The Design of Aircraft Cockpit Displays for Low-Visibility Taxi Operations

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1.0 ABSTRACT
A suite of cockpit navigation displays for low-visibility taxi operations was developed by researchers at NASA Ames Research Center. The displays, called the Taxiway Navigation and Situation Awareness (T-NASA) system, were created using a human-centered design and evaluation approach that involved over 300 commercial pilots participating in part-task simulations, high-fidelity simulations, and a flight test. This design process helped to ensure that the system would meet its objectives of increasing airport surface operations efficiency and safety in low-visibility conditions, while at the same time considering the capabilities and limitations of the human operators system-wide, including the flight crew and air traffic controllers.

2.0 INTRODUCTION
Surface (taxi) operations is a demanding and high-workload phase of flight. Pilots rely largely on visual navigation aids on the airport surface in order to navigate their assigned taxi route. In low-visibility conditions, airport surface operations become less efficient as taxi speeds decrease and the likelihood of making a navigation error increases (Hooey & Foyle, 2001). These and other factors translate into costly delays for airlines, incoveniences for passengers, and potential safety concerns. Recently, researchers at NASA Ames Research Center have developed a suite of displays for low-visibility surface operations called the Taxiway Navigation and Situation Awareness (T-NASA) system. The goal of T-NASA is to improve the efficiency of low-visibility surface operations while maintaining a high degree of safety.

A human-centered design and evaluation process was developed and used to guide the design of the T-NASA system (Foyle et al, 1996). The process began with a task analysis to develop a clear understanding of the taxi task. In parallel, technology that was available or expected to be available upon implementation of the system was defined in order to identify constraints and limitations. Subsequently, the precise nature of the information that pilots require for successful taxi operations was identified. This information was used to develop a set of system requirements and a formalized design philosophy that guided all design decisions. The exact content of the displays was determined using an iterative process incorporating both existing literature and T—NASA-specific human-in-the-loop research. The iterative evaluation loop, which included simulations (McCann et al, 1998; Hooey, Foyle, & Andre, 2000) and a flight test (Andre, Hooey, Foyle, & McCann, 1998), assessed objective and subjective measures of pilot performance and system usage in both nominal and off-nominal operating environments. Results of these studies were used to further the understanding of the taxi task and refine the display components. The off-nominal test scenarios were designed to assess the potential for new problems that may arise from unanticipated interactions among technology, the operators, and the environment.

3.0 UNDERSTANDING THE TASK
An effective visual display cannot be designed in isolation of the actual use context. The designer must understand the tasks, the environment, and the problems that may be encountered by the operator. To collect this information, an initial task analysis was conducted by Andre (1995), who observed and interviewed 35 commercial crews during regularly scheduled flights.

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During taxi, the pilot controls the aircraft by adjusting speed (using throttle and brakes) and steering to negotiate turns and maintain centerline position (using a tiller and toe pedals). At all times, pilots remain in radio contact with ATC, who issues the taxi clearance and other instructions. Pilots report that communications are problematic because radio frequencies are often congested, their communications may be 'stepped on' by another pilot sharing the same frequency, and ATC commands are often difficult to hear and understand because of the rate of speech and poor radio clarity (Andre, 1995). To navigate the cleared taxi route, pilots identify their assigned taxiways, determine the direction of required turns (not provided in most clearances), identify runways for which they are required to hold, and monitor traffic around them to avoid incidents. In addition to these tasks, pilots also engage in tasks such as cockpit reconfiguration (e.g., resetting flaps), communications to determine their often-changing gate assignment, and preparations for upcoming flights.

Currently, there are no cockpit technologies to assist pilots in navigating the airport surface, except for ground speed and compass heading indicators. Pilots use a paper map (called a Jeppesen Chart) that depicts the airport layout and denotes runways, taxiways, and concourses. Pilots report that the paper taxi charts can be confusing, cluttered, and difficult to read, promoting excessive head-down time (Andre, 1995). Further, pilots must translate information on the chart to the out-the-window view, which often requires mental rotation from the north-up chart to their actual heading. The difficulty of the taxi task is compounded further by the complexity of the navigation environment. Airport surfaces consist of a tangled network of taxiways and runways identified by signs and painted markings. As signs cannot be placed overhead (as with our road networks) they are placed on grass and cement islands to the side. Navigation errors are often attributed to the necessarily awkward placement of the taxiway signs and complex taxiway geometry (Hooey & Foyle, 2001).

