location, current airliners have separate devices for input and output. Input functionalities can be further divided into tactical and strategic operations [7], each governed by respective systems.

Flight deck evolution can be divided into three eras: mechanical, electro-mechanical and electro-optical (E-O) [9]. The electronics and touch screen displays that this report concerns belong to the current E-O era. Before the 1980s', flight display instruments mainly consists of electro-mechanical dials [2]. There are six basic flying instruments defined by [10]. Three of them, namely Altimeter, Air Speed Indicator (ASI) and Vertical Speed Indicator (VSI), rely on air

Aircraft Types	Boeing 707	H.S. Trident	DC-9-10	Tu-154B	Boeing 767
Country	United States	United Kingdom	United States	Soviet Union	United States
Year	1959	1964	1965	1967	1982
Captain	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
First Officer	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Flight Engineer	**Yes**	**Yes**		**Yes**	
Navigator	Optional	Optional	Optional	**Yes**	
Radio Operator	Optional	Optional	Optional	**Yes**	
Min. Crew	3	3	2	5	2

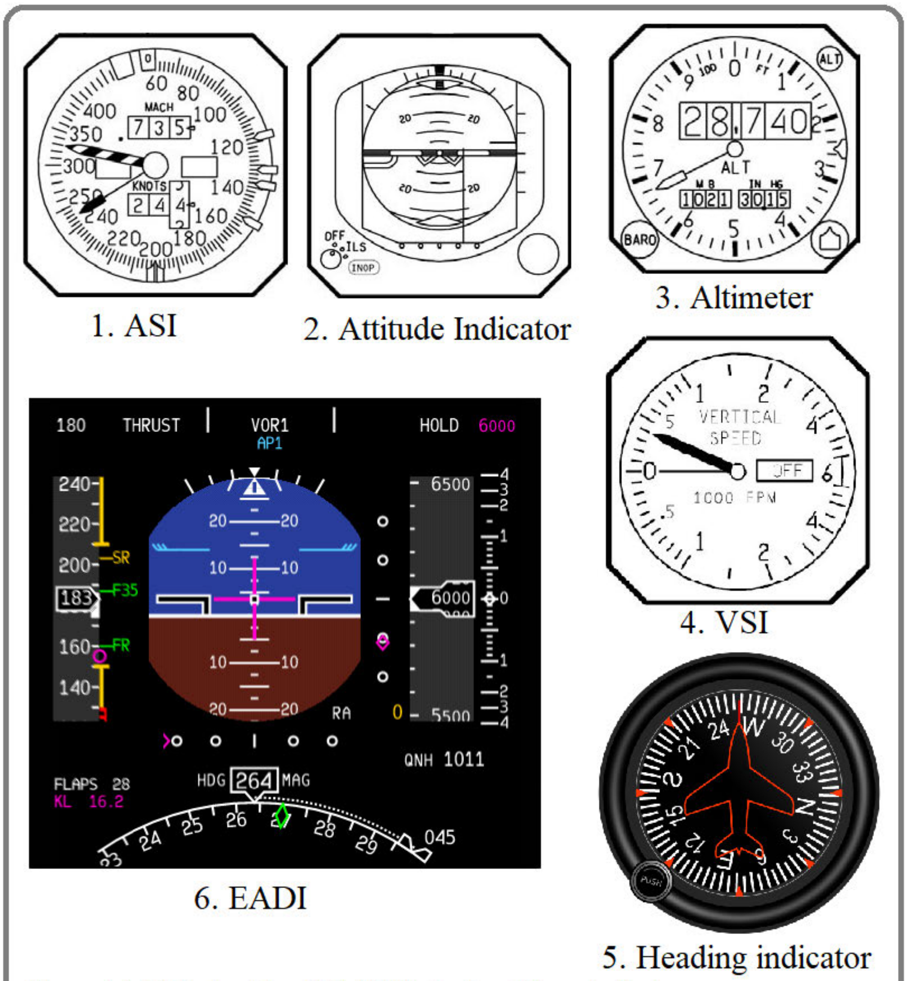
Table 1: Minimum number of crew for a selection of aircrafts

