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Investigating Interaction Conflicts in Collaborative Cockpit Displays

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Emerging cockpit architectures that use cursor control devices and keyboards for input and control of independent and shared cockpit displays raise important challenges for supporting effective task performance. A key challenge is the amount and variety of information located on these shared displays causing interaction conflicts between the pilots. The Single Display Groupware collaborative interaction model and previous research in cockpit systems is used as a framework for investigating interaction conflicts in collaborative cockpit systems and for developing conflict mitigation strategies. Informed by operational sequence modeling and an action/information requirements analysis, gaze tracking and associated interface modifications were identified as potential design changes that would not only help address the interaction conflict problem, but also to support individual and collaborative work in other ways. Initial development of interface concepts taking advantage of gaze tracking outputs are presented and plans for experimental evaluation of those concepts described.

I. Introduction

As cockpit displays have progressed from using largely analog instruments to using integrated digital avionics (i.e. glass cockpits) with significant levels of automation, there is a commensurate growth in the need to interact with and control computers driving the displays and automation functions. Data input into these flight computers has traditionally (and successfully) been accomplished using entirely keyboard, button, and knob-based input. However, emerging cockpit configurations are based on the concept of a “Windows-style” interface that uses an on-screen cursor with a cursor control device and a keyboard for input. Many of these systems propose a layout similar to the one shown in Figure 1, in which there is a display on each side of the aircraft (one or more screens for each pilot) and a center display (one or more screens) that is shared between the pilots.

The primary function of the shared display is to allow the pilots to complete flight planning and flight management tasks, and it therefore allows for the display of flight planning and management tools and visualizations such as digital maps, waypoint lists, and air traffic information. The shared display is also used to access secondary functions, including aircraft systems management, navigation sensor management, communications management, maintenance information, and checklists. Finally, if a primary flight display fails, the shared display can also be used as a back-up primary flight display.

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With such a wide range of functions being monitored and controlled on the shared display, it is likely that situations will arise that create conflicts between the pilot and co-pilot interacting with the system. Such “interaction conflicts” can be defined as situations in which one user’s interaction with the system interferes with another user’s interaction. In addition to these interaction conflicts, the multiple parallel tasks that pilots must accomplish leads to the potential for interruptions. Aviation systems are safety-critical, so it is important to assist pilots in achieving robust control and in recovering from any interruptions as quickly and effectively as possible. The goal of this research is to more clearly understand the challenges of interaction conflicts in the cockpit environment, to identify related challenges, and to develop design methods to mitigate these challenges. This paper presents the preliminary phase of this research, which began with an analysis of the work domain to help ground our understanding of the potential human-computer interaction challenges in the emerging cockpit architecture discussed above. We then discuss a design opportunity inspired by this analysis that we believe has the potential to mitigate the interaction conflicts and interruption recovery challenges mentioned above, as well as to help provide pilot situation awareness, which is known to be of critical importance in cockpit operations[1]. To demonstrate this design opportunity, we introduce some preliminary display concepts. We then conclude with a discussion of our ongoing and future research directions.

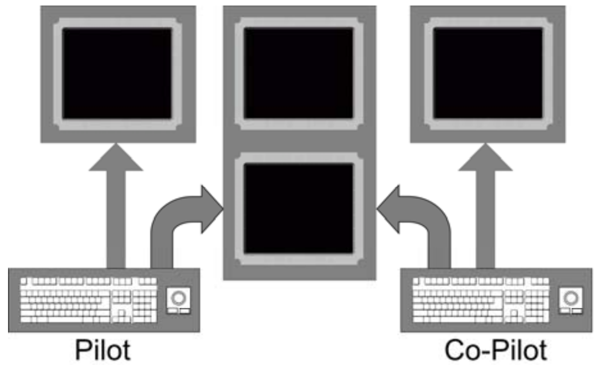

Figure 1. Emerging Cockpit Architecture.

II. Background

To put our work in context, this section provides a brief review of the relevant literature, and details some of our preliminary efforts to explore this problem space. We begin by considering literature related to interaction conflicts and by explaining our framework for understanding the multiple conflict types that may occur. This is followed by a discussion of previous work on interruptions and interruption recovery support. Finally, a section dealing with awareness research examines how awareness concepts from aviation and other work domains can be applied to the emerging cockpit context.

