Video Prototyping for Interaction Design Across Multiple Displays in the Commercial Flight Deck

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Abstract
The commercial flight deck is a workspace with more than a century of knowledge in human-machine interaction, pioneering the transition from direct analog displays to computerized screens. The flight deck is a collaborative workplace where pilots interact with automated systems and flight information that is distributed across an array of screens that present information in spatial alignment to tasks and flight situation. This pictorial examines new Interaction Design video prototyping techniques for spatially aligned and collaborative interactions across multiple screens for a next generation commercial flight deck.

Authors Keywords
Interaction Design; Design Methods; Design Prototyping Techniques; Video Prototyping; Flight Deck Design

ACM Classification Keywords
H.5.m. Information interfaces and presentation

Introduction
The commercial flight deck is a rich interaction environment that is based on a century or research. The flight deck has been the birthplace of complex human-machine interaction, a work setting that connects human perception and cognition with advanced technological systems that mediate the environment of flight with the reasoning and decision making capabilities of pilots to control the aircraft [1]. Early flight was direct as pilots reasoned about flight conditions and the route ahead using their vision, as well as audible and tactile feedback from the airplane.

Flight controls were directly coupled with the airplane engine and control surfaces on the wings. Today's airplane flight systems mediate pilot awareness and control across automated control systems [2]. Flight deck instrumentation augments the view out of the window and pilots can rely on the instrument's representation of flight conditions and navigation when the view conditions are poor. During instrumentation-based flight at night displays replace the view into the world ahead. The flight deck also provides a rich collaborative work setting [3] where two pilots interact with each other and jointly interact with the automated systems that fly the airplane (Figures 1-4). Single pilot operation of commercial airplanes is still a vision of the future as complex work tasks during high pressure work sequences require the distribution of workflows across the captain and the first officer. On the other hand there are low work load periods, for example during cruise between take-off and landing when the automation flies the plane without pilot intervention [2]. During this period that can last many hours, pilots become supervising agents that monitor the automation [4]. Outside the flight deck, commercial interactive technology has rapidly developed and has in many aspects surpassed the technological state-of-the-art of the commercial flight deck [5]. We set out to explore how the current state-of-the-art for consumer interactive devices could affect the design of flight information displays and control of the aircraft in future commercial flight decks. Together with pilots, human factors researchers, cognitive scientists, ethnographers, and engineers, our team of interaction designers set out to explore the future of interactions in the flight deck in a concurrent design approach [6] to ground design in observation and use design ideas to probe and contextualize knowledge at the intersection of people, technology, and work. Design ideas were based on ethnographic studies of pilots at work and thorough process traces of flight operations. In aviation, flight operations are designed sequences of action that are driven by checklists and communication and interaction protocols that pilots learn during flight training [7, 8]. The trends were apparent: screens would become larger and pilots would bring mobile devices on board.

Figure 1. A typical gauge- and dial-based flight deck pre-1984 comprised of an array of analog displays for the different flight data components

Figure 2. A current glass cockpit with the main flight display suite of large integrated digital displays.

Figure 3. Captain and first officer engaged in take-off and landing calculations. Thrust levers are in the foreground, centered in front of the Flight Management System.

Figure 4. Collaboration between Captain (right) and First Officer. Notice that there isn't workspace in the center console. Exchange of information takes the form of conversations and paper.

What are the expectations of tomorrow's pilots when they enter the flight deck? How could flight operations unfold given that rich visual interaction would become the norm in commercial flight decks—screens would continue to increase in size and resolution, new interaction techniques such as touch screens and direct surface interaction would be integrated in the visual displays? [9, 5]. How could these new interaction models be integrated in future concepts? How would the new interaction sequences play out during operational scenarios? [10, 7] How would these new interactive systems have to be designed to support the collaboration between pilots? [11] How could the collaboration between pilots be improved using new types of visualizations that would provide more transparent representations of flight systems and better navigation and planning support? [1] Our design of the new interaction concepts for the commercial flight deck took the form of three design efforts: 1) Design of a new suite of flight displays that is based on the traditional display set in glass cockpit airplanes 2) Design of physical control interfaces 3) Design of flight interactions that are contextualized in the flight deck workspace.