pressure measurements, while Attitude Indicator (Artificial Horizon), turn coordinator and heading indicator are gyroscopic. Principles and applications of the six pack can be found at chapter 8 of FAA's PilotS' Handbook of Aeronautical Knowledge [11]. Due to the popularization of radio navigation systems, Course Deviation Indicator (CDI) and Automatic Direction Finder (ADF) became standard. Details of electromagnetic version of these two instruments is provided at chapter 15 of Aircraft Electricity and Electronics (1994) [12]. As number of instruments continue to grow, panels became complicated and crowed. In some aircraft types, the space of the main panel is used up so other separated panels were designed at alternative locations in cockpits, potentially needing more crew to monitor and operate. Table 1 is a comparison of typical allocation of flight crew of a sample of types (Based on flight deck photographs available at *www.airliners.net*).

In order to de-clutter the instruments and accommodate two-man crew, electronics displays began to replace classic gauges. The two-crew flight decks became a standard with the introduction of Boeing 767 [6], which deployed CRT displays for engine systems. [2] further classified this trend of 'glass cockpit' into two generations, with increasing portion of digital output devices. In the second (current) generation, primary displays (PD) contains two sets of electronic attitude-director indicator (EADI) and electronic horizontal-situation indicator (EHSI) (referred to as Navigation Display (ND) by [7]), one set each for the captain and the first officer [12]. Figure 1 shows a sample EADI and its mechanical counterparts, and Figure 2 is the equivalents of EHSI.

Inputs on flight decks can be classified into two categories: tactical controls and strategic controls [7]. As displays are not yet touch screen, buttons and knobs for inputs are located at different locations with the screens. The flight control unit (FCU), which is located on the top of the main panel in front of both pilots, provide tactical flight control functions which put direct commands to the aircraft [7]. Amid the changes in display devices, the FCU design remained largely unchanged since the mechanical era [2]. The strategic functions are provided by the Flight Management System (FMS), which communicate with pilots through keyboard and screen on the Multi-Function Control and Display Unit (MCDU). This is a overall management over the entire flight [7]. The FMS and FCU are partially independent, with some coupled functionalities [12]. An introduction of history and structure of FMS is provided by [13].

There are two ways of upgrading a flight deck design, which are retrofit and a total redesign. [3] mentioned that the total redesign method is only suitable for new aircraft types, while retrofit is a practical solution to add new technologies to older models. As of the current development of touch screen avionics, both methods received academic attention. [3] and [8] proposed devices to work in parallel with existing controls and displays, while [7] aimed to use touchscreen to



* image 1-4: M. Tooley, Aircraft Digital Electronic and Computer Systems.
** image 5: https://en.wikipedia.org/wiki/File:Heading_indicator.svg.
*** image 6: taken from PMDG MD-11, a Boeing licenced product, on platform: Microsoft Flight Simulator 2004.

Figure 1: EADI and equivalent dials

replace vital devices and fundamentally changing the way of operations.

2.2 Regulations and Considerations

There are several international or national standards relating to cockpit display design. One of the widely recognized general standards is the DO-178 published by the Radio Technical Commission for Aeronautics (RTCA). Based on it, [4] summarized a high-level software designing process to ensure safety using a top-down manner. The DO-178 is not compulsory but an acceptable mean of compliance to the FAA ACs while alternative means are still being sought after [4]. Four other regulations were reviewed in [5], where fifteen criteria is set up to evaluate these standards. Though focus may be different for each standard, the paper concluded that no one is superior than others.

There are currently no regulations specifically designed for touchscreen displays, but FAA