A. Interaction Conflicts

To help structure our investigations of the task domain, we developed a framework for understanding the types of interaction conflicts that may occur in the context of a shared cockpit display. This framework is grounded in the background literature from the human-computer interaction (HCI) research community, in particular the HCI work focused on Single Display Groupware (SDG) systems, and from prior cockpit research.

1. Single Display Groupware (SDG)

The SDG model was introduced by Stewart et al.[2] to describe co-located multi-user computing systems with multiple, independent input channels (generally, one for each user) and a single output channel (shared between all users). Research on SDG systems has more recently expanded to include co-located collaborative systems that comprise one or more shared displays (such as tiled wall displays) that are simultaneously used by multiple people[3], similar to the shared display in the cockpit architecture shown in Figure 1.

Research examining interaction conflicts in SDG systems often assumes that conflicts will occur and moves on to developing software techniques (such as translucent pop-up menus[4] and flexible interface artifacts[5]) or general strategies[6] to mitigate them. One example of a general conflict mitigation strategy proposed by Morris et al.[6] is the “no selections” policy, under which an input to the system would only be accepted if no other user has an active selection that would be affected by the input. Though this strategy and widget-driven approach is effective as a generalizable method for mitigating conflicts, when designing an interface for a specific task it would likely be more effective to examine the task to identify potential conflicts, determine their source and impact, and tailor the interface for optimal performance.

2. Cockpit Research

When designing a shared cockpit display, an important part of this task-based design process is to examine existing cockpit procedures and work practices. While much of this information is available from subject matter

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experts, ethnographic studies that have carefully examined the interactions between members of the flight crew and between the flight crew and the cockpit have revealed work practice information that is difficult for experts to articulate. These studies include investigations of the use of cockpit elements as memory aids[7] and the use of paper in the cockpit[8]. Knowledge obtained from these studies provides important insights into potential interaction conflicts. For example, Nomura et al.'s[8] research on paper use in the cockpit showed that the pilot flying and pilot not flying kept much of the same information (such as approach plates, airport maps, departure and arrival procedures) easily available, but some specific pieces of data (such as crosswind tables, circling charts, and V speed references) were only used by one or the other. The incorporation of any of this information into the shared display will have implications for the design of the interface. For instance, when information is used by only one pilot or the other, it will be important to ensure that the pilot who needs the information can access it when required without affecting the ongoing tasks of the other pilot.

Another important point to consider in this context is that most modern two-pilot cockpits are intended to be operated such that that one pilot is always "heads-up" (actively flying/monitoring the state of the aircraft) so that interaction conflicts should never occur in-flight. However, anecdotal evidence from pilots indicates that occurrences of "two heads in the cockpit" can readily occur in modern, automated aircraft. Thus, interaction conflicts are possible in the advanced cockpit and should be considered in the design of the shared cockpit display.

3. Interaction Conflict Framework

When trying to understand computer use, it is important to consider both "active" and "passive" use. Design for active use is concerned with the design of effective mechanisms for direct interactions with the system, while design for passive use is concerned with the design of effective information visualizations to help with decision making or data comprehension; these design elements are intended for the visual channel only and do not require user interaction. Both active and passive computer use are relevant for a discussion of interaction conflicts in a shared display situation. To understand the interaction conflict space, we propose the framework illustrated in Figure 2. This framework contains three main categories of potential conflicts:

1) input-input (i.e. active-active) conflicts, in which the users attempt to issue mutually exclusive inputs to the system;
2) input-visual (i.e. active-passive) conflicts, in which one user attempts to issue an input that affects the display of the other user's desired output; and
3) visual-visual (i.e. passive-passive) conflicts, in which the users desire information that requires mutually exclusive outputs.

		User 1 Interaction	
		Input	**Visual**
User 2 Interaction	**Input**	Input-Input Conflict	Input-Visual Conflict
	Visual	Input-Visual Conflict	Visual-Visual Conflict

Figure 2. Interaction Conflict Framework.

