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Interaction Design in High-stakes Domains: The Impact of Design at the Intersection of Expertise and Technology

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Abstract: The design of interactive systems in high-stakes work environments such as medicine and aviation, is guided by domain knowledge. The design of artifacts and interfaces for use in these "expert domains" is driven by the explanations and expectations of practitioners who use these interactive systems to complete work tasks. Interaction designers may be new to the expert domain under design yet need to gain a solid design expertise within the domain before they can propose innovations. How do interaction designers gain deep conceptual understanding of the domain under design? A research collaboration between the University of Washington's Interaction Design Graduate Program and Boeing's Flight Deck Concept Center explored new directions in interaction design for the commercial flight deck. As a case study, the project demonstrates how interaction designers can successfully contribute to innovation in the high-stakes environment of aviation, where design impacts practice at the intersection of technology, experts, and their work. A review of the design process outlines the challenges of designing for expert domains and describes new strategies for interdisciplinary collaboration between designers, researchers, and engineers in the fields of interaction design and aviation.

Keywords: Interaction Design, Human Centered Design, Cognitive Systems Engineering, Conceptual Models, Design Process, Expertise, Decision-Making, Innovation, Aviation

Introduction

HUMAN-CENTERED DESIGN HAS been the central topic of design practice and research throughout the past three decades. In the design of complex technology, the drive to put people first was initiated by large systems failures that have been attributed to breakdowns in human/technology interaction. The 1979 Three Mile Island nuclear accident is one of such significant events (Roesler, 2009), but similar patterns of interface breakdown have led to a number of accidents in aviation, medicine, and military operations. Many of these design failures can be attributed, in part, to a design philosophy that was technology-centered, not human-centered. Human-centered design methods explore the potential of design changes in existing environments based on how practitioners perceive their usefulness and usability. Human-centered design is preceded by contextual research, such as field study, that examines the domain under design, its practitioners, the nature of their work, and their work setting. Though it was pioneered in expert domains such as aviation, military, and process control, human-centered design today is also used in the design of consumer products. IDEO's design process is exemplary for this approach (Moggridge, 2007, Brown, 2009). The methods and techniques for studying the environment and the situations into which design will be integrated are rooted in the work on user-centered design by Don Norman (1988), studies of plans and situated action (Suchman, 1987), distributed

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cognition (Hutchins, 1995), and naturalistic decision making (Zsambok & Klein, 1997; Klein 1996).

There are fundamental differences between design in the consumer market and design in expert domains. In the consumer market, designers and researchers explore how new technologies such as smart phones, tablet PCs and cloud computing transform everyday settings. In contrast to technology designed to perform non-critical tasks such as text messaging, social networking, and mobile computing, interaction design for critical applications in domains such as medicine, process control, military, and aviation are highly regulated, and the attitude toward innovation is conservative. However, for practitioners responding to the complex challenges that characterize expert settings, design innovation is necessary. Because consumer markets are driven by innovation and novelty, their defining design theme is *otherness*; because expert domains are driven by complex processes and the procedures that have historically been effective, their defining design theme is *consistency*. New designs in expert domains must undergo thorough testing for reliability, compliance, performance, and safety.

As mobile devices continue to migrate between expert and consumer domains, the gap between possible technology found in smart phones and tablet PCs in the consumer market and the certified technology in high-stakes work settings is growing. The use of third party consumer tools in addition to technology in the work place is transforming the work of expert practitioners. Doctors, for example, may use third-party smartphone applications to work around limitations of medical IT systems. General aviation pilots may review approach charts on their smart phones and tablet PCs. So how can designers help bridge the gap between commercially available interaction technology and regulated technology in high-stakes domains?

In response to the limitations of the technology-centered design process that characterized early human-computer interaction design, interaction designers have developed new methods frameworks to explore potential innovation at the intersection of technology, experts, and their work (Buxton, 2007; Kolko, 2006; Roesler, et.al 2005).

Interaction designers work directly with practitioners *and* field observation experts (social psychologists, human factors researchers, cognitive systems specialists, and technical ethnographers) to learn about the adoption of new technology in expert domains. Interaction designers then transform their observations of what is meaningful to practitioners into new, promising design concepts. Before designs are worked out in detail, interaction designers use design mock-ups and prototypes to investigate practitioners' views on how new artifacts and environments affect their practice. Researchers and experts in field observation bridge the gap between designers and practitioners. Representations of design concepts that are developed during this collaborative process form the basis for a shared understanding of the design intent that can be validated by practitioners and further developed during participatory design and feedback sessions. Design representations are low fidelity prototypes produced at low cost. As design artifacts, they make the design-in-progress tangible, create common ground among the design team, and invite design feedback from practitioners and researchers. Such direct collaboration between designers, practitioners and the research team keeps overhead costs low. Design representations, which can exist in a variety of forms, such as mock-ups, paper prototypes, scenarios, and video prototypes, provide a new form of design definition that can be reviewed by practitioners and can serve as hand-over specification for engineering.

