Exploring the Physical Design Space for Situation Awareness and Performance in the Interactive Cockpit

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Abstract
We explore the design space for interactive instruments in the cockpit of the future. Touch technologies are going to replace current electronic displays for flying and navigating instruments. For safety and performance reasons, interactive instruments should however maximize the perception, action and collaboration spaces of the pilots, and the literature highlights the limits of touch interaction as for these aspects. Our objective is thus to explore how the physicality of interactive technologies could address this issue. Based on a set of elicited requirements for interactive instruments in the cockpit, we explore the literature on tactile, haptic, tangible, gesture-based, organic and smart material-based interaction along a multi-dimensional design space, based on shape, perception and programmability.

Author Keywords
Haptics; Tangible interaction; Transformable Surfaces; Gesture-based interaction; Organic User Interfaces; Smart Material Interfaces.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous. Human Factors; Design.

Figure 1. a) Navigation and flight displays in the cockpit of a TB20; b) buttons of the EFIS (Electronic Flight System) control panel that control the display mode of the navigation display (ND) (2nd from the left).

Figure 2 : Avionic 2020 tactile screens.

Introduction

In the past century, aircraft cockpits have heavily relied on dials, knobs and switches to provide all the flight information and retrieve the pilot input. LCDs panels have nevertheless been integrated all over the flight deck in the latest decades, making the move from the analogue to the so-called glass cockpit. Real dials are indeed replaced by digital, flexible and reconfigurable displays (Figure 1.a), which are currently not touch capable, as input is generally provided through various physical buttons. For instance, Figure 1.b highlights buttons of the Electronic Flight Instrument System panel for selecting navigation display modes. Today, as different aircraft systems have been aggregated at the data level, ongoing research tries to push this concept further and explores relying solely on large, seamless multi-touch displays, both to provide the flight information and to retrieve the pilot actions. ODICIS or Avionic 2020 (Figure 2) explore large, unique or connected continuous surfaces that will provide more synthetic and interactive views of flight and navigation data to pilots.

Although such options bear obvious advantages such as a dynamically reconfigurable cockpit, getting rid of the physical knobs and switches, it is not without introducing strong drawbacks such as the lack of references or physical feedback. Touch-based interaction 1) provides limited feedback to the user [17], either regarding the direct feedback of the command or more general feedback from the system and 2) provides a narrower action space in terms of graspability [5], bimanuality, 3D manipulations and more generally digital objects manipulation [26]. In this paper, we explore how advanced interaction techniques, such as multi-touch, haptic, tangible, gesture-based, organic or smart material-based interaction, by overcoming the limitations of touch-based technologies, could better support pilot flying and navigation activity. To structure this exploration, 1) we elaborate explicit requirements for interactive instruments in the cockpit, from which 2) we draw a set of candidate dimensions for a design space.

Requirements

The relevant requirements for interactive flying and navigation tools are being iteratively elaborated through previous work (e.g. [30]), user studies (2 contextual interviews, 2 workshops) with pilots and instructors. They belong to three categories: 1) cognitive and collaborative concerns, 2) safety, and 3) industrial constraints.

Cognitive and Collaborative Requirements

R.C.1. *Direct localization perception*. Even for experts, as told by a pilot we interviewed, flying feels like being in a "non-usual" universe: you are in the middle of the sky, without any landmark, so you do not immediately know "where you are". For this purpose, pilots need devices providing few and directly available parameters (altitude, speed, heading, artificial horizon).

R.C.2. *Situation awareness*. Pilots need to be able to both get information related to the context of the flight (e.g. closest air traffic) and to predict the state of the system with respect to e.g. autopilot, in order to avoid cognitive conflicts and anticipate actions [4].

R.C.3. *Collaborative awareness*: Major procedures must be collaboratively performed and each individual pilot action needs to be shareable and visible to the other.

R.C.4. *Operational Performance*. Devices and interactors should show a high degree of usability, for instance to enable the selection of discrete values (e.g. button with notches, Figure 3.top) while not requiring too much focus; these devices should provide perceptible feedback (e.g. force feedback of the gas throttle) or on the opposite prevent non reversible action (e.g. guarded buttons, Figure 3.bottom).