These problems are exacerbated in low-visibility and night conditions. The degraded visibility of signs and markings contributes to lower taxi speeds, increased navigation errors, and increased workload (Andre, 1995). Although airports have embedded pavement lighting to improve visibility, when viewed off-axis these lights can be disorienting and may contribute further to navigation errors (Hooey & Foyle, 2001). The culmination of all of the required tasks, the difficult operating environment, and the lack of aiding technologies results in a very high-workload, time-pressured phase of flight.

4.0 DEFINING THE INFORMATION REQUIREMENTS

An important phase of the design process was to define the precise nature of information required by the pilots, with a particular emphasis on determining the information that pilots currently have available in clear visibility but is degraded in low visibility. Lasswell and Wickens (1995) identified two classes of information necessary for successful taxi navigation: Local guidance and global awareness. Additionally, when ATC issues an assigned taxi clearance, a third piece of information is required, route awareness. The *local control* task of maneuvering the aircraft is comprised of lateral loop closure (e.g., minimizing lateral deviations), directional loop closure (e.g., steering around turns), longitudinal loop closure (e.g., maintaining speed and braking), hazard detection (e.g., monitoring for traffic and obstacles), and information gathering (e.g., scanning signage and markings) (Lasswell & Wickens, 1995). In order to maneuver the aircraft on the correct route, pilots also need *route awareness,* or knowledge of their position on the airport surface relative to their cleared route. This includes knowing the name of the next required taxiway, the distance to the turn, and the direction of the turn. Finally, pilots must also maintain a sense of *global awareness,* which refers to knowledge of the general layout of the airport surface, the location of their destination concourse or runway, and traffic (Lasswell & Wickens, 1995). This information is necessary to navigate to a known destination, to avoid potential hazards along the way, and to recover quickly in the event of a navigation error. Lacking any one or more of these pieces of information can cause the pilot to become spatially disoriented. The results can range from an increase in workload to catastrophic accidents. Thus, the information requirements for the cockpit display system were to replace the global awareness information that is missing in low visibility, augment the local awareness information that is degraded in low visibility, and provide route awareness information that is currently lacking even in clear visibility.

5.0 DEFINING THE SYSTEM REQUIREMENTS

Armed with a full understanding of taxi operations and the specific information requirements, a set of desired system characteristics and a design philosophy were developed (Foyle et al, 1996). First, it was determined that local guidance and local route-following cues should be provided in a way that would allow pilots to capitalize on their experience and remain eyes-out while taxiing. In essence, this meant a conformal, ecological display that reinstates visual cues so pilots can use the same local guidance cues (i.e., centerline and taxiway edges) in low-visibility as they do in clear weather. Second, it was determined that global awareness should be provided by depicting both global navigation and traffic awareness on a 360-deg representation of the airport surface. Therefore, given these two divergent goals, and the very different display requirements inherent in each, it was determined that T-NASA would be comprised of two complementary displays: A conformal, ecological HUD that constantly supports the local control task, and a head-down electronic moving map (EMM) display requiring only occasional, short glances to maintain global awareness but not intended for steering control or centerline tracking.

6.0 DEFINING THE SYSTEM COMPONENTS

The information and system requirements were translated into the display interfaces resulting in the Taxiway Navigation and Situation Awareness (T-NASA) cockpit display suite shown in Figure 1. The design considerations of each display component are presented below.