How does this design approach scale to design work in expert domains? Approaches to design field study developed for consumer domains are often not suitable for design field study in expert domains. Expert domains are highly structured; regulations, established procedures, domain-specific language and culture, and training requirements make expert work settings difficult to access and often restrict direct observation. Designers who conduct field observation in everyday settings can often assume the presence of "common sense" and they frequently identify with the design audience under observation. In contrast, designers who work in expert domains are often novices within the domain under design. Pilots for example, are highly trained specialists. Their culture is one of precise language, quick assessments, and efficient communication. Interacting with pilots can be difficult for designers who do not have a similar background. Given the position of the designer as outside their field of practice, how can they work with practitioners in expert domains to integrate potentially promising new design concepts into the work setting to improve workflows, make complex systems more transparent, and make operations more safe?

Human/Technology Interaction in Expert Domains

In expert domains, radical technological innovation is not an option. For consumers, the extent to which they depend on the design of commercial products is limited, so they can generally choose to purchase a new product, design, or system over an existing one. Unlike consumers, experts rely heavily on the technology that is already in place, so they often have no choice but to work with the provided technology, make it work for them, or work around it. Pioneers in human factors engineering recognized the high level of experts' dependence on technology while studying the work environments of humans in manufacturing, and the military during World War II (Dreyfuss, 1953). Increasing computerization of high-stakes environments in the 1970s led to the foundation of new human factors fields such as human-computer interaction in computer science (Carroll, 2003), and cognitive systems engineering in interface design for complex human/machine interaction systems such as control rooms, operations rooms, and flight decks (Hollnagel & Woods, 1983). This foundation of knowledge in cognitive work is an important resource for designers in high-stakes domains.

In cognitive systems engineering, field studies inform conceptual models that help designers understand the complex intersection of technology, people, and work. For example, Ed Hutchins' ethnographies of team navigation (Hutchins, 1995) show how collaboration, artifacts, and procedures form the basis for distributed cognition. To determine patterns in cognitive work, designers and researchers employ field observation techniques that help them better understand reasoning strategies and decision-making in technical environments. These techniques include cognitive task analysis, protocol analysis, and technical ethnography (Hollnagel & Woods, 2005). Observational studies have contributed to an expansive knowledge base of cognitive work.

Because there is little margin for operator error in technology-intense settings in high-stakes domains, work demands posed on expert practitioners are high: they must assess critical situations case-by-case and perform to the highest standards. Work settings are complex, work tasks require sophisticated technology, and technology failure has severe consequences. Because their tasks can generally not be completed without the support of technology, experts depend on the technology they use and are trained to work within the

technology's limitations. For interaction design, this implies that interaction affordances, artifacts, and environment shape the nature of the work.

Design of New Directions for Interaction Design in the Commercial Flight Deck

In a research collaboration between the University of Washington's Interaction Design Graduate Concentration and the Flight Deck Concept Center (FDCC) at Boeing, designers worked with researchers, practitioners, and engineers to develop concept designs for the next generation of the commercial flight deck. The commercial flight deck is a classic example of a high-stakes work environment within an expert domain. In this setting, two pilots interact with a sophisticated, automated flight management system that is highly computerized. As the result of computerization, aviation tasks have drastically changed. While 50 years ago a single engine plane could be flown by a single pilot, flying today's larger multi-engine aircraft requires pilots to interact with complex computerized systems. In today's fly-by-wire configuration, electrical and hydraulic systems transfer yoke and pedal interaction across large distances to the configuration of control surfaces on the wings and tail. Instrument flight procedures enable pilots to fly without visibility, and densely packed airspace and fuel optimization require pilots to pre-plan flight routes and allow a fully automated flight control system to control large portions of each flight. Historically, pilots defined flying as 'aviate, navigate, communicate,' yet over time, the current work environment of commercial pilots has been transformed and now entails more and more information management. Pilots are now required to perform new tasks such as programming the flight management system, monitoring the automation, and transferring control from automation to manual flight that require new types of cognitive work.

