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Exploring a touch-based flight control panel for pilots using tangible design principles

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Abstract

Touch technologies tend to replace the existing pilot-system interfaces in airliner cockpits. The use of touch screens offers many advantages for pilots and manufacturers. However it also presents major potential risks for air safety. In this paper, we explore the design space of future touch-based flight control panels for aircraft pilots. We attempt to design gestures that are more physical and robust in unstable conditions and require less visual focus, based on directional gestures and layouts that leverage spatial and proprioceptive skills. We observed the use of the control panel during a real flight in turbulent conditions. This let us explore the limits of touch-based interaction techniques in degraded contexts of use and to explore how tangible properties found in tangible and embodied interaction could help design these gestures. This also let us better understand the blurred frontier between touch-based and tangible interaction, and to reflect on interaction design principles in degraded contexts through the iterative building of an explicit design space.

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Keywords: Touch-based interaction; gesture-based interaction; tangible interaction; tangible interaction design methods; tangible frameworks; degraded contexts; aeronautics

1. Introduction

In the « life-critical » context [Boy (2012)] of airliner cockpits, the trend is to replace the current pilot-system interfaces that combine screens and physical controllers with large touch surfaces. The challenge for industry is to respond to the growing complexity of systems with greater flexibility and lower costs. This change is imposed by new

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concepts and tools of air traffic management (ATM), involving extensive air-ground data processing and dynamic flight contexts. Touchscreens also allow efficient interactions for pilots, thanks to the direct manipulation of objects, interface plasticity or context adaptability. Although this change offers many benefits to both pilots and manufacturers, the use of touchscreens has drawbacks that might severely limit their operational use in aeronautics and thus present major potential risks to air safety. While safety and performance require interactive systems that maximize perception, action and collaboration for pilots, the literature highlights the limits of touch-based interaction regarding these aspects [Alapetite et al. (2012), Hamon et al. (2014)]. This is especially true for degraded use contexts in flight (e.g. smoke inside the cockpit, turbulence, stress or cognitive load) [Hourlier et al. (2015)].

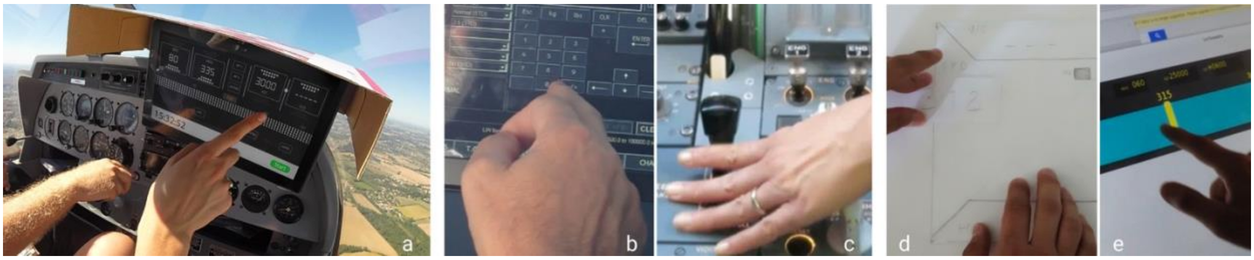

Fig. 1. a) The touch-based flight control panel prototype tested during a real flight (DR400) in unstable weather conditions ; b) an A320 pilot using a touch-based screen for a mission management task ; c) stabilizing the fingers before an action (flaps in an A320 cockpit) ; d) paper-based prototyping with a pilot ; e) walkthrough of the first implementation with a pilot.

Overcoming these limitations is an interesting issue for Human-Computer Interaction (HCI). For example, using a mixed approach based on touch screens and physical objects may better take into account the sensory motor skills of pilots and allow for more effective collaboration, thereby overcoming the disadvantages of touch interactions in safety-critical systems. Tangible, Embedded and Embodied Interaction (TEI) frameworks and themes [Mazalek and Van den hoven (2009), Hornecker et al. (2006)] are a promising way to address these questions and can provide useful directions [Vinot et al. (2016)] for designing cockpits. However, there are hurdles to overcome before applying TEI frameworks to cockpits. First, tangibility, despite its interest and relevance, cannot be considered in isolation from other desired qualities, such as performance, mutual awareness, directness, but also flexibility, genericity or configurability. It is not even a customer requirement, and designers must be able to legitimate its use by the desired general properties. Next, previous studies focusing on the physical dimensions of pilots' activity [Letondal et al. (2018)] challenge some of the classical TEI themes and design concepts: they foster rich and expressive representations [Hornecker et al. (2006)], while pilots prefer abstract, objective and minimal representations; they favor the use of everyday physical objects to interact with digital systems, but physical objects are potentially dangerous projectiles for the cockpit in case of instability. As described by Letondal et al. (2018), a specific status of sensations and body, the complex structure of the pilots' physical space and the level of awareness and control they need on the systems warn against the direct application of tangible principles.