Flight Displays

Currently, the main flight display set (Figure 5) is comprised of a primary flight display, a navigation display, and an engine and crew altering system display. The primary flight display shows the attitude of the plane—its pitch, roll, and yaw relative to a horizontal plane and lateral axis. The navigation display shows a map-like top down view of the airplane with the location of the plane in the center at the bottom of the display. The engine-indicating and crew alerting system displays engine performance and flight systems notification and alerts. The flight management system programming and control panels are used to program flight route and adjust course. We took a radical design approach to the visual displays when we adapted current display content to the much larger 19" panels we explored. We also introduced two large displays in

Figure 5: Current pilot display suite in the commercial glass cockpit with call-outs of key instruments and physical controls.

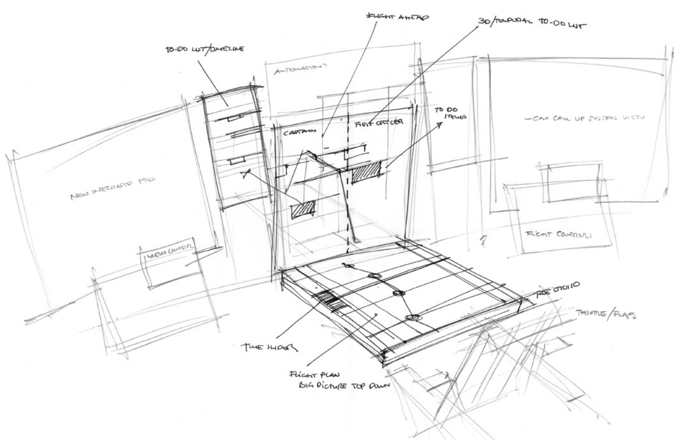
the center main panel and center console that would expand the collaborative display work space between the two pilots (Figure 7). The center console display is a touch screen used for strategic flight planning tasks along a flight mission timeline. The center panel screen is an external view of how the automaton is flying the airplane. Left and right main panel displays show primary flight display, navigation display, and/or flight timeline in combined views. Instead of adding more information into the larger screen spaces, we reduced the amount of numerical information and focused the design on large and open visualizations of maps, diagrams, timelines, and alignment geometry in order to provide big picture views on the relationships between flight data [12]. We also reduced the current 31-hue color coding of the aviation displays to black and white [13] in order to experiment with a minimal display approach.