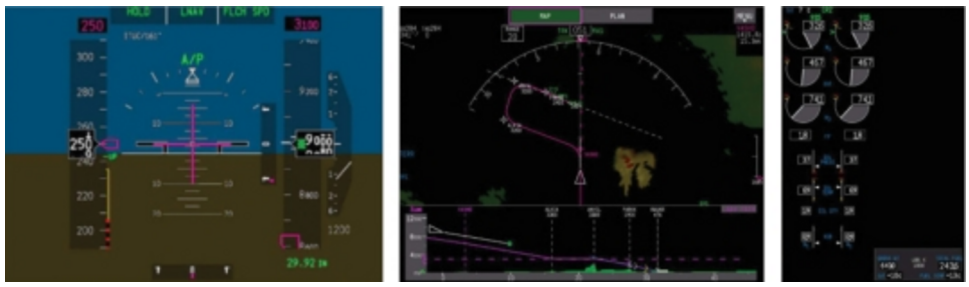


Figure 1: State of the Art Main Flight Information Panels in Boeing's 787 Dreamliner (From Left to Right): Primary Flight Display (PFD), Navigation Display (NAV) and Engine Indicator and Alert Systems Display (EICAS).

(For an overview of current flight deck technology and future directions see Shay, 2005).

We are investigating how new commercial technologies such as surface interaction, mobile devices, and new display technologies could potentially innovate flight deck operations. Pilots use smart phones, tablet PCs, and laptops while working in the flight deck—How can we implement these technologies in designing flight deck operation procedures? How can we design computerized systems to be "team players"—partners with the human crew? And

how can the design of the flight deck work environment better support the collaboration between the pilots and the automation?



Figure 2: Pilots at Work in a Boeing Airplane. Note the Amount of Paperwork and Spatial Arrangement/Storage and Posting of Paper Notes and Folders. How can New Mobile Devices Incorporate this Spatialized Flow of Paper Management?

Understanding the Domain

To begin to frame these questions in early design concepts, the design team met with researchers and engineers at Boeing's Flight Deck Concept Center (FDCC) to identify a possible scope for the project. Our team translated notes from the meeting into concept sketches. As design seeds, the concept sketches explored how to better support the collaboration between pilots and a new layout of flight information displays and flight controls. This set of concept renderings provided a shared design vision and objective that the design team could refer to throughout the subsequent months.

The initial meetings showed the design team the knowledge we needed to acquire, and early design concepts captured as notes and sketches formed a starting point for literature research. Aviation is the birthplace of human factors engineering—the flight deck is a physical environment that can be studied, and many studies are documented. During this secondary research phase, we shifted our attention from design ideation to a focused study of the existing literature on aviation and flight operations. Flight operations procedures (Degani & Wiener, 1994) are specifically designed and provided by airplane manufacturers and airlines. They are the basis of flight training, and they directly reflect the affordances and limitations of both the flight deck interface, and the knowledge, skills, and decision-

making strategies of pilots. To a large extent, the design team can rely on the documentation of flight of operations to study interaction flows during flight procedures. But do real operations differ from the protocol of flight operations procedures? If so, how do they differ, when do they differ, and why do they differ?

Primary Research: Field Observation Studies as Bridge to Practitioners

The close collaboration between designers and practitioners throughout the design process is key to understanding how a new design will transform work. Ideally this interaction between designers and practitioners is established during direct observations of work in the field under study. Participatory design is a primary approach to human-centered design projects in the consumer domain. Using this approach, designers observe prospective users completing tasks in their own work environment, and the designers may even try completing the tasks themselves. However, this approach cannot be applied in the aviation context because access to the work setting of the flight deck is restricted.

Commercial pilots have densely packed work schedules and getting direct access to pilots in participatory design sessions is difficult. Because opportunities to directly observe pilots using the flight deck interface are rare, to get the most out of these direct interactions, designers need to be prepared. Ideal preparation for designers would entail the acquisition of aviation knowledge and practice, and a familiarity with the social context, but typically designers do not have time to develop this deep level of familiarity with the design situation.