In this paper, using a tangible design framework [Vinot et al. (2016)], we explore the design of a touch-based control panel for the cockpit, the FCU (Flight Control Unit), reflecting on the continuum between extremes such as touch interfaces and physical controls to analyze their boundaries with other paradigms. The reason why we choose to redesign this instrument is mainly that the existing touch-based solutions for the cockpit exclude this device as it is considered a "sensitive matter" for tactilisation. This exploration does not aim to produce a certified operational device, nor a new interaction technique that we would evaluate or compare to existing techniques as in Rümelin and Butz (2013). Our objective, through design work, effective implementation and observations of use, is twofold: 1) we explore whether applying tangible principles may help in the design of a touch-based control panel and 2) we seek to build a consolidated design space for future airliner cockpits that is able to take into account relevant design properties, whatever the technology they originate from.

The paper is organized as follows. After reviewing the state of the art and describing the design framework that we used, we provide some context, describe the methods we used in our study and provide a few explanations on the cockpit activity. Then we present the principles we applied to design the touch-based control unit for pilots, followed by a description of the UI design and the prototype. We had the opportunity to observe the use of the prototype in partially realistic conditions, which enabled us to refine our design hypotheses further. Based on this exploratory design, we finally discuss research questions related to both tactile and tangible design.

2. Related Work

This work relates to research exploring the frontiers between tangible and touch-based systems. Several studies balance physical versus digital interactions such Alapetite et al. (2012) that compares the performances of a touch-based and a physical control display unit in cockpits. Other studies describe the limitations of non-tangible systems in terms of identified tangible properties, such as Voelker et al. (2015) that argues that virtual knobs may be 20% slower than physical ones. Exploring the frontiers between tangible and touch-based systems may also attempt at combining physical and digital interaction such as HaptiCase [Corsten et al. (2015)] that combines touch and tangible interaction using the shape of a device to complement touch-based interactions through physicality (e.g using edges, back, etc.) [Grisvard et al. (2014)], Lagrasta (2017) that reflects on multimodality in future helicopters, or Kirk et al. (2009) that combines tangible user interfaces and touch-based interaction in various dimensions. Another direction is to add physicality to the surface itself, for instance through the addition of physical guides, such as Cockburn et al. (2017) with the addition of a physical guiding layer on a touch screen in an airplane cockpit in a turbulent situation, or more generally using shape changing interfaces [Rasmussen et al. (2012)].

Closer to our approach are studies that aim to design multitouch interactions with performance, safety and degraded contexts in mind. For instance Hamon et al. (2014) design multitouch interactions for safety-critical systems. Studies on designing touch-based interaction for blind users [Guerreiro et al. (2008), Kane et al. (2011), Yfantidis and Evreinov (2006)] also attempt to add physicality to touch-based gestures. Our paper is also close to work that pushes touch-only interaction techniques to their limits, such as Rümelin and Butz (2013) that explores directional and proprioceptive gestures on large areas during driving, but only for secondary tasks and for a context where eye-free interaction matters more than unstable conditions [Hourlier et al. (2015)].

This work also builds, to a lesser extent, on the literature on guidelines and models for domain-based design spaces, such as Maquil (2015) design space for tangibility in urban spaces that elicits 10 dimensions related to 4 main directions for redesign decisions. We compare to these approaches by using an explicit and systematic process to gather design directions. So, using the map from Mazalek and Van den hoven (2009), our method to build a design space for aeronautical cockpits can be described both as an abstracting and designing framework.