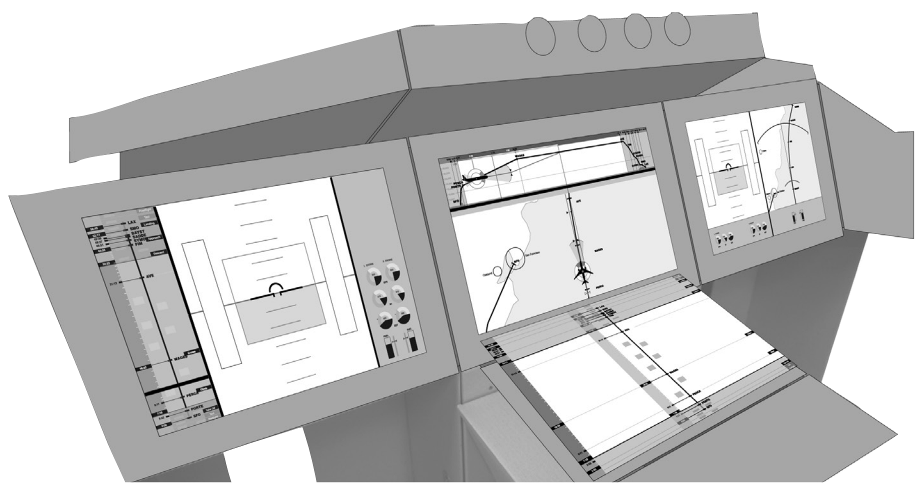
Flight Deck as Physical Workspace

All digital flight displays and physical controls in the commercial flight deck are located in specific locations relative to the pilots, their work tasks, and in alignment with the airplane, flight direction, and view out of the window (Figure 5). Most flight controls and display views are replicated so that both pilots have access to them during flight to distribute work tasks and hand over control of the airplane. In order to redesign interaction flows we had to carefully examine the relationships between display content and the location where information would be presented. We conducted process traces of typical normal and non-normal flight operations [7] with pilots and technical ethnographers. We examined which flight controls would remain physical and which one could be integarted as display interaction. Pilots use primarily physical flight controls to provide tactical input for the plane. The yoke is a hand interface that controls the attitude of the airplane: A pilot can pull it back to pitch up the nose, push it forward to point down the nose, rotate it to roll the plane in order to change the lateral direction of flight. The thrust lever is used to control the airplane engines. Foot pedals are used to rotate the plane around its vertical axis to counter cross winds. Other physical switches and levers are used to control the landing gear, extinguish engine fires, control systems on the overhead systems panel, and control the magnification scope of maps in the Navigation Display. The main interface input elements for the automation are the alphanumeric keyboard of the Flight Management System and the physical dial knobs for airspeed, vertical speed, altitude, and heading on the flight management control panel (Figure 5).

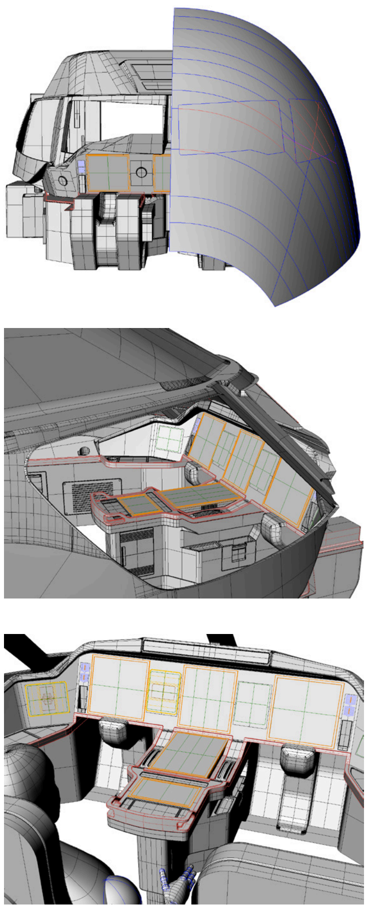
(Below left) Figure 6. Early design sketch of the new physical flight deck layout as four-panel large screen arrangment with new main panel and center console displays.

(Below right) Figure 7. New four-panel layout of the main flight deck panel and enter console. Vector illustatration with display designs. The mission planning screen in the center console provides a new collaborative workplace for both pilots.





Figures 8-10. Hand sketching (Figure 11, right) and 3-D computer modeling (below) alternated: We used 3-D modeling in Rhino to adapt our flight deck panels to the actual flight deck space of a Boeing 787-size airplane.



From the moment when we moved from process tracing to design development it became clear to us that in order to present and share design concepts of interaction flows, display content, and display locations in the flight deck effectively, we had to move beyond traditional presentation formats such as sketches, illustrations, and slide shows. Flat, static and partial representations turned out to be insufficient to share a big picture of an integrated design concept for the flight deck as workspace, as images showed either individual displays and decontextualized them from relationships with other displays, or they flattened out the display space by showing all displays in the same plane. We began to build full scale cardboard mock-ups of the flight deck [14, 15] and used paper print-outs of display screens at full size, positioned in their respective screen locations in the flight deck mock-up to discuss interface concepts during meetings (Figures 13-17).
To capture envisioned interaction flows during flight operations we began to experiment with video prototyping techniques [16, 17].