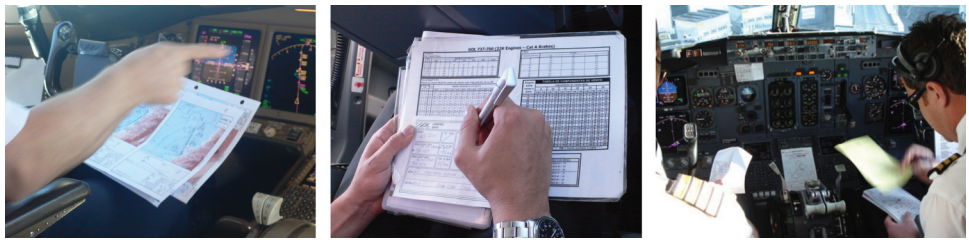


Figure 3: Pilots at Work: (from left to right) Preflight Weather Briefing, Take-off Calculations, Placing the Take-off and Landing Data Card on Display in the Flight Deck

In complex domains such as the commercial flight deck, designers are not prepared to conduct direct observations on their own. Even if they gain access to the work setting, it might be difficult for them to identify when practitioners divert from routines because they are not familiar with practitioners' routine behavior. In highly structured, technical work environments, designers may seek guidance from field study experts who are trained in ethnographic observation. In our project, such guidance was not only advisable, it was necessary. The researchers at Boeing's FDCC provided our design team with this important guidance. FDCC researchers conducted ethnographic field studies with pilots during actual flights, which gave us insight into what pilots consider meaningful during flight operations. Our new understanding of what matters to pilots informed our design explorations.

Process Tracing: Understanding Flight Operations

Aviation literature review grounded the design team with the required understanding of procedures, adaptations, and design challenges in the conversation with FDCC researchers. The knowledge the design team gained from field observations provided a test bed for our assessment of how pilots would adapt to the proposed design concepts.

To put our understanding of flight operations to the test, we conducted a detailed process trace of a typical flight segment. This process trace challenged our understanding of the conceptual model that structures the work of pilots in the flight deck—how pilots interact with flight deck systems and how they collaborate with each other. In a meeting with the FDCC team, we analyzed a flight between Chicago O'Hare and Denver in detail.

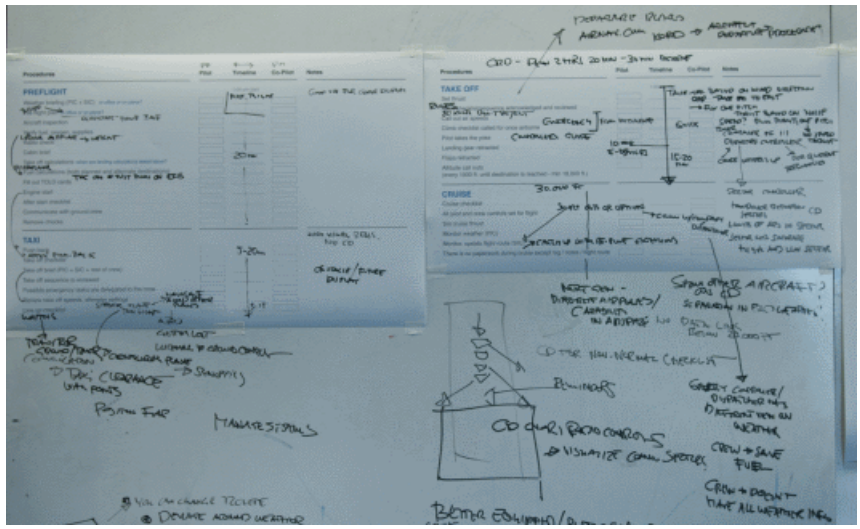


Figure 4: Process Trace of a Typical Flight between Chicago O'Hare and Denver (Excerpt)

As was our practice for all meetings, we made an audio and visual recording of this discussion and white-boarding session. These recordings allowed us to conduct a secondary analysis of the meeting and decode domain-specific language and analyze the researchers' quick verbal references.



Figure 5: A Typical Early Stage White Board Meeting

In a retrospective analysis of the process trace recordings, we used an abbreviated version of Rasmussen's abstraction hierarchy for complex systems as functional decomposition

(Rasmussen, 1985) to identify the functional reasons, rules, processes, roles, and physical artifacts used by pilots during key interaction sequences.

