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Taxiway Navigation and Situation Awareness (T-NASA) System: Problem, Design Philosophy, and Description of an Integrated Display Suite for Low-Visibility Airport Surface Operations

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ABSTRACT

An integrated cockpit display suite, the T-NASA (Taxiway Navigation and Situation Awareness) system, is under development for NASA's Terminal Area Productivity (TAP) Low-Visibility Landing and Surface Operations (LVLASO) program. This system has three integrated components: Moving Map -- track-up airport surface display with own-ship, traffic and graphical route guidance; Scene-Linked Symbology -- route/taxi information virtually projected via a Head-up Display (HUD) onto the forward scene; and, 3-D Audio Ground Collision Avoidance Warning (GCAW) system -- spatially-localized auditory traffic alerts. In this paper, surface operations in low-visibility conditions, the design philosophy of the T-NASA system, and the T-NASA system display components are described.

INTRODUCTION

Currently, from the pilot's perspective, surface operations is one of the least technologically sophisticated components of the airspace operations system. The taxi technologies available to a pilot today are the same as they have been for years: Ground control clearance communication and airport Jeppesen charts. Pilots are given little or no explicit information about their current position, other than that which they can determine from airport signage, and routing information is limited to ground control communications and paper airport charts. Under low-visibility conditions, pilots normally reduce taxi speed to avoid conflicts with other traffic. Further reductions in taxi speed occur in cases when they become spatially disoriented, and must engage in time-consuming interactions with ground controllers. For these reasons, there exists the likely potential for improving surface operations through the implementation of new technologies into the cockpit.

The Federal Aviation Administration (FAA) reported that between 1990 and 1993, on average, 312,000 flights were delayed more than 15 minutes, with 64% of these delays being caused by poor weather, 28% by congestion, and 8% by other reasons [1]. It was estimated that the cost to airline operations was $3 billion, while the cost impact due to passenger delays was $6 billion in 1990 alone. To mitigate these delays, NASA's Terminal Area Productivity (TAP) Program was developed with the goal to safely increase capacities in the airport terminal area in non-visual or instrument weather conditions to that of clear weather conditions [2]. Specifically, the technical goals for the TAP program are to demonstrate feasibility of: At least 12% increase over that of current non-visual operations for single runway throughput (averaged over major U.S. airports); effective tactical and strategic planning of arrival and departure traffic flows in instrument weather conditions, or non-visual conditions, to be equivalent to those in visual conditions; reduced runway occupancy time and taxi operations in instrument weather conditions, or non-visual conditions, to be equivalent to those of visual conditions; and, lateral spacing reduction below 3400 ft for independent operations on parallel runways for applicable airports.

Under the Low-Visibility Landing and Surface Operations (LVLASO) element of the TAP program, cockpit technologies are being developed to safely improve airport throughput to that of visual conditions under Category IIIB (300 ft to 700 ft runway visual range, RVR) operating conditions. Specifically, under TAP/LVLASO, systems are being developed for reducing runway occupancy time, improving the efficiency of taxi operations and providing the flight deck with integrated surface automation systems and tower guidance. Advanced technologies such as satellite navigation systems, digital data communications, information presentation technology, and ground surveillance systems will be integrated into the flight deck to enable expeditious traffic movement on the airport surface. Consistent with the potential capacity benefits of technologies developed by other elements of TAP (i.e., Air Traffic Management, and Reduced Separation Operations), the LVLASO element will develop and demonstrate technology for maintaining the throughput capacity of Visual Meteorological Conditions (VMC) under

Instrument Meteorological Conditions (IMC) for the takeoff, landing, rollout, turnoff, and taxi phases of flight. This technology will be subjected to safety, reliability, and cost/benefits analyses. The primary results of LVLASO are flight deck requirements and recommended procedures for integration with the emerging surface automation systems that will enable increased capacity for weather conditions to Category IIIB [3].