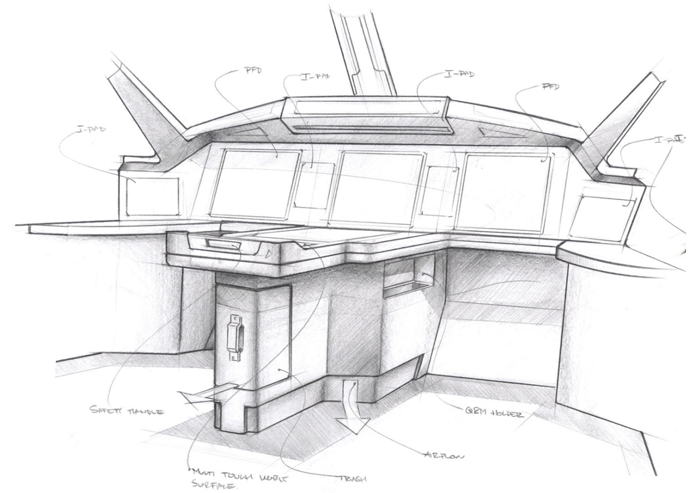


Figure 11. Design sketch of the physical flight deck design.

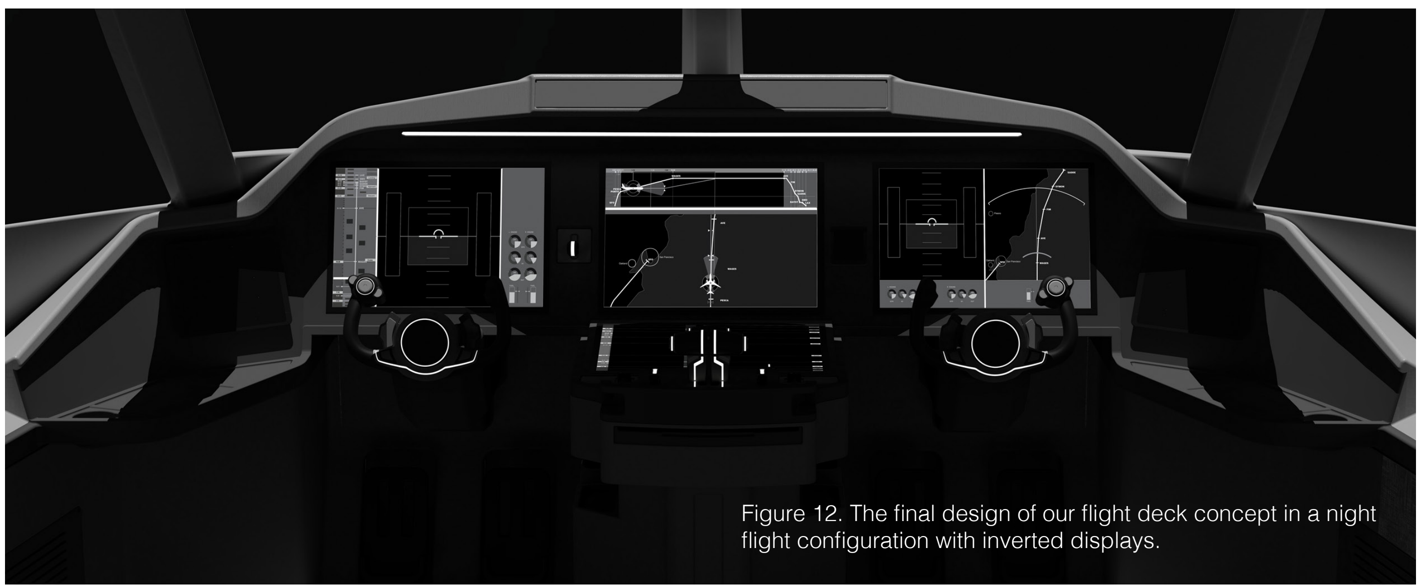


Figure 12. The final design of our flight deck concept in a night flight configuration with inverted displays.