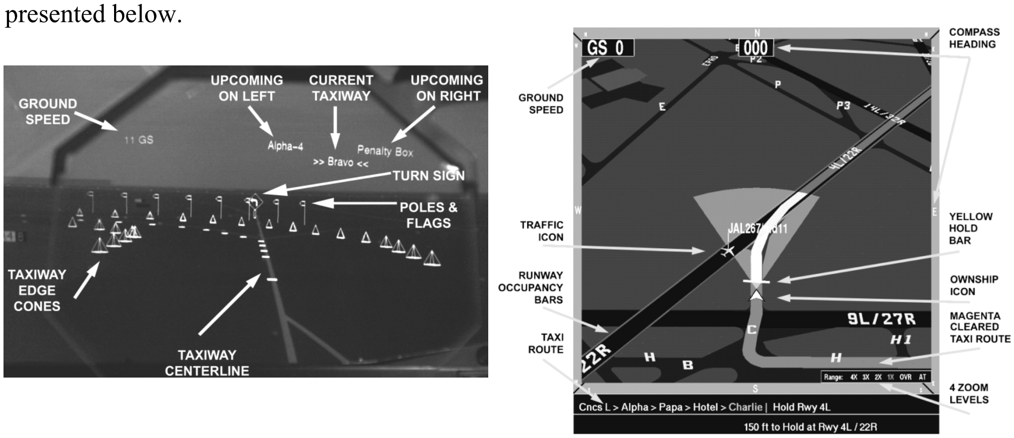

Figure 1. T-NASA HUD (left) and EMM (right)

6.1 T-NASA Head-Up Display (HUD)

Recall that the main design goal of the HUD was to re-establish cues that pilots normally use (but are missing in low visibility) by enhancing local control and route guidance information in an ecological and conformal display. To move from this high-level design philosophy to an actual design implementation, the designers turned to empirical HUD literature.

6.1.1 HUD Design Considerations - Of particular importance was to design a HUD display that would not create the potentially dangerous condition known as attentional tunneling. Attentional tunneling, or attending to information on the HUD at the expense of out-the-window environment, has been observed and documented in several studies (e.g., Fischer, Haines, & Price, 1989; Wickens & Long, 1995). In these studies, pilots encountered an unexpected aircraft blocking the runway on which they were about to land. The time required to detect and respond to the unexpected airplane was longer when flying with a HUD than with a head-down display, and some participants failed to notice the airplane at all with the HUD. Clearly, this is to be avoided in the dynamic, closely spaced environment of airport surface operations.

Two characteristics of HUD symbology that may promote attentional tunneling have been identified. First, Foyle, McCann, Sanford, and Schwirzke (1993), found that when symbology is presented in a fixed location that is visually near the pilot s primary tracking task, pilots are more prone to attend to the symbology at the expense of the primary task. In a simulated helicopter flight task requiring simultaneous path and altitude maintenance, path performance was degraded when the altimeter was placed visually near the out-the-window path, but not when placed either 8 deg or 16 deg away from the path. This result was taken to suggest that if symbology is located at least 8 deg away from center, the pilot is forced to make a visual saccade to gather information from the display and/or environment, and the saccade breaks the attentional lock. Second, McCann & Foyle (1995) reported that differential motion between the world and the symbology creates attentional tunneling because it causes the visual system to interpret the virtual symbols as part of a perceptual group distinct from the world. Subsequently, Foyle, McCann, and Shelden (1995) reported that virtually and conformally projecting symbology on to the HUD such that the symbology appears to be part of the out-the-window environment leads to efficient cognitive processing of both the symbology and the environment, and mitigates problems of attentional tunneling due to differential motion. They proposed the concept of scene-linked symbology, in which the symbols are fused to the external scene and move and act as if they were real objects in the environment. Foyle et al (1996) described three types of scene-linked symbology: Scene-enhancements (enhancing information that exists in the real world); scene augmentations (pictorially augmenting the real world), and virtual instruments (projecting instruments onto the environment as if they were actual objects in the outside world).

6.1.2 Design of the T-NASA HUD - Empirical research coupled with the identified information requirements for local control, contributed directly to the design of the T—NASA HUD. As shown in Figure 1, the T-NASA HUD depicts the centerline and the sides of the ATC-cleared taxiways using conformal, scene-linked scene enhancements (i.e., centerline markers), and scene-augmentations (i.e., taxiway edge cones and virtual turn signs) (Foyle et al, 1996). The scene-linked centerline enhances the actual centerline painted on the airport surface. Scene-linked augmentations, such as the cones that mark the side of the cleared taxiway, also support local guidance. The cones are conformal, overlaying and transforming optically as if they were actual stationary objects in the world. The vertical development and constant spacing of the side cones increase the capability for estimating ground speed, drift, and look-ahead information for turns (Foyle et al, 1996). Local route guidance is implicitly embedded in the local guidance symbology as the scene-linked symbols only outline the cleared route. The symbology provides predictive information about the cleared route (i.e., distance and direction of next turn) that is not always available in the environment, even in good visibility. The virtual turn signs, also scene-linked augmentations, provide information about the angle of the upcoming turn as the angle of the arrow on the sign represents the true angle of the turn. Finally, three additional pieces of information (hold instructions, ground speed, and taxiway identifiers) were added to the symbology based on information collected from pilots. Hold instructions provided by ATC are depicted as a scene-linked augmentation that depicts a virtual hold bar and a stop sign in the center field of view of the HUD. Ground speed is presented digitally in the upper left corner, and taxiway identifiers are presented in the upper right corner. The latter two, requiring fixed-location, non-scene-linked symbology, were placed at least eight deg from the centerline to minimize attentional tunneling.