3. A tangible design space for cockpits

The design work that is presented in this paper is based on an approach to develop an adapted design space for the future tangible cockpit. Starting from the elicitation of relevant properties in the TEI related work and a set of aeronautical requirements, this process had produced a series of design principles [Vinot et al. (2016)]. The resulting design space (Table 1) is thus composed of requirements (columns), design properties (rows) and design principles (cells). Requirements for an interactive cockpit have been identified, drawn from activity analyses during several research projects [Conversy et al. (2014), Letondal et al. (2018), Letondal et al. (2015), Vinot and Athenes (2012)]. This includes 1) usability requirements that apply individually to each pilot, such as "direct localization perception" (RU1), "operational performance" (RU4), or that relate to crew and collaboration between pilots, such as "mutual awareness" (RU3); 2) industrial requirements, such as "dynamicity & adaptability" (RI1), related to software development costs and hardware adaptability; and 3) safety requirements, such as "availability" (RS3) or "resilience" (RS2), that include certification processes or resilience in degraded contexts, also including the avoiding mobile elements that may constitute dangerous projectiles.

Then, abstract design properties of tangible technologies have been analyzed (rows), such as *eye-free interaction*, *graspability*, *flexible physical structure*, *body parts reachability*, etc. As illustrated in Table 1, design properties are also grouped into three more general design dimensions: shape (top row section), embodied action and perception (middle row section), and programmability (bottom row section).

Finally, design principles (cells), such as **not too much focus**, or **alternative modes**, refine requirements and are rules to follow or features to provide in a design. They are translated from requirements based on relevant design properties: for instance, the *graspability* property is relevant for the "operational performance" requirement (RU4), in particular to enable action while **not** requiring **too much focus**. This property is also a call for the principle of providing graspable

alternative modes, which is relevant for the “resilience” requirement (RS2). The “*visibility in physical space*” property enables to define the **easy and direct access** principle that follows the "direct localization perception" requirement (RU1) together with the “availability" safety requirement (RS3). We can see that the *haptic, palm, fingertip* property refines the “operational performance” requirement (RU4) into the principle of providing **perceptive feedback**, directly available through finger and palm haptic abilities that are harnessed for instance by technologies such as imaginary interfaces relying on palm-based input and output [Hamon et al. (2014)].

Table 1. A tangible design space for airliner cockpits

	USABILITY REQUIREMENTS					SAFETY REQUIREMENTS			INDUSTRIAL REQUIREMENTS		
	R.U.1 Direct localisation perception	R.U.2 Situational Awareness	R.U.3 Collaborative Awareness	R.U.4 Operational Performance	R.U.5 Usability in Degraded Context	R.S.1 Safety-critical system	R.S.2 resilience	R.S.3 availability	R.I.1 Dynamicity & adaptability	R.I.2 engineering	R.I.3 Configurability
DEVICE SHAPE PROPERTIES											
Visibility in physical space	Easy & direct access	contextual awareness	shareability					Easy & direct access			
Flexible physical structure					re-configurable if required	re-configurable if required			adaptable & responsive	Reusable shape & devices	customer needs
Eye-free interaction					robustness	robustness					
Graspability				not to much focus		comprehended data & control	alternative modes	availability			
Salience	peripheral perception		shape & relief shareability	shape & relief expressivity							
Safety attached objects					secure access to data and device	avoid dangerous projectile					
EMBODIED PERCEPTION & ACTION											
Non-fragmented visibility			comprehensibility			overall perception					
Performative action			comprehensibility								
Universality of sensorial perception			mutual awareness			ensures mutual awareness		not culturally dependent	easy internationalisation	fewer training, internationalisation	
Body part availability and accessibility	accessibility				degraded context		allows resilience	Ensure accessibility			
Haptic, palm, fingertip				Easy & direct access							
Physical constraints, bimanual gestures	favor physical skills			favor physical skills							
Proprioceptive perception, spatial knowledge	favor physical skills			favor physical skills		performance of physical skills		performance of physical skills			
PROGRAMMABILITY											
Sofware and physical dynamicity		contextual information	contextual sharing-based information	end-user custom. coherence physical-digital	coherence physical-digital	adapted constraints	alternative modes	availability given phase of flight			end-user customing
genericity				improve learning & skills					widely adaptable	cost effective reusable & settable	
synthetic 3D view	reduce perceptual distance			synthetic information						integrated product	
dynamical composition		cognitive externalization	sharing-based information			hierarchical & contextual data		free movability of components	multipurpose use	allows genericity & complexity	allows modularity
contextual filtering		context + focus information		makes tasks easier		reduces cognitive load		make relevant data available		adaptation to customer needs	

The concepts and method described above provide a method that, besides providing a design space for tangible aircraft cockpits, has several potential advantages in the context of an actual tangible research project. It allows to articulate desirable tangible properties to explicit requirements, including safety related ones. It provides a rationale for a large technological space, showing why techniques as different as shape changing user interfaces [Rasmussen et al. (2012)] and imaginary interfaces [Gustafson et al. (2013)] are related through common requirements, such as “usability in degraded contexts” (RU5). Finally, it helps designers to abstract their work from specific technological trends.