Video prototyping of interaction sequences was introduced in the early 1990's to capture future design scenarios [9,18, 19, 20, 21], but its application for detailed interface scenarios was limited due to constraints of earlier video technology, in particular the low resolution of video in 640x480 standard definition. We used full HD 1920x1080 resolution and multiple camera angles to capture mock-ups of screen content, pilots, and physical flight deck layout during realistic operations scenarios that reflect current flight procedures. Capturing this information rich environment was key for reviewing interaction design and physical design of the flight deck with pilots in context during participatory design sessions.

Paper Video Prototype

For our first video prototype experiment, we used our full scale cardboard flight deck mock-up as stage (Figure 17), and working with the full scale screen print outs in 17x11" we developed continuous display screen flows and used a stop-motion video technique to simulate direct screen interactions (Figures 18-21). Our pilots would point at a button in the paper print-out, hold the position, we would replace the print out with a new interface screen print out, and continue interaction gestures from there; the transitions would be edited out during digital video post production later (watch the video at https://vimeo.com/213371977). The paper video prototype was great for sketching out interaction sequences.

(Above) Figures 13-16. We set up weekly meetings in our lab adjacent to the Interaction Design studios of the University of Washington's Division of Design in the School of Art + Art History + Design to meet with airline pilots, human factors specialists, ethnographers, engineers and designers involved in current flight deck design to conduct hands-on design sessions and reviews of our design concepts and scenarios. These check-ins were instrumental in developing realistic operations scenarios [7, 8, 10] for workflows that would shape the Interaction Design of the flight deck.

(Right) Figure 17. The full scale cardboard mock-up provided common ground during discussions. We pinned screen print-outs in their respective locations and were then able to annotate the interface designs with hand sketches, ideas, and suggestions directly on the paper print-outs.

Shooting in stop motion manner was quick but required significant preparation as hundreds of screens needed to be designed, printed, and organized sequentially. This preparation work oftentimes revealed gaps in the screen sequences such as screen states, transitions, and continuity elements that we had not considered. In hindsight we look at this as a benefit as the paper video prototype served as an effective test bed for the completeness and flow of interaction concepts. From the point of view of the actors, another strength of the paper video prototype was that all screens and gesture touchpoints were visible to them during filming. This made hand/eye coordination straight forward and turned out to help evaluate the physical ergonomics of touch gestures: When gestures felt clumsy because of their location and orientation in relationship to the operators we were able to sketch out new touch locations that felt better suited directly on the paper print-outs and then adapted the digital display design files accordingly.

Figures 18-21: Video prototyping was an effective prototyping technique to identify gaps in the interaction model. We scripted operations scenarios in real time and developed key frame screen sequences that were drawn in Illustrator, then laser printed in black and white at the size of the envisioned displays. The aesthetic of the video left a good space for feedback, as attention was focused on content rather than form.

Paper video prototype
Full video at **https://vimeo.com/213371977**

Green Screen Video Prototype

We moved to the next level of fidelity for video prototyping by capturing all surface interactions in a green screen compositing approach (Figures 22-24). We gestured interactions on screen areas of the displays that were masked out in green during video shooting, and then timed an animation of all six screens in an After Effects file to synchronize it with the timing of the screen gestures captured in the video. We then matched the scale and perspective of the animated screen sequence with the captured video and composited both videos together using chromakeying so that the screen animations would appear in the green masked areas of the camera video and hand and finger pointing over the green screened display areas would occlude the display beneath. The result was a fairly realistic video prototype from the perspective of a jump seat observer in the flight deck (watch the video at https://vimeo.com/213372407). The green screen video prototype allowed us to demonstrate fluid screen transitions and swipe gestures with motion elements. This would have been very production intense in the paper video prototype approach, as it required several in-between paper print-outs. A challenge that we discovered was that touch locations wouldn't be visible to the actors during filming as the screens were added later during post production.