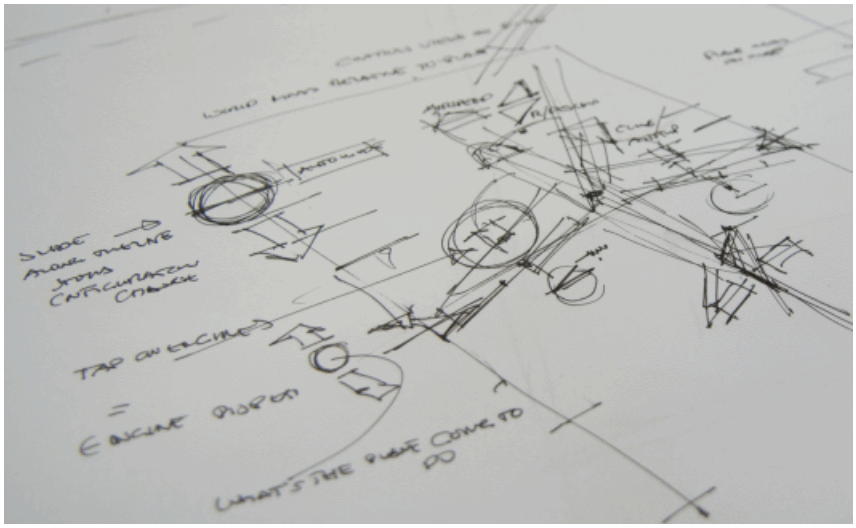


Figure 6: Sketch from the Process Trace Analysis

Interaction sequences during flight operations are also structured by procedures (Degani &Wiener 1994) and checklists (Degani & Wiener, 1990). For example there are specific checklists that walk pilots step by step through setting up the plane in a specific control surface configuration before flight or provide instruction on how to isolate and respond to faults during non-normal operations. After we documented all normal procedures during the timeline of a typical flight, we contrasted these normal operations with a number of operations for non-normal scenarios, such as an engine failure. We reviewed the impact these non-normal operations had on the flight plan to challenge our conceptual model of the system under design with interruptions that required us to explore the transition between interaction flows and mechanisms to resume operations after the non-normal operation fault had been resolved.

Scenario Building and Video Prototyping as Concept Testing

We tested our process trace by developing an authentic flight operations scenario that used the new interaction concepts we proposed in our design. The scenario was intended to capture a narrative of the pilots' interaction with our design. The development of the scenario tested our understanding of the temporal and procedural dynamics of flight deck operations, and it provided the framework for the scope of the design in progress. Developing the scenario also helped us to identify key interactions that the design needed to encompass—entrance and exit points in interaction sequences and task switching that might occur during parallel tasks in the scenario. Developing the scenario also forced us to tune each step in the interaction to concrete sequences of operations, causes and effects, and realistic timeframes. Identifying these timeframes allowed us to produce a timeline that revealed high workload and low-

paced flight segments, and provided us with a concrete understanding of pilots' attention management, and the associated display and task switching demands. We used the scenario as a script for a visual storyboard. At each stage of the interaction sequence, the storyboard prompted us with the flight deck's requirements and constraints for display views and interaction affordances.



Figure 7: A full Scale Cardboard Mock-up of the Flight Deck Provides an Authentic Spatial Setting to Evaluate Information Display and Physical Interactions with Screens and Physical Controls (Dan Ostrowski and Nate Landes)

The storyboards served as an outline for the design work needed for each display sequence. Once the display design work was completed, the scenario and display printouts allowed us to implement paper prototypes of operations captured within the scenario. Enacting the scenario in the form of a paper prototype session allowed the design and research teams to experience flight deck operations from a first-person perspective. A series of such paper prototyping sessions served as anchor points for design meetings and gave us opportunities to verify the authenticity of the scenario with the domain experts.

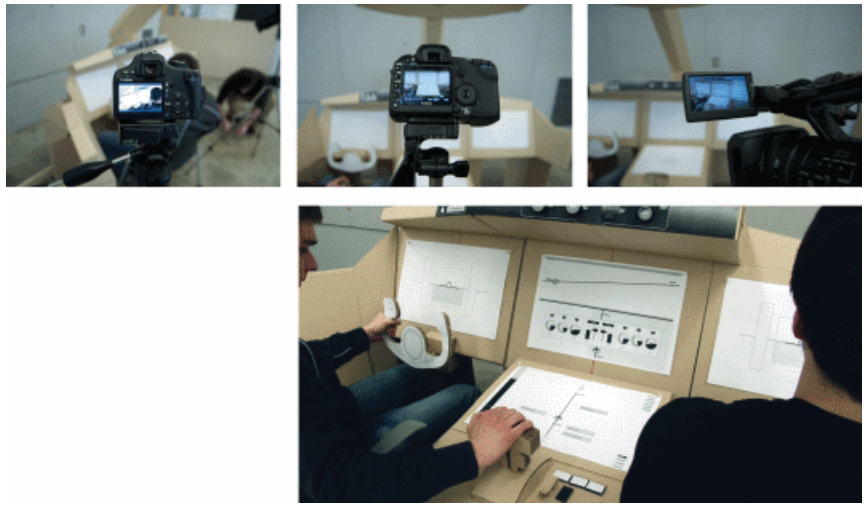


Figure 8: Video Prototyping of key Scenarios that Demonstrate Innovative Aspects in the New Interface Design and Their Effect on Flight Operations (Nate Landes, Dan Ostrowski, and Sergei Larionov)