CURRENT TAXI OPERATIONS

To better understand the problems facing pilots during taxi operations in general, and especially in low-visibility taxi operations, Andre [4] recently completed a study of flight-deck observations, pilot-controller communications, and pilot interviews aboard thirty-five revenue commercial flights. The purpose of the study was to gain valuable insight into potential causes of current inefficient taxi operations, and to understand the pilots' views and opinions about potential cockpit technology aids, such as electronic taxi map displays and other guidance displays, as these preferences and attitudes will have a large influence on the ultimate acceptance and utility of any new technology. Andre [4] found that pilots' general concerns about conducting current taxi operations formed six classes:

- Situational awareness degrades due to the inherent loss of visual cues in low-visibility conditions. Sample pilot comments included, "Under low-visibility conditions I taxi at 1/2 to 1/3 the speed of high-visibility conditions." and "Delays in taxiing under low visibility conditions are sometimes caused by ground control having to tell you every turn and where you are at a given point in time".
- Navigation problems may arise due to deficiencies in the visual airport surface environment. It has been noted that the biggest obstruction to safe and efficient taxi operations is the design of the outside airport surface environment, including surface markings, lighting and signage [5]. In the observational study [4], one pilot noted that on their last flight most of the signs were covered with weeds, and that they "only knew where to go using the map".
- Inefficient taxi operations may result from ineffective communications between ground control and the cockpit. In fact, poor communication was cited as the causal factor in the second largest number of runway incursions and incidents from 1988 to 1992 [5]. For example, in response to Ground Control's command to taxi to gate, one pilot voiced, "He didn't say which way to go, did he? Then we'll just go our way."
- Increased workload due to mid-taxi route changes Pilot comments included, "Taxiing to the gate is most difficult when the route is changed in mid-stream. Once you get a mental picture of the route you need to take from the runway to the gate, it's hard to replace it with another route."
- Increased complexities due to taxi sequencing (i.e., taxiing in reference to other aircraft). Pilots reported that, "Most of the time the clearance is 'follow that guy' at O'Hare and other large airports." Aircraft sequencing especially poses a problem to the avionics designer. Most cockpit taxi navigation efforts (e.g., [6][7][8]) have focused on the spatial layout of the airport and the traffic operating in it, and not on relaying taxi information that is referenced to specific aircraft or flow of aircraft.

Except for consultation with the airport layout chart, and initiating communications to ground control, current taxi operations are clearly an "eyes-out" or "head-up" task: The pilots are required to navigate via airport signage, manually control the aircraft based on the visual environmental cues, verify route safety (check for traffic conflicts), and maintain an appropriate safe distance from other aircraft traffic, ground vehicles, and obstacles. Andre [4] noted that while many pilots were excited about the development of a cockpit taxi display, others were clear in their concerns about adding a head-down display to aid a predominantly head-up, eyes-out, task. Some of the comments directed at this issue included: "I don't want a display that keeps me heads-down while taxiing. Even at night and in poor weather I see things out the window (lights on other aircraft, runway markers)"; "I like idea of moving map display for taxi operations, but it should be a secondary display, not a primary display, since it requires me to be heads-down"; and "An auditory beep when off path or near other aircraft would be useful. Then we would only have to look at display when it beeps, otherwise we are eyes out."

SUPPORTING TECHNOLOGY

In order to design a display system, it is necessary to define the technology assumptions for that display system. The TAP/LVLASO program assumes the implementation and integration of new technology systems in support of airport surface operations. To this end, a flight demonstration was conducted to provide an early identification of flight deck and surface automation issues associated with these technologies [9]. These systems and functions demonstrated included:

- Electronic surface (runways/taxiways) map in the research flight deck to provide the pilot with surface information (cleared taxi routes, hold bars, safety warnings, ownship and proximity traffic);
- Differential Global Positioning System (GPS) to accurately position the aircraft on the taxi map;
- ASDE-3 RADAR, and Westinghouse Norden Airport Movement Safety System (AMASS) to provide other traffic and safety warnings;
- ASDE-3 activated transponder-based system for positive vehicle identification on the ground controller's display;
- High speed data link for taxi clearance, proximity, and AMASS warnings.

The demonstration successfully established the feasibility of the integration of these systems, and provided the technology assumptions for the current development project.

This taxi demonstration also provided a baseline capability upon which to address system integration issues and to develop more effective ways to present information to flight crews.