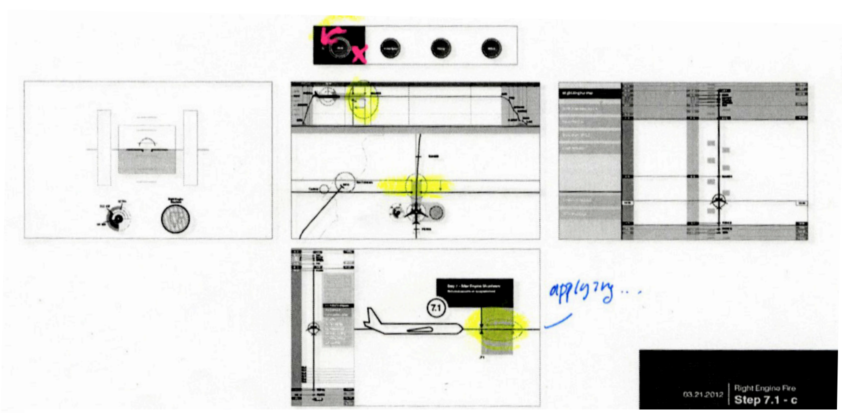
(Top right) Figure 22. Green screen video prototype shooting set-up.

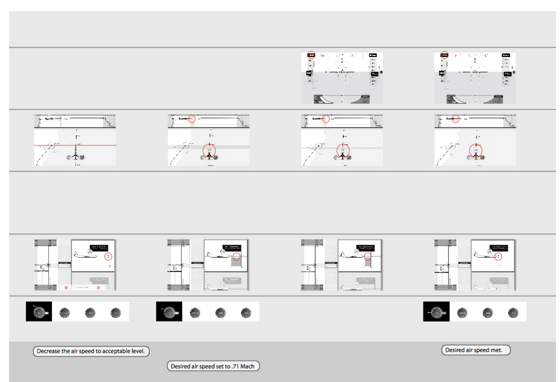
(Bottom left) Figure 23. Frame from the green screen video prototype. In this scene the first officer monitors the airplane slowing down to a new air speed setting.

(Bottom right) Figure 24. Transfer of paper screen print-out to a hand gesture trace on the green mask for the overhead panel. The marks were used to identify touchpoints on the screens during the green screen video shooting.

To provide our actors with view and touch targets, we had to mark touch locations and swipe tracks on the green screen masks using push pins to transfer location points from the paper prototype screens into the green masks and then add annotations to identify the push pin marks using green pencil (Figure 24). Our actors then followed the annotations to synchronize finger gestures with the progression of the screen animations. This approach required paper print outs of key screens that we already had from the previous paper video prototype. Overall, the production of the green screen prototype turned out less time consuming than the paper prototype because the entire interaction sequence was developed and the timing was down as result of prior paper prototyping. Digital files for screen design were linked to the animation file. This provided a great organization framework. Where needed, screen design adjustments could be made directly in the Illustrator source files (visual design) or the After Effects animation sequence (timing and motion design) and didn't require print-outs and sequential file and paper organization.

(Below) Figure 25: Screen array status for a scene in checklist step 7.1. Excerpt from the screen state rehearsal script that our actors used to familiarize themselves with upcoming screen transitions that they would follow with screen gestures.





(Above) Figure 26: Full scale flight deck mock-up equipped with six 19" LCD displays for the six-panel video prototype.

(Bottom Center) Figure 27: Notation of the screen sequence for the three main panel and center console screens.