Iterative human-in-the loop testing was conducted throughout the HUD design process. From these studies, it became apparent that the nature of a truly conformal display, while advantageous for straight segments and shallow turns, simultaneously created a problem for pilots on sharp turns. Because of the small horizontal viewing angle of a HUD (~30 deg), and the fact that the aircraft nose blocks a substantial part of the lower front view, the conformal, scene-linked symbology drops out of the HUD field of view on turns. This clearly was of concern to pilots, as the symbology vanished just when they needed it the most. To address this problem, a study (Atkins, Foyle, Hooey & McCann, 1999) was completed to assess pilot performance with five competing scene-linked symbology augmentations. The symbology that produced the most efficient and accurate taxi performance is shown in Figure 1, and consisted of a series of poles with directional flags, offset beyond the edge of the taxiway on turns. Because the poles are set beyond the edge of the taxiway, and have height, they remain as a visual reference throughout the turn.

The T-NASA HUD provides cues for local guidance and local route awareness. However, given the limited field of view, the HUD is not an effective medium to support global awareness. While it is possible to provide some global awareness information (i.e., symbols indicating the distance to destination or traffic), the T-NASA designers chose to refrain from presenting this information to reduce HUD clutter and obscuration of the environment and maintain the scene-linked nature of the display. Therefore, when necessary, this information is gathered by glances to the head-down EMM.

6.2 T-NASA Electronic Moving Map (EMM)

Recall that the main design goal of the EMM was to allow pilots to quickly gather global navigation and traffic information while minimizing unnecessary eyes-in time. An abundance of literature existed regarding navigation displays, and further human-in-the-loop research was conducted to move from this high-level design philosophy to the detailed EMM design.

6.2.1 EMM Design Considerations - Much research has compared rotating, track-up maps with fixed, north-up maps, and in general, has revealed that the advantages of the two map types are task dependent (Aretz, 1991). A map designed with a track-up orientation eliminates the need for the operator to perform mental rotations of the map (Aretz, 1991) and simplifies control of the aircraft because all turns are simply left or right of the aircraft's current heading. Track-up maps have been shown to be most advantageous when used for pilotage tasks such as navigation with reference to ground landmarks (Aretz, 1991). Tu and Andre (1996) found that a 3-D perspective rotating taxi map allowed faster route completion times than north-up, fixed map display. On the other hand, a north-up map that offers consistent location of landmarks relative to the north-up map serves tasks that depend on locating landmarks on the map and tasks that depend on learning the relative location of features in the environment (Aretz, 1991). In the case of taxiing, a north-up map may support route planning and communications with other operators within the system (i.e., other pilots or ATC).

6.2.2 Design of the T-NASA EMM - The EMM (Figure 1) was designed to provide global awareness information such as the location of the runways and concourses as well as general orientation/directional information. It incorporates two map views: A track-up, perspective view for taxi movement and a north-up view for route planning. The EMM track-up view is from an eyepoint that is tethered to a location above and behind the ownship. The distance of the eyepoint along the tether is adjustable, creating four zoom levels from which the pilot can choose. The ownship icon is a fixed point on the display with the airport layout rotating and translating underneath the icon. This mode is presented in perspective, allowing the pilot to easily process orientation information. There is also a north-up airport view similar to the standard Jeppesen airport paper chart intended for route planning purposes.