Each potential interaction conflict in a shared cockpit system architecture fits into one of these three categories, and the need to identify and assess potential conflicts of all three types helped to determine what type of analysis process would be used in examining the task domain. This framework can also provide a focus when designing conflict mitigation strategies, as it is important to recognize that different conflict types may require different mitigation strategies.

B. Interruption Recovery

The potential for interruptions to occur and distract an operator from their task is an issue in many work domains, but is of particular relevance when examining complex domains. A sizeable body of research has been published examining interruptions in a variety of tasks, with results almost invariably showing that interruptions have a significant effect on task performance[9-17]. In a study examining interruptions in relatively simple tasks (such as addition, counting, reading comprehension, etc.), Bailey et al.[10] found that interrupting a user decreased their task performance and increased their level of annoyance with the task, and that the magnitude of these effects was related to their perceived mental workload at the time of the interruption. These detrimental effects can also be observed in more complex tasks; McFarlane[12] discusses how interruptions are more likely in tasks involving automated systems (including aviation) and demonstrates that there is decreased performance on such tasks when interruptions occur.

In a time and life-critical domain such as aviation, interruptions and the resulting negative effects can have disastrous consequences. For example in 1987, Northwest Airlines Flight 255 crashed on takeoff after the pilots were interrupted from their normal pre-flight routine and failed to set the flaps[18]. In a study specifically examining interruptions in an aviation setting, Loukopoulos et al.[11] found that aircrew performance on flows and checklists was noticeably affected when the crew members were interrupted while carrying out these tasks.

Many researchers have proposed and studied methods for mitigating the effects of interruptions on task performance. In a series of studies examining the effect of providing users with a warning before the onset of an interruption, Altmann and Trafton[9, 17] found that the availability of primary task information during the warning period improved recovery performance after the interruption. Additionally, they speculated that when resuming the task, the presentation of primary task cues (such as the active window or cursor position when the interruption occurred) would improve recovery performance. While this method is simple to implement and does provide some benefit, it is limited in that it does not provide any information about what occurred in the primary task while the user was interrupted. Other interruption recovery assistance research has focused on providing specific tools to address this limitation, including change logs[15], instant replay tools[16], and integrated change log/instant replay tools[13, 14]. All of these methods have shown some success in improving interruption recovery performance; however, tools of this type tend to require dedicated display space (which is difficult to provide in a cockpit application) and generally require the user to interrupt their primary task to recover from a previous interruption.

C. Awareness

In the aviation domain, the concept of situation awareness[19] has become very popular over the past two decades as a metric for and predictor of pilot performance. In other work domains, the term "awareness" has been used with many other modifiers, and some of these other "types" of awareness are useful to consider in the context of the emerging cockpit architecture. Some examples include peripheral awareness (awareness information sourced from an operator's peripheral attention[20]) and group awareness ("the up-to-the-moment understanding of others' activities in a shared space"[21]). In the cockpit environment, there are a variety of ways in which a pilot can obtain awareness information. For example, in older two-pilot cockpits, peripheral awareness information was available simply from peripheral vision, by observing that a co-pilot was reaching to adjust something on the panel. However, in software systems (such as modern glass cockpits), this "natural" form of peripheral awareness information is often lost, which has led to research in providing analogous information on a computer display[20].

An important limitation of existing approaches to providing on-screen awareness information is that (in most cases) this information is displayed separately from primary task information. In addition to requiring dedicated screen real estate, this approach increases the cognitive burden on the user by forcing them to interpret how the awareness information relates to the primary task. Group awareness information can also be found in a number of different forms, including some notable research into the development of software "widgets" (such as buttons and menus) that provide real-time information about collaborators' actions[21]. These widgets are useful at providing information about the current situation, but are less useful in providing an overall context for how the situation has developed. There has, however, been some research into providing such contextual information; notably, Hill et al.[22] suggested creating a computational analogy to paper document "wear" (e.g. dog-earing, annotations, etc.) to provide information about the history of collaborative work on an electronic document. For example, in their "EditWear" shared editor software application, visual traces of user activity in an electronic document is indicated via a dynamic histogram embedded into the scrollbar of the document window.