DESIGN PHILOSOPHY

INFORMATION REQUIREMENTS -- In the development of display systems, one must merge a task analysis of the problem with the assumed available technology: The task analysis defines, in very specific terms, the information that is required to conduct the task. When information is lacking, the display system should supply it. In general, different operating conditions would, and possibly should, lead to variations of the final display system design. The operating conditions for the TAP program are down to CAT IIIB conditions, corresponding to 300-700 ft RVR, roughly translating to visual range conditions of 300 to 700 ft. In these conditions, it is only necessary to replace visual information that is missing, or augment visual information that is degraded. In contrast, lower operating conditions, such as 0/0 weather conditions, in which there is no visual out-the-window information available, requires a system in which the display system must provide <u>all</u> information for taxiing.

NAVIGATION VS. CONTROL -- In fog or rain, when pilots might see only 300-700 ft, there are many sources of visual information that are missing or degraded, compared to surface operations in VMC. In general, most moving aircraft and ground vehicle traffic in the terminal area are not visible from the cockpit. Additionally, global visual navigational references are not available. That is, it is not possible to sight visually the gate, concourse, or possibly even the terminal. Without these global visual navigational references, incorrect taxi turns are more likely, and complete disorientation is possible. Likewise, some local visual navigation references may not be available. For example, the pilot may not be able to see a distant upcoming turn, and may only be able to see as far as the next intersection, if that.

On the other hand, even under these weather conditions of 300-700 ft visibility, some visual cues are still available to the pilot, although they are in degraded form compared to VMC. For instance, the centerline and lights, the taxiway edges, the edge lighting, and taxiway signage are visible out the front and side windows, out to 300 - 700 ft away, but at lower brightness and contrast levels. What is clearly missing, however, is appropriate information for navigation and orientation, corresponding to directional changes (turns onto different taxiways). Pilots may miss turns, because they did not have adequate time (because of the inability to see distant signage), or may pass a turn because they did not realize that the assigned turn was so close. More likely, rather than missing turns, pilots may slow down drastically so as to increase the time to read signs and plan for turns. (As reported in Andre [4], one pilot commented "Recently at SFO, in dense fog, you couldn't tell where you were, you could only see gate numbers lit up. It took almost one hour from gate to runway.")

Lasswell and Wickens [8], in a task analysis of low-visibility taxiing, use the terms "local guidance" to describe the control task of maneuvering the aircraft along a route, and "global awareness" to describe the task of maintaining positional awareness relative to the gate and other airport features. They assume that the local guidance task is supported by the out-the-window visual information, and the global awareness task must be supported by a global visual display. The design philosophy of the T-NASA system is consistent with this parsing. In an analysis of a navigation study by Schuffel [10] with 2-D plan-view displays and 3-D egocentric views (outside views), Lasswell and Wickens [8] concluded that the outside view provided a preview of upcoming maneuvers allowing the anticipation of control inputs, as well as better estimation of rate information. Schuffel [10] found that navigation performance was best when both information sources were available. Lasswell and Wickens [8] note that this confirms the suggestion by Spoerri [11] that having the <u>combination</u> of features from an egocentric (pilot eyepoint) forward view supplying local guidance information and an exocentric (eyepoint above and behind pilot) plan-view display supplying global awareness information allows for better navigational performance. In a test of the T-NASA system [12] in low-visibility airport taxiing, this result was also obtained.

SYSTEM CHARACTERISTICS -- Having established the information required for current taxi operations, the degradation imposed on that information by the presence of low-visibility weather conditions, and research on pilot interactions with navigational displays, a set of desired system characteristics can be determined. These characteristics, which the design of the T-NASA system incorporates, are:

<u>Augmentation of global awareness cues that are missing</u> in low-visibility weather conditions. These cues include aircraft and ground vehicle traffic, general global orientation/directional information, and overview route information (i.e., the general mental "picture" of the route referenced to the aircraft and the general direction to the gate). This information requires a 360-deg field of view, and is instantiated on a head-down computer-graphics imagery moving map display (and audio display in the case of conflict traffic information). In the T-NASA system, the moving map display is meant to be a situational awareness display. That is, its function is as a display for navigation orientation and planning -- not as a display to aid the fine-grain steering required to track a taxi centerline.