During the paper prototyping sessions set in the full scale flight deck cardboard mock-up, we used video recording equipment to document display and paperwork flow between the pilots. When we edited the video, we were able to observe the interaction flow in the new design environment in direct correlation with current operations—all this with minimal prototyping requirements and a very cost-efficient mock-up.

Design Concept Representations and their Role in Meetings

Various design concept representations, such as sketches, diagrams, live white-boarding, process trace, and the full scale cardboard mock-up of the flight deck played a central role in meetings throughout the design process—they grounded discussions with concrete views on design ideas. Sketches and diagrams helped us identify common ground among team members, and during our discussions, design aspects could be addressed by pointing at them or annotating them—we accomplished this by sketching over display printouts or making marks on the flight deck mock-up. During our bi-weekly meetings with the Flight Deck Concept Center, we found ourselves using the full-scale flight deck mock-up to illustrate our discussions, and eventually, we began to convene our project meetings there. The flight deck mock-up completely replaced slide decks or printouts of design concepts we had previously used to illustrate our discussions.



Figure 9: A Typical Design Meeting During the Video Prototyping Stage Using the Full Scale Flight Deck Mock-up as Shared Representation of Design Intent

Because we held our meetings in the mock-up, we were able to point at areas of design interest, possible locations for features, and to sit in the pilot's seat while talking to a team member in the co-pilot's seat. This provided us with a simulated first-person perspective into the flight deck as work setting—all during the emergent phase of the design before concepts were realized as higher fidelity models or working prototypes.

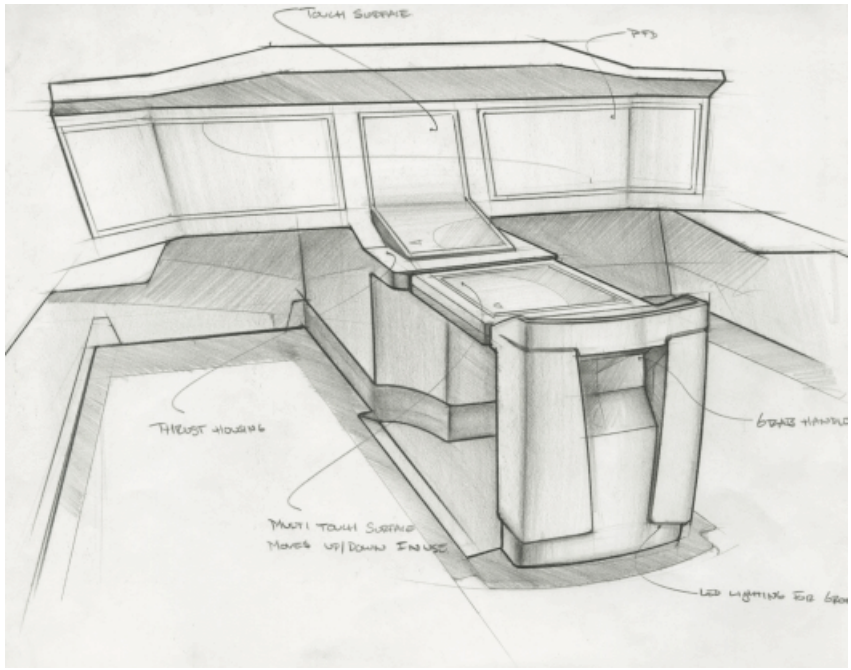


Figure 10: Industrial Design of the Physical Flight Deck Layout, Mid-stage Design Sketch (Stephen Minarsch)