III. Domain Analysis

A. Research Approach

To expand our understanding of the task domain and the challenges associated with the emerging cockpit architecture, we developed a multi-stage analysis approach. The first two stages in the approach focused on understanding the cockpit environment and the functional requirements for a modern cockpit system, while the third stage (conducted partially in parallel with the first two stages) aimed to confirm the validity of the first two analysis stages and provide an operational context for the results.

Our domain investigation began by creating a form of Operational Sequence Diagrams (OSDs) for representative scenarios of cockpit interaction. Operational sequence diagrams "are graphic representations of operator or user tasks, as they relate sequentially to both equipment and other operators."[23] Since it is difficult to examine the richness of collaboration (for example, ongoing coordination of interrelated activities) using the low-level task approach that is typical to operational sequence modeling, we used a modified approach to instead consider coordination and collaboration in the performance of higher-level functions. This approach ensured that we did not lose the richness of collaboration through an overly analytical approach, yet still helped us to leverage the strength of OSDs to identify elements of operator work where collaboration is important. Using this approach we were also able to perform our analysis at a level that is relatively independent of specific technology solutions, which should help to ensure that our results can generalize across low-level differences in cockpit technology.

The basis of operational sequence modeling is an appropriate operational scenario, and the scenario selected for our purposes was a change of approach during a flight. This scenario was selected to provide a series of tasks and decisions that were sufficiently challenging to stress the collaboration between the two pilots without making the analysis excessively complex, allowing us to explore key information sources and interactions within the cockpit (both between humans within the cockpit, humans and automation, and humans outside the cockpit).

Our high-level operational sequence modeling approach was used to create an OSD for this scenario, and this model was then used as the basis for a more detailed analysis of the action/information requirements of a limited set of tasks. These tasks (e.g., evaluating and discussing options for a new approach) were selected based on their relevance to the emerging cockpit architecture and on the extent to which they were a venue for collaborative interactions between the two pilots. Each of the functional requirements selected from the OSD was broken down into action requirements (the actions that must be carried out to accomplish the function) and information requirements (the pieces of information needed to carry out the actions).

To supplement the above analysis activities, we performed a third stage of analysis in which we conducted several informal subject-matter expert interviews. The interviews were conducted in parallel to, and helped inform, the functional and action/information requirements analysis. Interviews were conducted with five pilots (including three former Canadian Forces test pilots and two current civilian airline pilots, with a minimum of 3,000 flight hours) and one additional cockpit design expert. Results were used to refine the understanding of the tasks, information requirements, and typical actions within the example scenario.

The information gathered in these activities clarified our understanding of the collaborative design challenges that may arise in the advanced cockpit, as discussed below. Our domain investigations also inspired a novel method of human-computer interaction and information display, described below, that addresses these challenges.

The operational sequence modeling approach was valuable and useful in helping us identify design challenges and implications, but it is not intended to be a singular, comprehensive analysis. The amount and scope of information available from an OSD is directly related to how representative the scenario is of the operational environment, and in the aviation domain there is a large amount of variation in the potential usage scenarios and in the particular organization of events within a given scenario. For example, considering just the approach phase of flight, potential scenarios could include a simple textbook approach, an approach change, a missed approach followed by either a second attempt or a change of approach, or a number of other possibilities. However, even considering this limitation, the operational sequence modeling approach did provide us with an initial step towards identifying several important design challenges related to the shared displays in an advanced cockpit.

B. Results

The results of the operational sequence modeling analysis identified several important design considerations and challenges, confirming some of our hypothesized challenges and raising additional design considerations. These design considerations and challenges are summarized below.

There is a need for team situation awareness. This refers to the fact that each pilot not only needs to be aware of the state of their aircraft and the environment (conventional SA[19]), but also of the actions and the awareness of their teammate. This shared situation awareness, a common understanding that collaborators are “on the same page”, is important for any team situation, but particularly relevant in time-critical or life-critical environments like aviation. Attempting to support this type of awareness in the proposed cockpit architecture has become a significant part of the focus for this project.

Significant collaboration occurs between pilots, and between pilots and other actors. The limited scenario investigated using the OSD approach showed multiple instances where the pilots must communicate decision options, provide instructions, confirm and cross-check the other’s actions, or otherwise engage in collaborative actions and activities. For example, the need to evaluate and discuss potential options for the alternative approach requires both information exchange both between the pilots, and between the pilots and other actors such as air traffic controllers. Examination of these instances of collaborative activity provided a focus for determining the pilots’ action information requirements.