In this paper, we study the design of a touch-based control panel for cockpits. Using the method, we were able to specify gestures and graphical layouts following tangible design principles complying with explicit requirements, and to characterize both design tensions and observations of use thanks to relevant and grounded design properties.

4. Methodology

This study is part of a larger project (AIRTIUS) whose objective is the design of a commercial flight deck based on tangible interaction. The study focuses on a single instrument, the Flight Control Unit, that enables the crew to interact with the Flight Guidance system, as described in the Activity analysis section. In this study, our purpose was to explore tangible design dimensions for touch-based gestures, which also resulted in a better understanding of usability limitations related to the use of touch screens in degraded contexts.

The project follows standard participatory design practice, including observations and contextual interviews with pilots. Interviews and observations included an interview with 2 airliner pilots (A320) during a real flight (Figure 1.b,c), two contextual interviews with 2 professional airliner pilots in a flight simulator, two observations of an airliner flight in a simulator with 3 professional pilots, one interview of a private pilot contextualized in a private plane on ground, an interview of a professional instructor dedicated to the control panel in a simulator. These interviews and observations have been recorded, and the major part has been videotaped and transcribed. For this study, a participatory brainstorming workshop was organized with 2 pilots (1 private, 1 instructor), as well as a prototyping session with a private pilot previously interviewed about a touch-based GPS, a design walkthrough and a test in flight.

5. Activity analysis

5.1. The Flight Control Unit in Airbus airliners.

In modern aircraft such as the Airbus A320, the pilots are able to interact with the Flight Guidance (FG) system (or FMGS : Flight Management and Guidance System for Airbus A320) and autopilots through a control panel called the FCU (Flight Control Unit). Through this panel, they can manually set the speed, heading, altitude and vertical speed, that are otherwise managed automatically, and switch between manual and automatic mode. This may be useful for instance to follow Air Traffic Control instructions or to make adjustments to the flight path, for example during approach or difficult weather-related situations. The FCU provides four knobs, one for each parameter, that the pilots can either rotate to change a value, pull to change control mode to “selected”, or push to go back to “managed” (auto-pilot mode). Changed values are visually available either directly on the FCU, which is shared and located in a central position between pilots, and, most importantly, on the Primary Flight Display (PFD) that stands in front of each pilot.

5.2. Observations, interviews and workshops.

During the activity analysis, we were able to observe several aspects that are relevant to this case study, in particular with respect to touch-based interaction. Notably, we could witness pointing issues, either during a real flight where the non-flying pilot had to enter various data with a virtual keyboard: he commented about missed keys and the conditions not even being unstable, which according to him, was due to far too small keys (Figure 1.b). Another pilot complained about the difficulties of using a touch-based GPS, not only because buttons and active areas were too small, but also because having to focus on dynamic displayed items while piloting (in a single pilot context) just broke his visual scanning of instruments. We also observed very articulated and sometimes exaggerated gestures, involving a kind of rhythmic acknowledgement such as “ok, done”, or frequent needs to place the hand, the wrist or some fingers onto a stable area, either for resting the hand or for preparing an action (Figure1.c). Also relevant for our design were observations on actions leveraging spatial knowledge [Letondal et al. (2018)]. Various participative and prototyping activities were conducted. A a brainstorming session a private pilot and an airliner instructor discussed with us two different designs of the panel (Figure 1.d,e). Then, during a participatory design session with a private pilot, interactions were experimented and discussed based on both paper and digital prototypes.

6. Design

Using the process described above, we refined the design principles from our initial design space [Vinot et al. (2016)] based on the design properties available with the chosen technology (touch-based surfaces) and desirable for the design of the control panel. Table 2 provides the list of these design principles (center column), the associated requirements (left column), and the desired design properties for the control panel (right column) that could implement the principles.