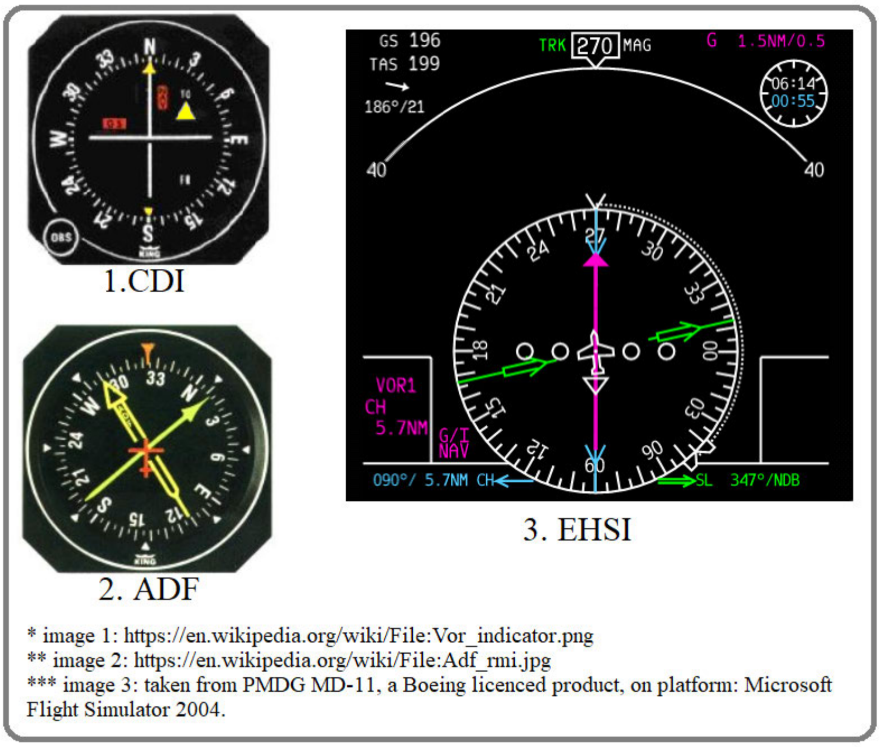


Figure 2: EHSI and equivalent dials

AC 25-11B lists requirements for a broader category of electronic flight displays. As 25-11B pointed out, in the field of human factors, the main goal is to reduce: 1.Flightcrew workload, 2.Flightcrew training time, and 3.The potential for flightcrew error (section 2.3). In addition, [9] considers situational awareness (SA), of both current and future events, as most important.

To achieve these goals, a fundamental consideration is to maintain consistency, as stated in section 5.3 of AC 25-11B, either between older and newer models, and also between displays across the same cockpit, the position and arrangement of display, font size, colour, symbols and logic should remain consistent. New designs of primary displays (PD) should accord with section 6.2.3 concerns the presentation of the 'basic T information', including ASI, Attitude Indicator, Altimeter and heading indicator. Taking MD-11's EADI as an example (Figure 1), 25-11B required that Attitude Indicator is placed at the centre, with airspeed indicators to the left and altitude indicators to the right. Direction of the flight must be displayed directly below the Attitude Indicator. We can see that MD-11's EADI complies with all the requirements above. The 6.2.3 section also required that the PD to be installed directly ahead of pilots. For conventional non-touchscreen displays this should not cause major difficulties, but touchscreen input operations may be blocked by the control column, which is also directly in front. This is the case for most Boeing aircrafts, while Airbus ones typically have side sticks that would not have the same problem. Anthropometrics is also relevant to the position of the displays, but is out of scope of this paper. A detailed review on that can be found at [14].

Still concerning consistency, another major consideration is colour-coding and symbology. Predefined colours can help pilots recognize important information in a compact display panel, and symbols which are familiar to target users can further accelerate the process [8]. While proposing an touchscreen navigation device, [8] used symbols similar to aviation charts to ensure consistency and clear information conveying. A standard colour coding is provided in the appendix of FAA Technical Standard Order (TSO) C113a. In [1], button symbols specifically designed for touchscreen to mimic physical buttons are presented. To display numerical information, three basic format is mentioned in [9]: digital counter, moving pointer and moving index. The later two can be implemented by either dials or tapes. [9] also list situations where each type should be chosen.