Information used in collaborative activities can be historical and dynamic. Follow-up interviews with subject matter experts (as described in Section III A above) indicated that beyond the instances of collaboration that can be explicitly identified, pilots’ work always includes an effort to maintain a common situational awareness picture. These interviews highlighted the need to consider how information requirements change over time, and how information gathered during one activity is used and supports later collaboration decisions and actions. These design considerations reinforced the need to provide a cockpit design that promotes awareness of current and historical events. Such design support would be particularly important to assist pilots in quickly regaining awareness of their previous task status and of the updated system state when resuming a task following a task interruption.

Pilots operate in a multi-task environment. The analysis of the scenario showed that both pilots had at least one and often two tasks ongoing related to the change of approach in addition to the continuous task of flying and monitoring the progress of the aircraft, as shown in Figure 3. In follow up interviews pilots indicated that it can be a significant challenge simply to keep up with all of the individual tasks required to safely complete a flight. This prevalence of multiple tasks competing for a pilot's limited attention resources highlights the need for the cockpit design to mitigate the costs of task switching, and to facilitate the pilot's ability to quickly resume a task after being interrupted by another ongoing task.

A wide variety of information is required and a large amount of this information is shared. Tracing the information requirements needed to support the collaborative activities involved in selecting a new approach in the flight plan showed the variety and amount of information that must be shared and commonly understood by both pilots. The variety of information required is demonstrated by the sheer number of qualitatively different information requirements that appear during this scenario; even a single function from the OSD can require many different types of information. For example, when identifying options for a new approach, pilots need access to approach plates for the destination airport, current weather information, airport traffic information, and potentially several other situation-dependent items. Considering that each pilot may be performing more than one of these functions at a time, the amount of information that may be needed at a given time could be significant. The large amount of shared information appears in several steps where both pilots are working to complete similar functions, such as evaluating and discussing a new approach. In this case, both pilots need access to the various pieces of information about the new approach, and they will likely need access to this information at the same time.

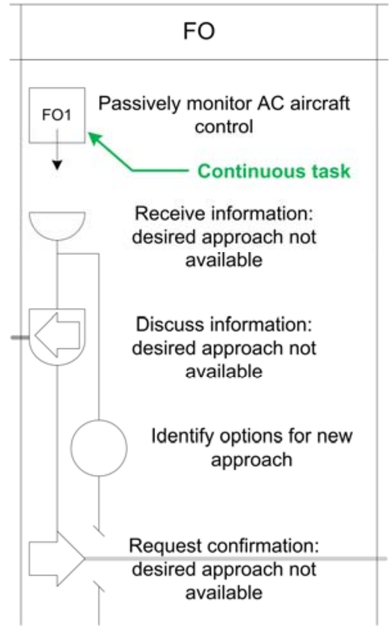


Figure 3. Example of multi-task environment.

IV. Cockpit Interaction Awareness Display Concepts

Based on the results of the analysis, a key challenge for maintaining awareness is the potential for the loss of peripheral awareness information, as many interactions that were once accomplished using physical controls on the instrument panel have been moved into software. We propose that these issues, as well as potential interaction conflict and interruption recovery issues, can be addressed by augmenting the interface with visualizations of the history of each operator's interactions with the interface (using a concept similar to the "computational wear" shared awareness design approach discussed in Section II C). This historical interaction data could include, for example, information about which interface components were most recently used or most frequently used by either or both pilots.

In addition, we suggest that to further improve the utility of this interface augmentation, a gaze tracking system could be added to provide additional data to the system of the pilots' use of the cockpit displays, allowing the system to detect input-visual conflicts, to determine when an operator has been interrupted, and to provide peripheral awareness to each pilot about their fellow crew-members activities.