Table 2. Design principles

Requirement	Design principle	Design property
RU2. situational awareness	**contextual information**	*P1. information from the systems (FG, PA)*
RU3. collaborative awareness	**comprehensibility**	*P2. performative gestures*
		P3. few distinguishable gestures

	shared visibility	*P4. shared location of the UI*
		P5. shared visibility of gestures
RU4. operational performance	**favor physical skills**	*P6. proprioception with large or rythmic gestures*
		P7. spatial 2D skills, learnable distances
	distributed focus	*P8. combined use of peripheral vision and proprioceptive perception*
		P9. reduced need to visually focus on the UI
	prepare and anticipate actions	*P10. possibility to anticipate and prepare gestures*
	simplification	*P11. few distinguishable and easy to memorize gestures*
		P12. non ambiguous UI elements
	perceptive feedback	*P13. control when selecting discrete values*
	enable value selection	*P14. ensured precision for narrow ranges*
		P15. whole range available for broad ranges
	direct validation	*P16. continuous actions*
	avoid discomfort and fatigue	*P17. possibility to rest hands and fingers*
	coherence physical/digital	*P18. coherence with physical space (e.g. thumbwheel)*
RU5. usability in degraded contexts	**coping with degraded contexts**	*P19. gestures robust to false releases*
		P20. skidding-free gestures
		P21. possibility to stabilize the hand and fingers before action
		P22. loose gestures
RS1. safety-critical systems	**avoid dangerous projectiles**	*P23. no detached objects*
RS2. resilience	**alternative modes**	*P24. combined use of visual and proprioceptive perception*
RS3. availability	**easy & direct access**	*P25. visually and physically available elements*
RI1. dynamicity and adaptivity	**adaptability**	*P26. gestures dynamically adaptable to the type of input*
RI2. engineering	**cost effective and reprogrammable components**	*P27. abstract gesture specification (FSM)*
		P28. generic interactors

6.1. Prototype design

In accordance with these principles, we designed the user interface and a set of gestures so as to reach the desirable properties. Table 3 provides a detailed specification of the features we wanted to get (SP), and the associated design properties (P). Regarding the graphical design, we balanced between direct manipulation of parameters (speed, heading, altitude and vertical speed) through the primary flight display (PFD), thus discarding the concept of a separate control panel, and indirect manipulation of parameters in a mimetic redesign of the current FCU (Fig. 3). We used our design space to guide our decision and chose to stick with the current shared central location of a separate FCU panel (P4 property). Our final design is divided in four main areas corresponding to each knob/parameter in the actual physical panel (Fig 3).

Table 3. UI specification

SP1. 4 gestures	P2, P3, P5, P11, P14, P28
The design should feature as few gestures as possible so that they are easy to discriminate and to tune by the system, and easy to perceive and understand by the other pilot (through direction, amplitude and space). See Table 4.	
SP2. Mixed visual and proprioceptive gestures	P6, P7, P8, P9
Reaching an area or swiping should require as few as possible visual control, relying rather on combined use of peripheral vision, spatial knowledge and proprioception, resulting also in gestures that can be perceived by the other pilot.	
SP3. 1.5D gestures	P8, P9, P20, P21, P22
Once detected as either horizontal, vertical, or made of taps, each gesture is uni-dimensional (e.g vertical mode selection can freely deviate along the x axis and horizontal value selection can deviate freely on the y axis).	
SP4. gestures on the entire surface	P6, P8, P9, P13, P14

Value selection is captured throughout the entire surface (no picking needed), thus enabling loose gestures, both easier to perceive by the other pilot and easier to perform for the operator, thus requiring less control and a providing a better precision.	
SP5. same interaction for each parameter	P27, P28
Value selection is performed with the same interactor (thumbwheel) for each flight parameter.	
SP6. Mode change	P7, P11
Vertical gesture on the large area of the parameter (see Table 4).	
SP7. Value change	P7, P11, P13, P14
Horizontal gesture either on the parameter value or following a mode change (see Table 4).	
SP8. Tap gestures	P2, P6, P9
Tap gestures enables final value adjustment through proprioceptive and eye-free interactions (see Table 4).	
SP9. Timers	P16, P19, P26
Timers have been set in order to: 1) enables the contact to be lost for a few milliseconds in order to cope with unstable conditions; 2) continuously change the parameter to adjust, to enable direct changes, without validation.	
SP10. Hysteresis	P20, P21, P22
Hysteresis is large, so as to be robust to involuntary gestures or directions due to unstable conditions.	
SP11. Regular spatial arrangement	P7, P8, P9, P24, P25
The regular arrangement of areas enables to complement one's visual perception with internal perception of 2D geometrical directions, and to combine peripheral vision and learnable spatial skills.	
SP12. Still surface	P10, P17
Just touching the surface should be possible for pilots without triggering any interaction; this is required either for preparing an interaction, for resting one's fingers, wrist or hand, or for stabilizing the hand before issuing an action (Figure 1.c).	
SP13. Thumb wheel	P2, P11, P13, P14, P18
The thumb wheel enables a more precise selection of values for parameters having a narrow range of change (e.g altitude, speed or vertical speed). We designed an interactor inspired by the current physical knob.	