As determined during the initial information gathering process, the EMM depicts the labeled airport layout, real-time positions of ownship and traffic, graphical route guidance, text clearance window, ground speed and heading indicators. Throughout the design process, a series of part-task studies was completed to ensure that each aspect of the EMM minimized unnecessary eyes-down time (e.g., Graeber & Andre, 1999, Purcell & Andre, 2001). In keeping with the eyes-out philosophy, the EMM supports route awareness by allowing for status-at-a-glance navigation checking. The map depicts an ownship icon (centered, one-third up from bottom of the map) and the route to be followed is presented via a thick magenta strip. With a quick glance at the EMM, pilots can determine if they are on route, the approximate distance to the next turn, and the direction of the next turn. The thick magenta path that depicts the cleared route was chosen over an actual depiction of the centerline to remove the temptation to track the centerline via the EMM. Similarly, information about the location of wheels, speed or braking parameters, and aircraft size and wingspan was purposefully omitted from the EMM.

7.0 EVALUATING THE T-NASA SYSTEM

Throughout the human-centered design process, the T—NASA system was subject to evaluations in a medium-fidelity simulation (McCann, Foyle, Andre, & Battiste, 1996), two high-fidelity simulations (McCann et al, 1998; Hooey, Foyle, & Andre, 2000), and a flight test (Andre, Hooey, Foyle, McCann, 1998). These studies, involving over 300 pilots, yielded consistent findings that held up across operational environments, and visibility conditions. A summary of the results is presented below.

7.1 Objective Performance Measures - Two main objective measures of performance were taxi speed and navigation errors. The two high-fidelity simulations revealed that in low-visibility and night conditions, the T-NASA displays increased taxi speed from 16% to 26% (2 to 3 kts) over trials without T-NASA. Navigation errors, deviations from the cleared route, were committed in 17 % of the current-day (no T-NASA) trials. With T-NASA, off-route navigation errors were eliminated completely. Further, comparisons of the EMM alone with the EMM + HUD combination revealed significant performance advantages when pilots used the full T-NASA (EMM+HUD) system over just the EMM (McCann et al, 1998). This provides support for the early design decision of two complementary displays.

7.2 Subjective & Observational Measures - It is conceivable that a system such as T—NASA may improve efficiency but create a high workload environment, or one in which the pilots are out of the loop and unable to develop an accurate representation of the environment. To determine whether T-NASA created such problems, pilots taking part in the system evaluations were asked to rate their perceived workload, navigation awareness, and traffic awareness after each trial or block of trials. T-NASA significantly reduced pilot-rated workload over current taxi operations without T-NASA. The pilots also rated their navigation awareness and traffic awareness significantly higher with T—NASA than without (McCann et al, 1998).

7.3 Display Usage - Under nominal conditions, investigations of EMM usage revealed that pilots used the north-up view for planning and the track-up view for taxiing as intended by the designers. Furthermore, these studies revealed that the captain and first officer use the map differently. The captains maintained a more zoomed-in view, while first officers were more often zoomed-out to provide a more global view of the airport (McCann et al, 1998). System usage was also investigated with off-nominal scenarios in a high-fidelity simulation (Hooey, Foyle, & Andre, 2000). Events such as clearance errors, near-incursions, and HUD errors were useful to understand not only how pilots respond to system failures, but more importantly to understand the strategies pilots implement while using the displays. Evidence that the displays were used as they were intended by the designers was provided (see Hooey, Foyle, & Andre, 2000).

8.0 CONCLUSION

A set of cockpit displays, the Taxiway Navigation and Situation Awareness (T-NASA) system, was developed following a human-centered design process. The design process began with an assessment of the pilots' task and environment, the constraints and limitations imposed by technology, and the information required by pilots for successful taxi in low-visibility conditions. T-NASA was designed to provide pilots with the local control information that is degraded in low visibility, global awareness information that is missing all together in low visibility, and route guidance information that is usually not present, even in clear visibility. In order to provide these varied pieces of information, T-NASA was designed as an integrated display system consisting of two complementary displays: A HUD to provide local control and local route information, and an EMM to provide global awareness and global route awareness. Each display component was designed using existing empirical literature and task-specific human-in-the-loop studies. The design and evaluation research effort included over 300 pilots who participated in part-task studies, full-mission simulations, and a flight test. Results of these studies showed that the T-NASA system does meet the intended goal of increased taxi efficiency and safety during low-visibility taxi operations without introducing excessive demands or new problems into the cockpit.

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10. ACKNOWLEDGEMENTS:

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