Figure 3 : (top) Airbus FCU physical buttons (Flight Control Unit); (bottom) overhead panel: guarded buttons.

R.C.5. *Degraded context*. In the cockpit, both environmental and cognitive factors can dramatically degrade the performance of human operators. For example, extreme lighting conditions, vibrations or degraded flying conditions (weather, aircraft failure), but also cognitive overload (fatigue, stress, time pressure), might greatly downgrade efficiency. This requires to include adapted interactive solutions, i.e. efficient in degraded contexts, from the start of the design process.

Safety Requirements

R.S.1. *Safety-Critical System*. The certification process imposes to comply specific standards, requirements or processes such as RTCA DO-178B on safety of software used in airborne systems [22], and to use formal methods to describe advanced interactions in the cockpit [8].

R.S.2. *Resilience*. The robustness of interactive systems is required in relation to various potential breakdowns or vulnerabilities regarding power, light, visibility (smoke), noise, etc. Techniques and modalities used (e.g. for alarms) must support critical context and enable alternative modes.

R.S.3. *Availability*. Redefining the cockpit interactive components forces us to re-examine availability and accessibility issues. For instance, interface elements must be dynamically adapted to the phase of the flight. Mobile, or detachable objects raise a challenge both as potential dangerous projectiles and as unreachable elements.

Industrial Requirements

This last category encompasses practical requirements related to industrial and commercial constraints.

R.I.1. *Dynamicity and adaptability*. Interactive components should dynamically adapt to numeric information flow (hence the progressive introduction of software components).

R.I.2. *Development*. Display and flight components should be less expensive to design, develop and certify.

R.I.3. *Configurability*. To reduce costs, suppliers promote the design of new product lines adaptable to different aircraft programs. Industrials thus seek technologies that are flexible enough to enable inexpensive components reuse and reconfiguration.

Design space

Our aim is to explore the tangible and embodied – the “physical” - design space as structured according to our requirements. From these requirements, a set of design principles might be drawn, that we try here to map to the properties of specific dimensions in this design space.

First, several requirements related to easy access (R.C.1, R.S.3) graspability (R.C.4, R.S.2) and eyes-free interaction (R.C.5, R.S.2, R.S.3), advocates for a dimension on form [11] and device shape. Second, interaction techniques based on embodied perception and action, in particular TPK-based perception (tactile, proprioceptive and kinesthetic), meet requirements related to performance (R.C.1, R.C.4), awareness (R.C.2) and degraded context (R.C.5, R.S.2). Third, programmability, even for physical objects, follows current development toward providing more dynamic software-based contextual information (R.I.1, R.C.2), where cost-effective (R.I.2) interface components show a high degree of configurability (R.I.3) and adaptability (R.S.3). So, the three candidate dimensions that emerge from our requirements would be: shape, embodied perception and action, and programmability (see the summarizing table provided as supplemental material).

Figure 4 : Mitsubitshu Emirai cockpit concept

Device Shape Properties

Although perception is already properly addressed by numeric technologies (e.g. visual perception), sticking with a flat input surface implies missing TPK properties supporting critical information available in former analog systems through eyes-free interaction and graspability (R.C.4, R.S.2). Shapes are also relevant for collaborative and contextual awareness [11] (R.C.2, R.C.3), as during the access of distant system: pilots are able to perceive a changed position for a salient device more easily than a change on a distant display area. Non-flat shapes have thus been explored, with a focus on either input or output.

Input

Cubtile [20] is a cubic input device that enables to manipulate 3D models. It strongly relies on multitouch and bimanual gestures to close the gap between digital manipulation and its physical counterpart. Touché [23] enables tactile input on any object, including for instance the knob of a door. Shape transformation can be used as input as in Gummi [24]. Tangible User Interfaces (TUI) [27], use physical objects to interact with digital systems. However, R.S.3 challenges tangible devices as mobile and potentially dangerous projectiles. Even vertical and adhesive devices such as [14] or [10] is difficult to certify.