Regarding the gestures, the selected design (Table 4) is based on loose, performative, distinguishable, visible, and proprioceptive large horizontal and vertical gestures on these regularly arranged large areas of interaction (P2, P3, P5, P6, P7, P9, P11). By proprioception, we mean the sense of position and orientation of the body's parts with respect to each other, and by proprioceptive gestures, we mean gestures, in particular directional and large gestures, that the user can "feel" and distinguish, as a mean to better control their action. Relying on proprioception and a simplified spatial arrangement into four equal area is meant to both enable to interact in a very unstable environment and to some extent to relax visual focus for interaction – although looking at the front panel does not have to be avoided for us as in Rümelin and Butz (2013). In the following we call "tangible" the gestures that are designed to be stable, controllable and performative, relying not only on visual perception but as much as possible on proprioceptive perception and spatial knowledge.

Table 4. Gestures

↓	changes the control mode to «selected» for the parameter corresponding to the area	↑	changes the control mode to «managed» for the parameter corresponding to the area
↔	changes the value for the chosen parameter	•••	small tap gestures were designed to allow the pilot adjust a value

When a parameter is selected, a digital thumbwheel fades in and the whole FCU becomes an interaction area for modifying the value of the selected parameter (P6, P8, P9, P13). After a small delay with no activity, the thumbwheel fades out and the application switches back to previous state. A touch or a gesture smaller than a fixed threshold only triggers the display of a white semi-transparent veil, indicating that the application is alive but not reacting to undetermined gestures. This feature (SP12) enables to either **anticipate and prepare an action** or to **cope with degraded contexts**. The upward, downward and horizontal gestures are assimilated to the push, pull and roll interactions on the physical FCU buttons. The gesture recognition algorithm includes a waiting state to support the gesture recovery in case of false release, in order to **cope with degraded contexts** (P19, P20, P21, P22).

We discussed these gestures with a pilot during a design walkthrough (Figure 1.e), where he was also invited to sit aside from the panel and to try to reach given parameters without "too much" looking at them. He approved the eye-free interaction and commented on the tap gestures as efficient: "I don't need to look at it, I have seen my value, it's 3 away, I make 1, 2, 3, then I check. It's fast.".

7. Prototype implementation

The prototype (see Figure 2) was implemented using the djnn framework, a free software development framework for highly interactive and visual user interfaces, based on reactive programming and a rich, unified model of event sources [Chatty et al. (2016)]. The developer used the *djnn* C library for defining the application behavior while the graphical components were produced in Scalable Vector Graphics (SVG) by the graphical designer, and loaded as software components by *djnn*. Several Finite State Machine (FSM) components were used to implement the gesture recognition algorithm, from a general recognition FSM (idle, pressed, moving) to domain specific FSMs. This allowed us to iterate separately on the gesture detection robustness (e.g. adding a waiting state for unintentional touch release recovery) and the domain specific test results (e.g. adding a specific behavior for Altitude parameter), complying with **cost effective and reprogrammable components** design principle (P27, P28). Attention was paid to the horizontal/vertical gestures discrimination, using the angle of the gesture pattern. The program was developed and tested on a large Wacom surface then installed on a smaller Microsoft tablet, both running Linux.

Fig. 2. Left and center: Final prototype design based on the current FCU; right: heat map of presses on the tablet (all flights) showing that the control area were reached accurately.