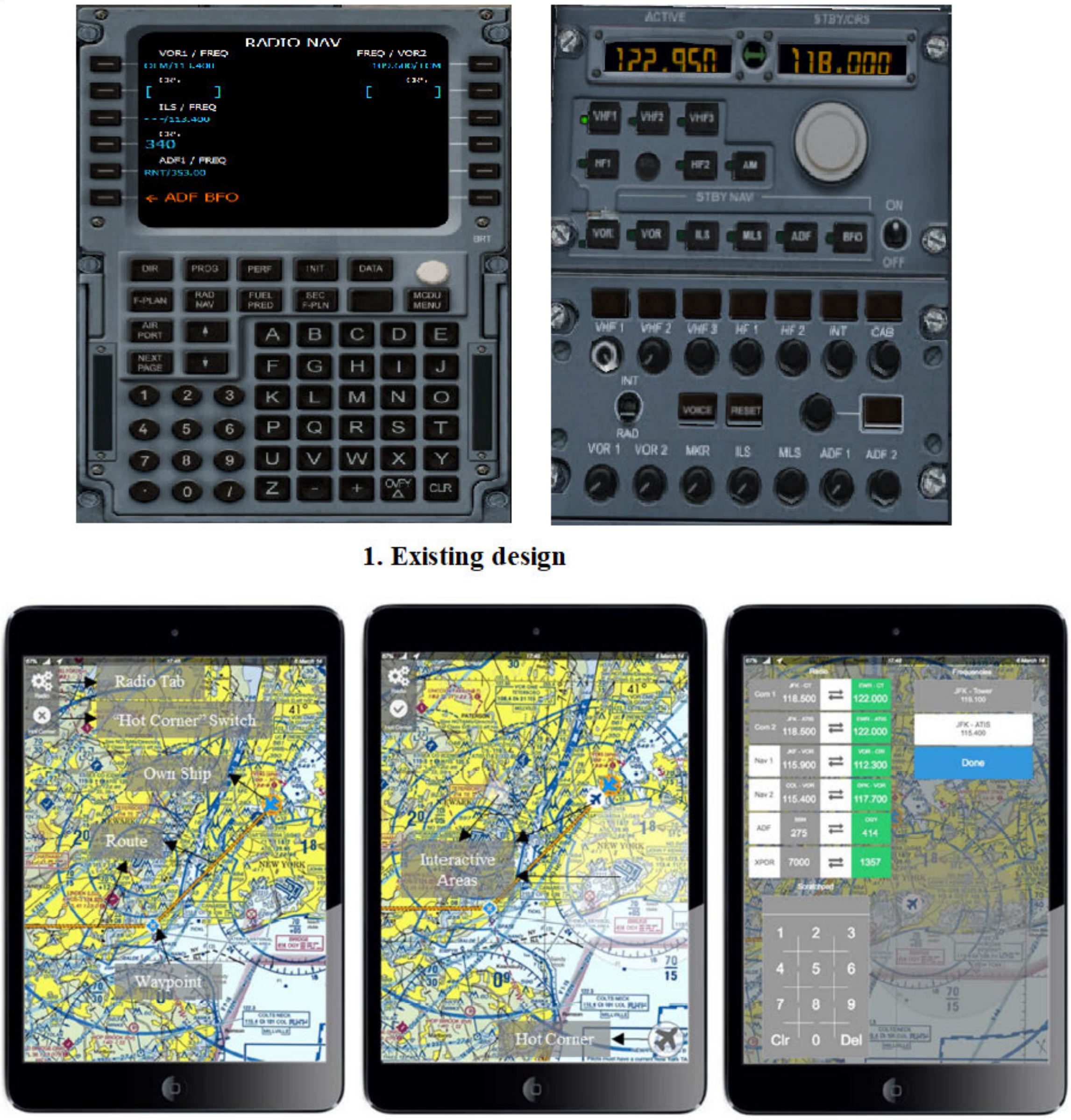
Another area of consideration is the size of display. AC 25-11B states that displays should be large and clear enough to provide viable information to the flightcrew in every scenario. While 25-11B did not provide definite numbers, individual researchers justified their size design based on specific applications, products available and users' feedback [3][8]. Linking sizes and the main goals mentioned above, [15] comprehensively showed the impact of touch target size and spacing on flightcrew errors and workload. The study proposed two button sizes (0.25" and 0.5") and three spacing sizes (0.03", 0.065" and 0.10") for touchscreen keyboard input, six combinations in total. The study also takes turbulence as a main affecting factor. The study found out that large target size can significantly ($p=0.02$) reduce errors with or without turbulence. For smaller target size (0.25"), errors are more negatively correlated with spacing size, and error rate is higher than larger target size's (0.5") in each spacing size. The workload data show similar pattern, where large target and spacing always outperform their smaller counterparts. The study concludes that larger target and spacing size improves pilots' performance, and is rated higher by the user. [16] also identifies increasing displaying size to be the best solution against vibrations. We should notice that [15] is in a theoretical setting, without considering actually display hardware available or space constrains in the real cockpit.