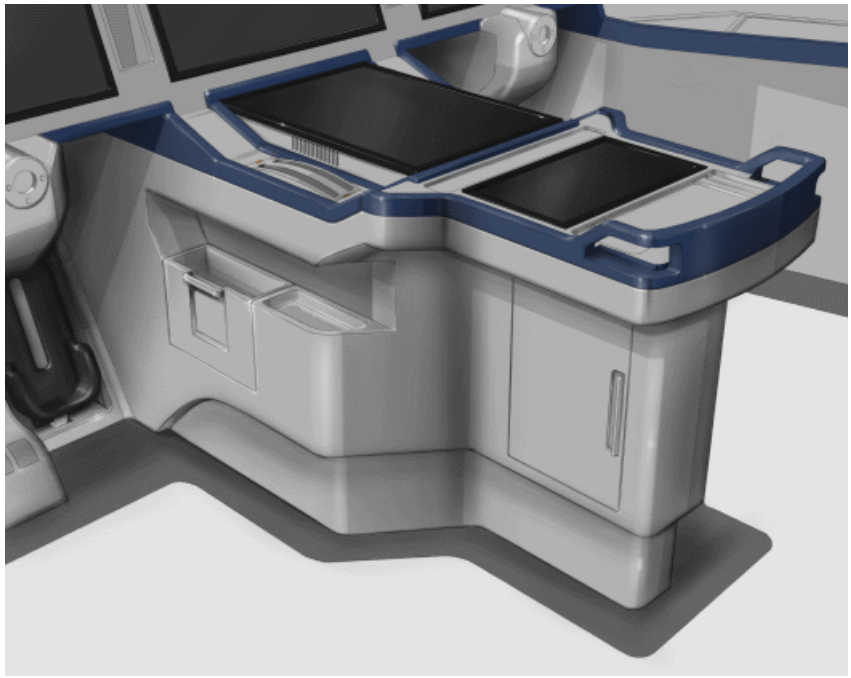


Figure 11: Mixed Computer / Marker Rendering of an Early Design Concept of the Aft Isle Stand/Center console (Stephen Minarsch)

At the end of the conceptual interaction design phase, the video prototype served as self-contained documentation of the design because it showed an outline of operations and associated display and interaction requirements that we had developed as a comprehensive design concept at this point in the design. The video prototype served as an "abstract" of the design and allowed the design team to quickly introduce the design concept and intent to pilots and technology experts. Practitioners shared stories of use with us in response to the video – accounts of flight episodes when a particular design feature was helpful, or stories of how pilots had coped with critical situations in the existing flight deck. These stories shed new light on the possibilities for novel operations in our flight deck concept design, and were particularly helpful to us because they hinted to tacit knowledge that was critical during operations. Because of the video prototype, we were able to elicit concrete feedback and clarify the design direction (what will be designed) before detailed aspects of the design and documentation (how it can be designed and implemented) were discussed in subsequent meetings.

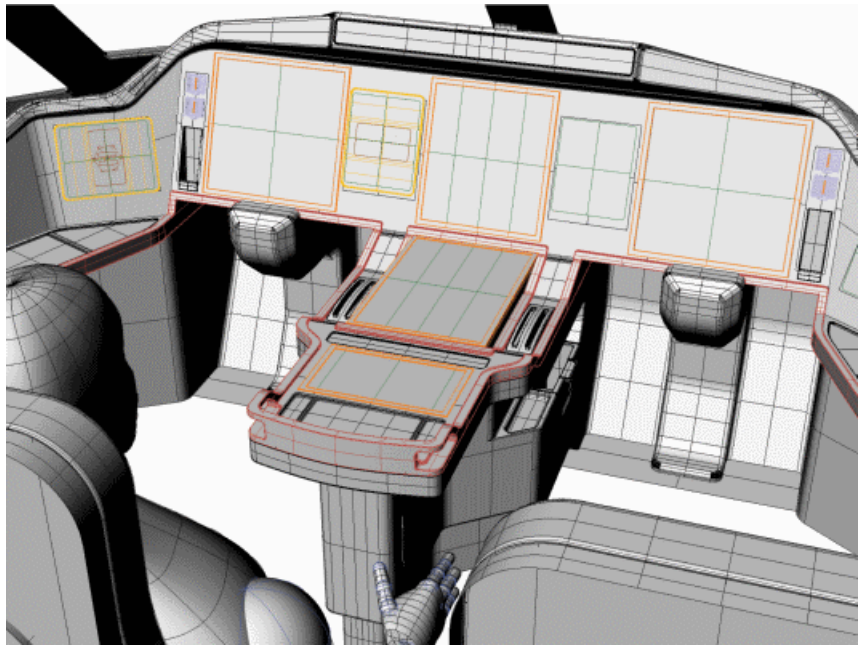


Figure 12: Computer Model Rendering of New Flight Deck Layout in Progress. Early Design Concept (Stephen Minarsch)

The video prototype serves as a working model—as a capture of the interaction flow it provides a sequence of interaction segments that can be re-ordered, edited or refined until the entire operations sequence is worked out to the satisfaction of the team. The refined video prototype then serves as a blue print for the next stage of design work—the detail design of the information content and its representation.