8. Observations

8.1. Setting

We were able to test the prototype during a real flight (Figure 1.a) and to observe aspects that can be related to the design properties of the prototype. We installed the application on a tablet (Microsoft Surface 2), and attached the tablet to the cockpit of a DR400 aircraft, using rubber tape and scratch fasteners. A scenario had been designed with the private pilot acting as the security pilot. This scenario was a set of operating instructions for the passenger seated at the right of the pilot. Following these instructions, the operators could interact with the application consistently with the actual flight. For example they were instructed to change multiple parameters (speed, altitude, heading) at the end of the actual climbing phase. The scenario also included autopilot mode changes from "managed" to "selected" when reaching a stable phase, and from "selected" to "managed" to simulate an auto-land in bad weather conditions. We chose to fly on a very hot summer afternoon in order to experience heavy turbulence. We organized 3 crews, each composed of the same pilot, an operator who interacted with the simulated FCU, and an observer who read the instructions aloud at the appropriate time. Each crew performed 2 flights, following the same scenario. The interactions were recorded in a log file and were videotaped with 2 cameras, a GoPro attached to the window and a camera held by the observer. Each operator was briefly interviewed after the flight in order to get some qualitative and subjective comments.

This experiment had many limitations with respect to a real airliner context or even on a simulator. To list the most significant, the performed actions had no actual effect on the flight, the aircraft was a small tourism airplane and the operators were not airliner pilots, the operator was not involved in a collaborative task and the activity did not involve concurrent tasks. Also, the operator interacts with a small tablet (located in front of them), not with a shared large interactive surface as planned for future cockpits. Finally, the context involved no stress related to the pilot's responsibility in the execution of the flight assignment.

8.2. Results

Table 5. Strengths and weaknesses reported from observations.

OPERATIONAL PERFORMANCE	
[+] P6, P11, P7, P22, P19, P20	[-] P17, P21
The vertical gestures for changing the parameter control mode were felt as comfortable and accurate: OP2: "Changing from selected to managed and back is super easy: you can feel the gesture quite well. You put your arm, and "zoop!" the gesture is loose, it has some weight, even when going up." The heat map on Figure 2.c also shows that even with turbulences the areas were well reached. And the qualitative feedbacks attest that all participants had this feeling of control: OP1: "False releases never occurred for me, even with freehand" OP3: "not too much problem of fingers losing the contact" OP2: "when it's unstable, it's quite ok, you can still use the controls"	The users reported the need to rest or grasp the hand: OP1: "I confirm that something is required to rest one's wrist" OP2: "My arms hurt!" OP2: "when there is a turbulence, it feels like your palm is pushed away from the tablet, so that it's hard to hang on to the tablet."
	[-] P11
	There were not enough tangible gestures to express directly all the possible interactions (here modifying the Altitude value in managed mode): OP1: "having to perform a slight move to activate value change is inconvenient, you feel like it would be easier to reach the thumbwheel after touching the parameter area"
[+] P13, P14	[-] P13, P15
The users had an impression of precision concerning the modification of the value: OP3: "most of the time, the value we had selected worked out right" OP2: "You feel that your move is precise, in other words, if you perform a small gesture, you get a small change." OP3: "I have used the tap gesture sometimes, to adjust a value, for instance when I needed to add 5 or 6: it was safer to tap than to drag" Observed values converge rather quickly for all participants, with a learning effect for Operator 1.	For the modification of the value of the parameters, overshoot problems were observed and recounted: OP3: "at some point I was far from the targeted value for heading, I have moved too fast, and I had to go back since I overshooted the desired value" OP3: "to get vertical speed to -400, I skidded and it changed to 1000, I probably made a wrong gesture, it didn't feel like it was a wide move but it resulted in a big change" This effect was worsened by turbulences: OP1: "If you target something and there is a turbulence, your finger can slip." OP2: "But if you get out of control, you feel lost. I mean when the hand moves. It feels like you cannot touch where you want to, and that you don't know how wide it's going to be."
GENERICITY	
[+] P27, P28	[-] P15
The users felt comfortable with the genericity and homogeneity of the thumbwheel. It was identified as the area dedicated to change the value for every parameter: OP3: "I tend to always go down to the wheel to change a value" OP2: "I found this to be very reassuring to target the thumbwheel" This aggregation of actions on one interactor allows to allocate a wide area and a simple gesture to this interaction, resulting in a secure feeling: OP1: "The gesture may be wider during a turbulence, but since the thumbwheel area is large enough, this is not a problem."	The setting of a value was harder for the Heading parameter because its range of values is wider: OP2: "it was a real effort changing heading" OP1: "changing the heading is very long" According to the logs, the time spent to set the Heading is much longer: 12 to 14 seconds compared for example with the Speed setting: 5 seconds. Here we replicated the problem of the physical interactor (need to turn the knob to change the value), adding an inconsistency on the plane direction vs. the interaction direction. We nevertheless identified improvement clues such as acceleration strategies or *orthozoom*.