An aviation device that already deploys touchscreen is the Electronic Flight Bag (EFB). This is a replacement of paper checklists and charts, to save weight, paper and time [17]. The EFB is not a part of standard flight instruments, and this report will not go into details. Some human factor related desiging considerations of EFB can be found at [17].

2.3 Examples of Touchscreen Designs

[8] proposed an hand-held device to display map and manipulate radio communication frequencies. Traditionally, maps are printed on paper, until EFB was made available. Radio stacks, or radio panel, handles radio communication frequency inputs. On some newer types, this is integrated in to the FMS and controlled by the MCDU. Some aircrafts, for examples the A320 series, have the radio functionalities on the MCDU while using mechanical panel as a back-up. Figure 3 is an comparison of the existing design and the new touchscreen design proposed by [8]. On the left of image 1 is the radio page of the MCDU, while on the right shows the old fashion radio panel. Both forms in image 1 use physical buttons as input. Below in image 2, the proposed design enables pilots to directly touch the navigation or airport icons on the interactive map, whose radio frequencies are already stored in the database. Frequencies can then be transferred into related systems, completing the same functionality of the old design. One part of [3] also concerns interacting with map and navigation display. The 2015 study focused more on strategic controls over flight routes, while combining weather information. Other parts of designs in [3] replicated more MCDU's functionality, including performance and systems pages with essentially the same layout and logic with MCDU's, albeit in a touch screen format.

Much research has been devoted to the primary display and tactical control. [3] proposed an complementary device that work alongside existing instruments, which combines the input and output functions of PD and FCU respectively. Users can make inputs on it to instruct the autopilot to change speed, altitude and heading by directly tapping on the readings tapes. It can also change the mode in which the autopilot is operating. The study also made an



* image 1: taken from FeelThere Airbus 320, on platform: Microsoft Flight Simulator 2004.
** image 2: H. Avsar, J. E. Fischer, and T. Rodden. Designing touch screen user interfaces for future flightdeck operations. In 2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC), pages1–9, 2016.

Figure 3: old and new design of radio manipulation

Left: J. Gauci, N. Cauchi, K. Theuma, D. Zammit-Mangion, and A. Muscat. Design and evaluation of atouch screen concept for pilot interaction with avionic systems. In2015 IEEE/AIAA 34th DigitalAvionics Systems Conference (DASC), pages 3C2–1–3C2–19, 2015.

Right: W. Rouwhorst, R. Verhoeven, M. Suijkerbuijk, T. Bos, A. Maij, M. Vermaat, and R. Arents. Useof touch screen display applications for aircraft flight control. In2017 IEEE/AIAA 36th DigitalAvionics Systems Conference (DASC), pages 1–10, 2017.

Figure 4: two designs of touchscreen PD

upgrade version which visually more closely resembles the PD of the A320 series. [7] took a step further, and aimed to replace the original PD and FCU completely. Apart from providing complete tactical control, the 2017 study had a specific focus on two scenarios: Alternate Airport Selection (AAS) and Late Runway Change (LRC). Figure 4 shows the scheme of the above two designs.

[1] provided an commercial project redesigning the cockpit of type of business jet. The new design added four touchscreen controllers (TSC), and also replaced overhead panel with touchscreens. However in this design, PD and FCU remained unchanged, using conventional screens, buttons and knobs. Another product ready for consumers is Appareo's Stratus Insight [18]. Though an EFB-oriented software design, the Stratus Insight also integrated PD, radio communication and weather information, running on a range of consumers' electronics.

2.4 Evaluation and Results

Human factors evaluation focusing on tasks and duties of crew has the same importance with equipment-based technical evaluations [19]. [19] recognizes customer acceptance as a essential evaluation topic, but it can be subjective due to variable user groups. More formally, [19] listed the following evaluation methods: qualitative, objective and computer-based modelling. These methods are all mentioned in AC 25-11B as means of compliance (section 8.2) along with other methods for non-human-factor issues. AC 25-11B also states that the more novel the design is, the more detailed and structured methods should be used. Hazards that may occur is classified

Hazard Classification	**Probability of Occurrence**
Catastrophic	Extremely Improbable
Hazardous	Extremely Remote
Major	Remote
Minor	Probable
No Effect	-

Table 2: Hazard classification and safety objectives

into five grades, requiring different target probability [5]. Table 2 is a list of the five categories based on [5] and 25-11B.