Conclusion - Interaction Design in an Expert Work Setting

Our process for developing new directions in interaction design for the commercial flight deck considered interfaces, interactions, and the physical work environment. Based on field observations of pilots at work, our design addresses the adaptive display of flight information in correspondence to the flight operations sequence. We examined new technologies to determine the best way to provide new affordances for improved work flows. The new work flows in turn required newly designed artifacts: new displays, new physical control devices, and a re-organization of the physical structure of the flight deck environment. At the beginning of each design revision, the design team carefully examined the relationships between designed artifacts and the operations they afford. Changes to the artifacts necessitated new operation flows which, in turn, led to the development of new artifacts.



Figure 13: Final Design Concept of Main Instrumentation and New Physical Layout of the Commercial Flight Deck

Our collaboration with domain experts, in this case, pilots and researchers, allowed us to identify promising design directions from their perspectives, and helped us identify concrete technology trends. As designers, we hypothesize about promising futures and then share our hypotheses with the various stakeholders who control the resources required to realize our designs.

Designing is hypothesis building and it is the hypotheses that appear realistic and desirable that delineate the design direction. From the existing literature on aviation, we know the limits of success and the boundary conditions that render operations brittle; these limits are documented in investigations following accidents that were the result of design failure. However, the same knowledge base that reminds us of our limitations also provides us with the criteria for excellent practice and working conditions for top-level performance; these criteria are documented in the many cases where, despite technical failure, the expert pilots turned a complicated situation around.

Designers are comfortable working with incomplete data—because they often work with concepts that have yet to be implemented, they understand that design innovation entails working with information that cannot yet be obtained. As a mode of experimentation, a design in the conceptual stage produces new data that cannot be collected in existing operational settings. Representations of design concepts provide an anchor point for discussions among the design, research, and development teams; they inspire experts in these various fields to exchange knowledge in response to concrete challenges imposed by the design. Because members of the design team have different roles and expertise, shared design issues are examined from several different perspectives. Sharing representations of design concepts helps elicit feedback from practitioners, and working with practitioners at this early stage of design ideation allows designers to explore the projected consequences of operations before systems are built. Understanding the perspective of experienced practitioners is invaluable for designers who wish to simulate possible operations with the new system under design; instead of the design being based on the designers limited, design-centered perspective, design concept representations form the basis for simulation by practitioners. Producing representations of design concepts transforms the design process into a mode of inquiry—design becomes experimentation.

Designers can use their representation capabilities to provide valuable insight into the collaborative process and to help develop the right design the right way. Design prototypes allow stakeholders to observe interactions and gather feedback from practitioners before they commit significant resources toward developing new technology.

Design can make a difference *before* concepts are realized. Design failure can be identified before it has real world consequences. In this participatory design process design failure happens on paper and in stories of use—not in the real world. Stories of use are based on the expertise of design participants—designers, researchers, and practitioners. Design concepts become representations of shared design knowledge at the intersection of technology, people, and their work.

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Dr. Axel Roesler is an Assistant Professor and Chair of the Interaction Design Program at the Division of Design at the University of Washington. He is also an Adjunct Assistant Professor at the Department of Human Centered Design and Engineering. He received his Ph.D. in Cognitive Systems Engineering with a specialization in Human Centered Design from The Ohio State University. He also holds an M.F.A in Industrial Design from The Ohio State University and a Diplom in Industrial Design (equivalent to M.A.) from Burg Giebichenstein, Hochschule für Kunst und Design (University of Art and Design) in Halle, Germany. He came to the United States as a Fulbright Scholar in 1998. Recent research projects address interaction design and cognitive support in decision-making aided by health information technology, new interaction design directions for the commercial flight deck, new concepts for interacting with procedural instructions and task plans, and an interface framework that applies principles of perspective to control remote views into dynamic spatial settings. Industry partners and research collaborators include Boeing, Microsoft, Intel, Group Health, and the Institute for Simulation and Interprofessional Studies at the UW School of Medicine.

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