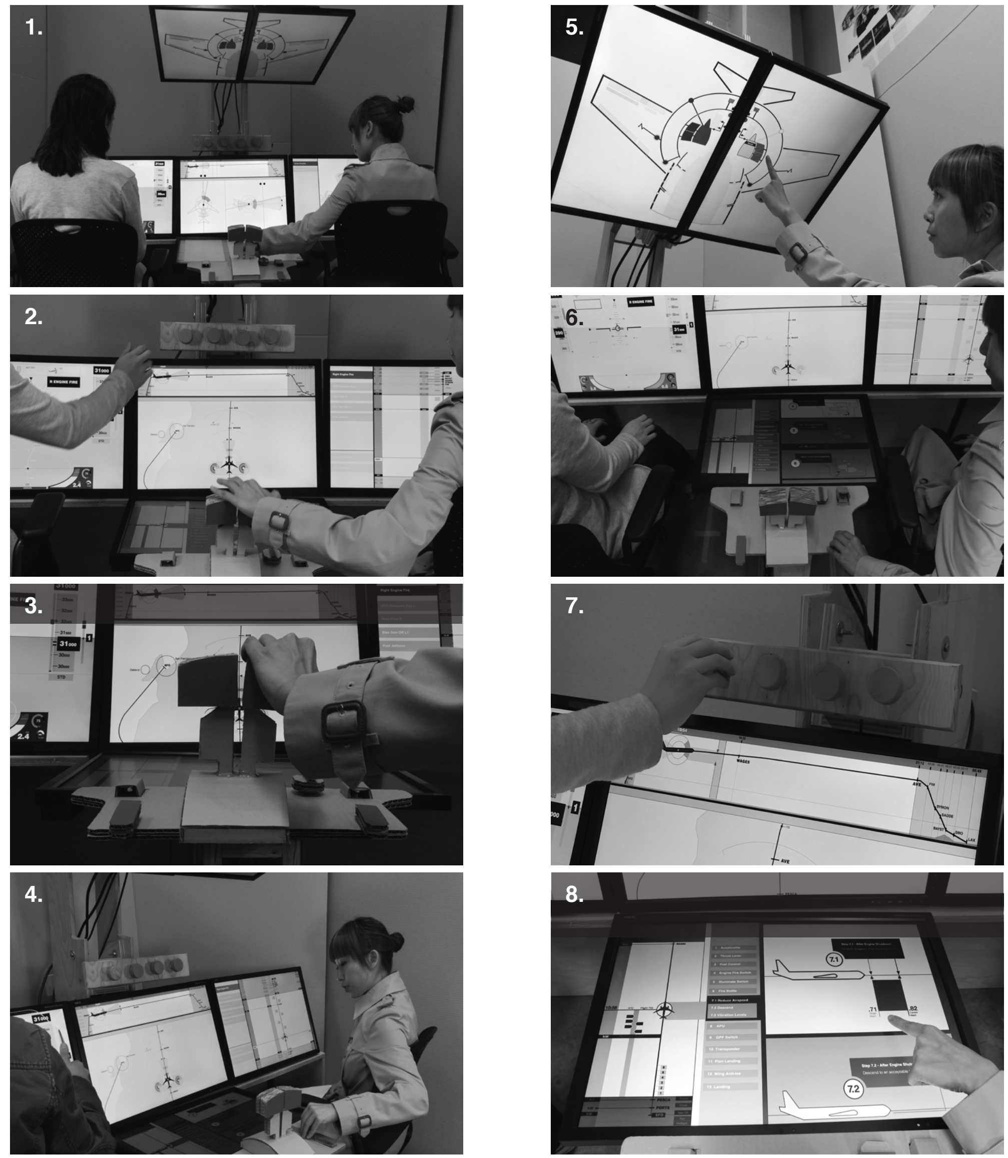
Six Panel Video Prototype

For our final video prototype we built a new physical flight deck prototype that was equipped with six 19" LCD displays (Figure 26). Our intent for this video protoype was to produce a promo-style video that incorporated dramatic camera angles and narrative-driven editing between camera views (you can watch the video at https://vimeo.com/213372846). We were able to use the same screen animation files we had produced for the green screen video prototype and ran these in a split-up version via six video cards from a single computer on six separate displays. Members of our design team then rehearsed finger point gestures, touch locations, and changing screen states to follow the various screens with interaction gestures as they were filmed. At any time during the shooting we were able to stop the playback of all six screens to adjust camera angles or run re-takes. After serving as stage for the six panel video prototype, the second flight deck mock-up was used to present live demos.

The six panel video prototype (Figures 25-39) provided freedom for camera placement and although we used cameras on tripods, fixed viewpoints weren't a constraint as there wasn't a critical post production step that required perspective matching. Even hand held camera work would be possible. The most significant time investment for the six panel video prototype went into the rehearsal of the screen sequences and gesture interaction steps that needed to be performed during acting to synchronize interaction gestures with the animated screen content.