Output

Tilt Displays [1] are display surfaces with multi-axis tilting and actuation, providing various shapes according to the context. The *Emirai* cockpit concept of Mitsubishu (Figure 4) provides both non-flat graspable input capabilities through a curved interactive surface and dynamic output through physical non-flat buttons.

Embodied perception and action

Interaction may benefit from a better use of perceptive channels by either being able to rely on non-visual information in case of degraded visibility or extreme lighting conditions (R.C.5, R.S.2), or for performance (R.C.4) and directness (R.C.1), in order to be able to use multimodal information. Fusion of this information is a major factor to obtain an improvement of the perceptive precision [6][25] and of the motor control [18][21].

Artificial Haptics Stimulation

Haptic stimulations may respectively be achieved through different devices. The force-feedback and the tactile devices address respectively kinesthetic and tactile perceptions. Reverse electrovibration [2] provides haptic feedback on any object. Perceptions are overall differentiated by frequency and force capabilities. Today, one of the challenges associated to these artificial stimulations is to integrate this duality in a single efficient device. This association should ensure a high dexterity to users by using all capabilities of hands [32].

Tangible Interaction

Tangible interaction principles [5][11], which rest in the reuse of physical space and objects for interaction, fully apply for the design of the interactive cockpit, as shown in [16]. Analyses such as [13] explain why tangible interaction results in better performance (R.C.4) and [11] describes that properties such as non-fragmented visibility and performative actions would be particularly suited for the cooperation between pilots (R.C.3).

Semiotic Gestures

Interaction metaphors on touchscreen are generally inspired by physical manipulations. Actually combining these solutions with semiotic gestures could be relevant for awareness (R.C.3) (R.C.4) by interacting without obstructing the view of the other pilot. Gestures may also be used to provide embodied proprioceptive perception: based on [28], we conducted a preliminary exploration for multi-fingers interaction on a tactile surface to implement guarded or complex actions for the Primary Flight Display (PFD) and Navigation Display (ND) (R.C.4).

Imaginary Interfaces

Palm-based interfaces, as demonstrated in [7], combine finger tips and palm perception to achieve efficient interactions such as selection (R.C.1, R.C.4), even in blind or poor light condition (R.C.5). Furthermore, they are accessible and non-detachable (R.S.3).

Virtual and Physical Programmability

Software–based components bring industrial benefits related to cost (R.I.2, R.I.3) and provide both rich contextual information and feedback (R.C.2). For instance, SV-PFD display is a synthetic geographical 3D view that merges aircraft and navigation data to reduce perceptual distance (R.C.1). Advanced technologies now let hardware elements show the same degree of contextual dynamicity.

Organic User interfaces

Organic User Interfaces [26][19] is an emerging paradigm where the feedback of an interaction is extended to the physical device. Actuated surfaces can dynamically change their output shape such as in Pneumatic Displays [9].

Smart Material Interfaces (SMI)

Smart Material Interfaces (SMI) [31] take advantage of recent generations of engineered materials that have capabilities of altering physical properties such as shape, texture and colour. SMI explore how to use material properties as programmable features for enhancing interaction. As opposed to tangible interfaces, where coherence might be an issue, especially for (R.C.5), they exhibit a coherent information space [15]. SMI can for instance change their shape as in SpeakCup [32] or Sprout I/O [3].

Conclusion

In this paper, we co-articulate explicit requirements and physical properties of a large set of interactive technologies along three axes that, according to us, best describe the features that we need. From this design space, our aim is to iteratively both design a real prototype for the interactive cockpit – hence I.S. (R.S.1) and industrial constraints (R.I.*) – and refine our requirements. We will start with the participatory design of demonstrators that explore and combine described features in order to produce new interaction techniques, and as a mean to better understand pilot needs. For instance, combining smart materials with gesture- or body-based interaction, or combining shape transformation with haptics, could bring interesting insights for evaluating their potential complementarity.

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