<u>Enhancement of local guidance visual cues that are present but degraded</u> due to the low-visibility conditions. These cues include visual flow speed cues and a forward visual representation of upcoming turns (the distance to the next turn and turn direction). Such cues augment the visual out-the-window view, in much the same way that taxiway lighting

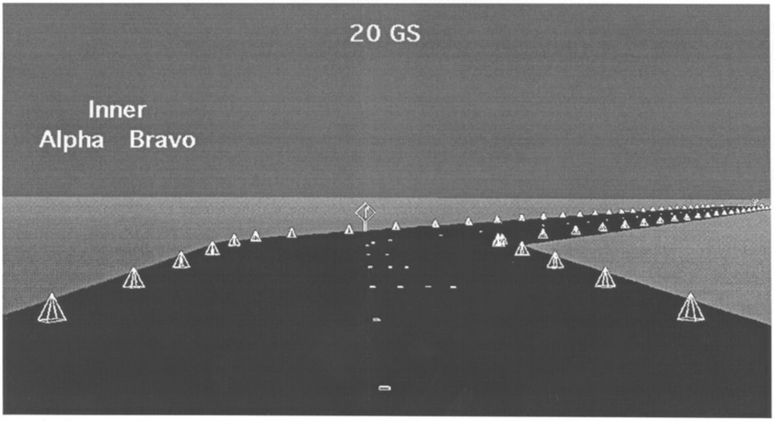

Figure 1: Scene-linked HUD symbology for taxi and surface operations (see text for description). Symbology (shown in white, actually green) includes Scene Enhancements (centerline "lights") and virtual Scene Augmentations (edge cones, turn signs and "countdown" warnings). Location information and ground speed are not scene-linked.

does, and are represented via "scene-linked symbology" on a head-up display (HUD). Scene-linked symbology, in which iconic information is virtually and conformally represented on the HUD, has been shown to be an efficient method for the presentation of information [13].

Capitalization on the many years of pilot's experience in aircraft taxiing in VMC by supplying the information, in similar form, that is degraded in IMC, as just described. Due to the weather conditions, some of these visual cues are lost. By reinstating these cues via the HUD scene-linked symbology, pilots now can use the same local guidance cues in IMC to control the aircraft. For example, virtual markers along the edge of the taxiways would reinstate the visual cue of taxiway edge location. Inherent in this is our philosophy of maintaining a natural, ecological, perspective display representation that supports control of the aircraft. Specifically, unless our future research informs us to the contrary, we do not intend on using derived display indicators, such as the turn trend vectors that have been incorporated into some moving map displays (e.g., [7]), or command guidance (e.g., a display that indicates current vs. commanded nose wheel position for a turn). These derived indicators have been necessary to provide adequate cues for control in conditions (such as 0/0 weather) in which those cues are missing. Additionally, adding derived indicators which support control to the map display might turn this display into a primary flight display, requiring a relatively large proportion of time "eyes-in", inconsistent with the view of taxiing as an "eyes-out" task (see pilot comments from [4] above). With the T-NASA system in 300-700 ft RVR, there is sufficient control information available from the combination of the out-the-window visual cues and the cues enhanced by the scene-linked symbology on the HUD (as shown by [12]).

Support of taxi operations as primarily an "eyes-out" task. In parsing the functionality of the visual displays as described above, with the HUD scene-linked symbology for local control and local guidance of the aircraft, and the moving map display for global awareness, it is expected that pilots will be primarily "eyes-out", with occasional glances head-down to the moving map display to maintain situational awareness. In order to inform the pilot of traffic alerts or AMASS warnings, in the T-NASA system, the 3-D audio Ground Collision Avoidance Warning (GCAW) system presents spatially-localized auditory alerts to the pilot [14]. Based on work described in Begault [15] and Begault and Pittman [16], these 3-D auditory warnings are directional: A traffic alert for an aircraft at the 10 o'clock position is processed such that the warning sounds as if it were emanating from the 10 o'clock position. Upon receiving the spatially localized warning, the pilot can go "eyes-in" to the head-down moving map display to confirm the traffic situation.

T-NASA DESCRIPTION

The problem statement, understanding of current taxi operations, technology assumptions, information requirements, and display philosophy have resulted in the architecture for a specific system: the T-NASA system.