Figure 28. For the six panel video prototype we filmed the engine fire response scenario from multiple camera angles and edited it for a dramatized, points of interest oriented visual storytelling style. In order to determine story flow and camera angles, we storyboarded the video to control the composition of each scene and continuity between edits. By documenting the interactions between the pilots in response to the non-normal event of the engine fire, the video scenario captures the key features of our design of the display suite and flight deck work space.

What we discovered during this process was that the six panel prototype really was a full scale physical demonstration set-up that showcased the integration of work environment and screens. All screens and display content were presented in full size and situated in their actual physical location to another, all this in relationship to the pilots. The unfolding scenario could be experienced by taking the seat of a pilot. Instead of just serving as a stage prop for video prototyping, the six panel display set-up could be used to evaluate display element sizes and placement, viewing distances, and the physical ergonomics of screen gestures. This allowed us to demonstrate flight deck and display scenarios to pilots who could now observe the design concepts in action from their familiar point of view in the pilot seat. Or they could sit in the jump seat, a seat behind the pilot that flight that instructors use to assess pilots. Pilots and aviation researchers are familiar with the perspective from this seat and shared with us observations of current flight operations and how these relate to the new interaction concepts presented.



Figures 29-38. Screen shots from the six-panel video prototype of an engine fire response scenario. The sequence unfolds as follows:

1. Flight operations are normal
2. Engine fire alert appears, autopilot disengages, captain takes over manual control, electronic engine fire response checklist appears in center console.
3. First officer throttles down the affected engine.
4. First officer activates fire extinguishing system.
5. After a waiting period of 30 seconds, the first officer checks in the overhead systems panel if the fire has been successfully extinguished.
6. The checklist moves to the next step and calls for a reduction of airspeed.
7. Captain dials in new airspeed.
8. First officer monitors airplane slowing down to new airspeed setting.

Full six panel video prototype: **https://vimeo.com/213372846**

Discussion

We set out to explore new Interaction Design opportunities in the commercial flight deck setting. We based display design and physical workspace design on the Interaction Design for key operations scenarios. To communicate our design concepts with pilots, human factors specialists and engineers, we captured the operations as video prototypes at various levels of fidelity. The video prototypes captured the collaboration between pilots, their interactions with the automated flight systems, and the spatial and operational context of the flight deck as distributed cognition [22]. Camera angles in the video prototypes resembled the perspective of pilots and flight observers. Physical flight deck mock-ups in combination with the video prototypes provided us with an effective demonstration and test platform for design reviews with pilots and engineers. Our video prototypes enabled us to record, annotate, and communicate concepts to gather feedback during the design process.

We intentionally choose a sketch-like aesthetic for the video production, using corrugated cardboard props and black and white laser print-outs as interface displays to encourage deep-level feedback that was targeted on the interaction flows, visual design and usefulness of the information displayed. The various video prototypes were extremely successful in capturing the contextual aspects of the interactions, such as the ensemble of flight information that resulted from multiple views on the flight mission across several screens, and interactions between the two pilots and their collaboration with each other during layered work tasks that required the monitoring of different screens and physical interactions, often situated in locations outside the displays. The video prototypes effectively presented workload and work setting aspects of the presented scenarios and proposed design concepts.

The paper video prototype was a great tool during the design process that helped us reveal gaps in interaction sequences. The green screen video prototype provided an effective presentation platform to share semi fidelity design concepts in realistic appearance. This was a very helpful presentation format to share the design work with pilots and aviation researchers for feedback.

The six panel video prototype provided a demonstration set-up where the flow of interactions could be experienced from the perspective of pilots with authentic timing, screen sizes, and viewing distances, potentially suitable to obtain early measurements for design evaluation.

Video prototyping enabled us to validate design concepts and improve various aspects of the design based on feedback from pilots and other design stakeholders. It also provided an effective platform to capture and document display design, interaction flows, and experience of new interaction concepts for the future commercial flight deck.

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Referenced video files:
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