Computer simulation is common in the mentioned projects above. [3] ran the designed software on a tablet computer, the coupled it to a X-Plane simulator running on a desktop, which provided a virtual cockpit environment. By putting the new device and the desktop on a regular table, this setup can simulate the basic working scheme of the system, but is not an accurate reconstruction of the cockpit, leaving out influences of turbulence, support points and space constrains for hand holding the device. A full flight simulator was used in [7], providing test pilots a realistic working environment. In both studies, testing scenarios were preset into the simulation system, requiring test pilots to perform certain tasks.

Running the simulation on an iPad, [8] designed three tasks that requires inputs to change radio frequencies. Two other input devices are used as comparison: the FMS and keyboard. Participants were divided into three groups, and were requested to perform the tasks in a prearranged order, using one input device at a time. This study just collected a simple positive/negative response from the participants, which turned out positive overall. Participants of this kind of subjective evaluation should be carefully picked, as [19] found out that bias of subgroups of users can affect the results significantly, quoting a 1997 study into a novel PD presentation. The qualitative method is also used in [3]. Data was obtained by direct observing, video recording and questionnaires. The test pilots provided feedback for each of the proposed displaying pages. A throughout table of strengths and weakness for each system is provided.

Objective and quantitative approaches were adopted by [7]. For the tasks designed, the time required to complete the task and pilots' blink rate was noted, which is thought to be related to workload. Another type of eye data is point of gaze measurements, where heavier workload and stress will lead to longer eye fixation time [19]. [19] also mentioned heart rate as a measurable parameter for task involvement, anxiety and stress. [7] found that although the new touchscreen design reduced the time required for AAS and LRC generally, the result was not statistically significant. Time required actually increased on the task of changing flight level, with a significance of $p<0.00396$. Crew workload was measured by the NASA Task-Load-Index (TLX) scales. The NASA TLX score is a weighed average of six aspects, which are scored by the participants [20]. The author of [7] scaled the scores to 0-20, with larger score indicating higher workload. The result was overwhelmingly negative, both for pilot flying (PF) ($p<0.05$) and pilot monitoring (PM) ($p<0.01$), both showing preferences to the original design. CARS rating was used to analyse situational awareness. CARS has eight scales, two each in the field of perception, comprehension, projection and integration [21]. Both PF and PM showed an insignificant downgrade of CARS score using the new touchscreen design [7]. Generally, [7] did not achieve improvements in workload and situational awareness by deploying touchscreen devices as PD and FCU.

3 Conclusion and further work

The cockpit design has underwent several revolutionary changes since the basic instruments were defined in 1937. As touchscreen technology became more popular in the consumer electronics field, researchers and manufactures developed and tested several novel designs deploying touchscreens, aimed to assist or replace existing display and control systems in the cockpit. Qualitative and quantitative methods were used for evaluation, by computer-based simulations. As a human-involved working environment, the evaluation can be subjective, and results vary between user subgroups [19]. While some collected positive feedback of the new touch-screen design [8], it is also found that co-location of input and output does not always reduce workload and increase situational awareness [7]. Some commercially ready software [18] and complete cockpit designs [1] are already available, but it is still left to be seen whether they can gain approval of the market and users.

In fact, touchscreen is not the only way forward. Trackball, touch screen and speech recognition were all identified as candidates in an 1990 study, which concluded that touchscreen was the most effective [22]. After all, [7] concluded that classic PD and FCU still have certain advantages.

In previous studies and designs, possible hazards are rarely evaluated. Further works should systematically identify hazards induced by device malfunction or pilot errors, and highlight any new hazards under the new touchscreen environment. Hazards shall be rated by any internationally accepted scales listed in [5], then provide probability estimations.

As AC 25-11B implies, crew training should be a important consideration. Current studies typically only provides very basic description sessions, and very short familiar period before simulated flight-test. This is understandable as researchers have limited time frame and budget. However, while pilots are not familiar with the new technology, they tend to make more mistakes [7], resulting in higher workload and stress level. To conduct a fairer comparison, longer periods of training should be provided to participants, to match their knowledge and experience of the classic system. After more formal training, the experience factor can be controlled, thus providing more credible comparing results.

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