SCENE-LINKED HUD SYMBOLOGY -- Previous

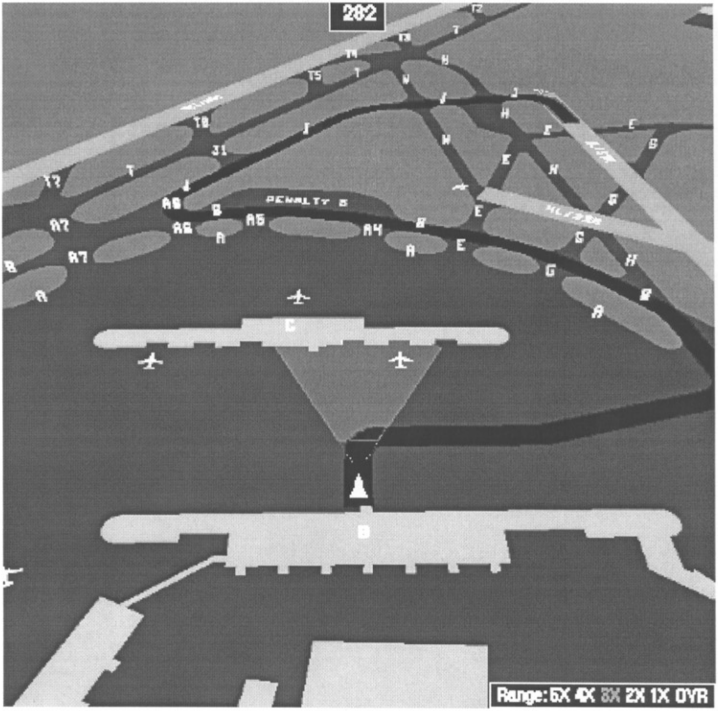

Figure 2: Perspective moving map display (gray scale representation, actual map in color). Ownship position shown as up-pointing triangle near bottom of figure, wedge indicates forward visual view from cockpit, black taxiway (magenta in color) is clearanceroute.

research has indicated that virtually and conformally projecting ("scene-linking") symbology onto a 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 and symbology fixation ([13], and for a review, see [17]). Figure 1 shows the T-NASA scene-linked HUD symbology overlaid on a representation of the visual scene.

The HUD symbology taxi display contains two types of scene-linked information [13]: Scene enhancements (centerline markers), and scene augmentations (taxiway edge cones pictorially augmenting the scene, and virtual turn signs). The pictorial scene augmentations shown include visual information that would aid the pilot in following the taxiway clearance and completing turns. Vertical side cones along the edges of the commanded taxiway path depict the ground controller cleared route on the HUD in superimposed symbology. The cones are conformal, overlaying and deforming optically as if they were actual stationary objects in the world. Both the cones and the centerline markings are shown repeated every 50 ft down the taxiway. The vertical development and constant spacing increase the capability for estimating ground speed, drift, and look-ahead information for turns. Turn "countdown" warnings are shown as 3, 2, and 1 markers perpendicular to the taxiway centerline spaced 150, 100, and 50 ft, respectively, before each turn, yielding additional distance and control cues for the turn. The virtual turn signs (with the arrows) give an added turn cue. In addition, the angle of the arrow on the sign represents the true angle of the turn (i.e., 30 deg right for a 30 deg right turn). All of the HUD symbology is scene-linked, enabling the pilot

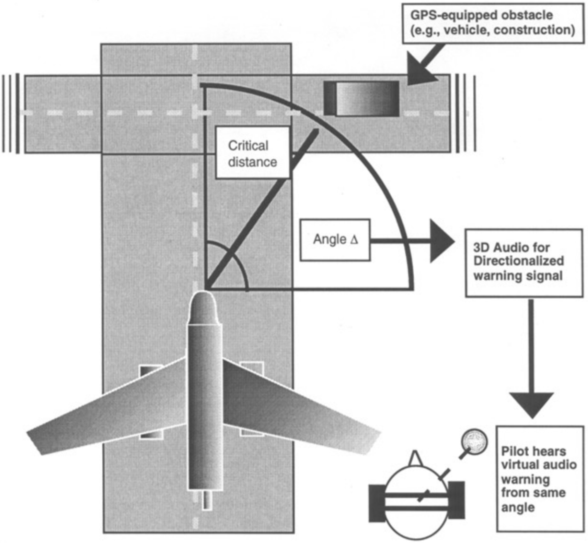

Figure 3: Illustration of the 3-D audio GCAW system. When a critical distance is reached by an oncoming vehicle that has not been cleared by air traffic control, an alert is sounded from the virtual location of the vehicle through the pilot's headset.

to process the symbology and still retain awareness of other visual traffic, including possible traffic conflicts.