We had some quantitative data, such as the time needed to select a value. We observed various features, such as a learning effect and interindividual differences. Notably, Figure 2.c shows that the control area (speed, heading, altitude and vertical speed) were reached without ambiguity. However, our goal was purely design-oriented, and mainly aimed at gaining insight into our design choices and our design principles. Formal performance evaluation based on carefully selected variables was out of our scope, and the we were rather trying to identify design questions. Table 5 reports some of the observations that may add to our design exploration of "tangible" gestures. The positive aspects that are listed on the left column mainly include properties related to physical and spatial embodiment, skills and broad control. There also are positive comments regarding the genericity of the thumbwheel, which departs from the specificity principle [Fitzmaurice et al. (1995)]. Reported on the right column are observed issues of inaccuracy which confirm previous observations of the poor use of hand motor abilities when interacting with a flat surface [Fitzmaurice et al. (1995)].

As illustrated with Table 5, the design space thus provided us with a convenient way to relate not only design decisions, but also observations and associated discussions regarding unresolved aspects to the explicit design properties listed in Table 1. This provides us with a convenient way to structure the process, and to prepare further iterations, where the method may support reflecting on other properties and refined principles.

9. Discussion

The results gathered from our observations confirm the general limitations of touch-based limitations in unstable contexts that are reported in the literature [Hourlier et al. (2015)]. Regarding operational performance in unstable context, we indeed observed some fatigue and discomfort due to the lack of possibility to grasp the controls as with physical controls. This was compensated by the use of timers (SP9) to enable the hand to rest on the surface without triggering an interaction and by the choice of a large hysteresis (SP10), to address involuntary lost of contact due to instability. Results related to control and precision are less clear: participants both reported their success in reaching a desired value thanks to proprioceptive gestures (SP2) or tap gestures (SP8) but also reported overshoots, a problem that was worsened by instability. On the other side, participants also reported that they were able to reach the controls correctly, so that our attempt to enable touch-based gestures in unstable context and relaxing visual focus by using loose gestures (SP1, SP3) and a fix and basic spatial design (SP4) seemed promising, even though it reduces the variety of interactions.

One of the objective of this design work is also to apply our tangible design space, using a set of principles that refine general usability, programmability and safety requirements and also to further inform our future designs for tangible cockpits. As explained in the introduction, we need as designers to be able to use a design space that enables to combine aeronautical requirements and desirable properties. Starting from properties that we mainly elicited from tangible themes, we want to include other relevant properties given our requirements. Through this study, we were indeed able to relate properties of the control panel to our requirements (Tables 2 and 3). For instance, we observed properties such as few distinguishable gestures (P3), shared location of the UI (P4), combined use of peripheral vision and proprioceptive perception (P8), together with desirable properties for gestures, such as being robust to false releases. (P19-P22). Following our method, this enabled us to relate our requirements to refined design principles and to include missing ones such as shared visibility, distributed focus, anticipate and prepare action, enable value selection, direct validation, and avoid discomfort and fatigue. As can be noted, several principles are common usability or direct manipulation principles [Shneiderman (1983)]: our aim was rather to ground them on actual design properties and draw them from requirements in a systematic way. The principle of supporting distributed focus refines the principle of actions that do not require too much focus. It is indeed critical in a real-time multi-tasking activity, and relies heavily on quite efficient physical skills. Principles such as prepare and anticipate action are related to operational performance required in aeronautics, and are highly relevant for tangible interaction in a degraded context.

10. Conclusion

In this paper, we have presented our design work on touch-based gestures for airliner pilots, designed with usability, collaboration, performance and safety in mind. The results of our observations of the prototype in use in a real flight show how properties of gestures mainly based on internal proprioceptive and spatial perception may help to design gestures for degraded contexts, and also to reflect on the continuum between touch-based and tangible designs, that we also explored to address touch-based limitations in the context of vibrations [Pauchet et al. (2018)]. Our aim is to refine and develop further our design space through additional design work, in order to provide an improved design space that, we hope, can be useful for the designers of future airliner cockpits.

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