A. Gaze Tracking

The concept of using gaze tracking as a component of a computer interface is not new; many researchers have experimented with different ways of using a gaze tracking system to augment or replace a cursor control device[24-26]. However, much of this research has been hampered by the accuracy of gaze tracking systems which, even under ideal conditions, are limited to 0.5-1° of visual angle. At a distance of 50 cm (the standard viewing distance specified in MIL-STD-1472F[27]), this allows for an accuracy of 0.45-0.9 cm, while typical windows toolbar buttons can be as small as 0.3 cm. Some research has attempted to find ways of mitigating this accuracy problem[26, 28], but the limited success of these systems indicates that gaze tracking has limited real-world application as a computer interface component. However, aviation computer interfaces are generally custom designed and are already required to use larger components than home computer systems; for example, MIL-STD-1472F dictates that "Aircraft display characters and symbols that must be read in flight shall subtend not less than 7 mrad (24 min) of visual angle"[27] (almost 0.5°). While this means that individual characters and symbols may be too small for a gaze tracking system to identify, components (such as buttons) that are made up of multiple characters should be (and could be designed to be) sufficiently large.

B. Concept Examples

To augment a cockpit interface with both input and visual usage history information, it was necessary to develop a method for showing this data that was simple enough to be easily understood, flexible enough to display several different types of information, and extensible enough to be used on a variety of interface components. The proposed display concepts for providing cockpit interaction awareness use a colored border and a variety of visual treatments to provide different types of information, including user identity, display use, recency, and importance (see Table 1, below).

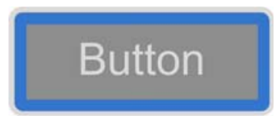
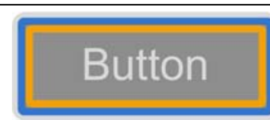
Treatment	Meaning	Example
Border and Color	Basic treatment to identify user and show usage	 
Fading	Border fades over time to show recency of use	
Thickness	Thicker border is used to indicate greater importance (based on frequency and total duration of use)	
Relative Position	Relative position of two borders indicates which user's interaction was more recent (outer border)	

Table 1. Proposed interface treatments for providing cockpit interaction awareness.

While Table 1 uses buttons to demonstrate the proposed interface treatments, the treatments themselves can be easily applied to other interface components. Additionally, because the treatments can be used to provide information about input interaction, visual interaction, or both, it was necessary to decide what level of information was appropriate for different components. To reduce the potential for clutter, the proposed concept provides visual interaction information (sourced from the gaze tracking data) at a general window level, and provides only input interaction information at an individual "widget" level (e.g. buttons, map symbols, etc). Figure 4 shows an example of what this concept might look like when applied to an interactive flight planning map window (map image adapted from work by Finlayson[29]).

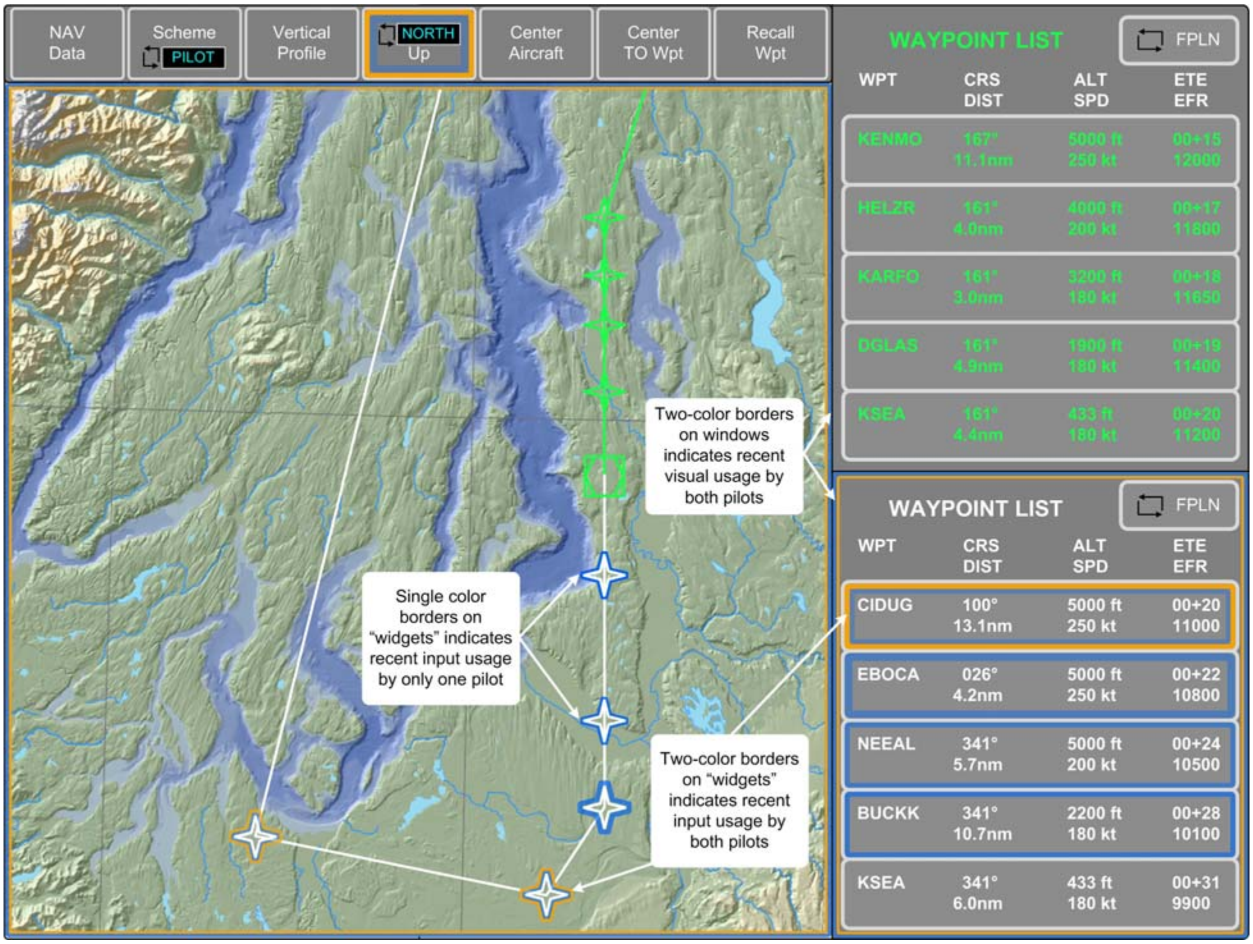


Figure 4. Example showing interface treatments on an interactive flight planning map.

V. Proposed Evaluation and Ongoing Work

The next major step in this research is to evaluate the proposed interface design approach. To this end, we are currently focused on improving the display concepts and integrating them into a working prototype that can be used for user evaluations. To conduct these evaluations, scenarios will be recorded using an existing prototype cockpit and a separate gaze tracking system. The data from these two systems (video and user interaction data from the cockpit interface and gaze data from the gaze tracker) will then be synthesized to create a video that displays proposed interface treatments on the cockpit interface. The two videos (original and synthesized) will then be shown to representative users to test the utility of the interface treatments.

VI. Conclusions

We have presented a domain investigation of collaborative cockpit operations aimed at identifying human-computer interaction design considerations and challenges with advanced cockpit displays that include a shared display component. An operational sequence modeling analysis, performed at a high functional-level on a typical aviation scenario of pilots conducting an in-flight approach change, was effective in developing an understanding of the collaborative work requirements in the cockpit. Combined with an action/information requirements analysis and informal subject matter expert interviews, the OSD helped to clarify our understanding of potential interaction conflicts, task interruption challenges, and awareness requirements in advanced cockpit architectures.

To address these challenges and design requirements, we are exploring potential interaction awareness display concepts designed to augment the cockpit interface that provide historical interaction data for each pilot. These display concepts, described briefly in this paper, can be used to visualize standard computer interaction (via cursor control devices, such as a mouse or trackball, and keyboard) or in conjunction with additional visual interaction data captured via a gaze tracking device. The first approach enables the display of pilots' "active" computer interaction and, thus, mitigation of input-input interaction conflicts. The latter approach enables the display of pilots' "active" and "passive" computer interactions and, thus, mitigation of both input-input and input-visual interaction conflicts.

Our ongoing and future research efforts will continue the development of these cockpit interaction awareness display concepts within the context of working cockpit interface prototypes, followed by planned user studies to evaluate their effectiveness.

Acknowledgments

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