Location and ground speed information on the HUD are given in a non-scene-linked triangular "Past/Present/Future" format. The example shown represents current runway or taxiway segment ("Inner" taxiway), the last taxiway intersection passed ("Alpha"), and the next upcoming intersection ("Bravo"). The example shows that this aircraft is on the Inner Taxiway, past Alpha, and before Bravo, with a ground speed of 20 kts.

PERSPECTIVE MOVING MAP DISPLAY -- The moving map display is presented as a head-down display in the cockpit and includes the labeled airport layout, ownship position, positions of other traffic, graphical route guidance, text clearance window, and heading indicator. The map is presented in track-up mode, such that aircraft heading is always at the top of the display. The ownship icon is a fixed point on the display with the airport layout rotating and translating underneath the icon. The pilot can dynamically switch between 5 fields of view (zoom levels) and an additional north-up full airport view which is likened to the familiar Jeppesen airport chart. This information allows the pilot to maintain global awareness, staying oriented to the cleared route and the destination gate or runway. An additional feature that is shown in Figure 2 is "the wedge." This shows the area of the airport that is visible through the forward windows (the sides of the wedge), as well as the forward visibility (the curved base of the triangular wedge mapping to the visibility range). This feature allows pilots to maintain reference between the forward view and the map display, as objects they can see out the forward windows will always appear within the highlighted wedge.

As seen in Figure 2, the moving map display is presented in perspective. This allows the pilot to easily process orientation information (e.g., "the gate is ahead and to the right"), but has the added feature in that the area near the aircraft is larger and correspondingly of higher resolution. In some sense, the perspective map is a spatially variable resolution display with higher resolution in the area of the highest interest (near the aircraft). In a recent study of low-visibility taxi with 2-D plan view and 3-D perspective displays, Tu and Andre[18] found that 2-D plan view and 3-D perspective taxi map displays allowed faster route completion times than north-up, fixed map/moving aircraft full airport display, and that the 3-D map display was preferred by most of the pilots. The largest difference between the 2-D and 3-D maps was the distribution in the percentage of time spent at each of the 6 zoom levels. Pilots mostly used the mid-zoom levels with the 2-D map. In contrast, when using the 3-D map, pilots predominantly used the closest zoom level. These data were interpreted as favoring the 3-D display, in that pilots only zoom in close when they are confident in their navigational awareness.

3-D AUDIO GROUND COLLISION AND WARNING SYSTEM -- Work in virtual reality systems at NASA Ames Research Center includes the area of aurally-guided visual search, using specially-designed audio cues and spatial audio processing (also known as virtual or "3-D audio") techniques [19]. By delivering both communications and warning signals through supra-aural ("on the ear") headsets, it is possible to predict and control the relative signal levels at the ear relative to noise. With stereo headsets, the perceived spatial location of audio warning signals can be predicted and varied using 3-D audio techniques. By covering both ears, it is feasible to include active noise cancellation; in commercial jet airliners, however, it is not necessary to use relatively heavy circumaural headsets that also include passive noise reduction. Additionally, the use of supra-aural headsets allows inter-cockpit communication to occur without an intercom system linking the pilot and first officer.

Since the crew must keep their head up and looking out the window as much as possible when taxiing under low-visibility conditions, the potential for "blunder" is increased under such conditions, especially when a potential collision is outside the lateral field-of-view. Previous studies at Ames had revealed that use of 3-D audio for Traffic Collision Avoidance System (TCAS) advisories significantly reduced head-down time, compared to a head-down map display (0.5 sec advantage) or no display at all (2.2 sec advantage) [15][16][19]; see [20], for an audio demo. An earlier study of the ground collision avoidance warning (GCAW) system found a favorable response for the system, for low- and normal-visibility conditions, either as a separate display or integrated with warnings with the visual system [14].

The current approach is an integration of 3-D audio cues with information on the moving map display to give situational awareness warnings regarding traffic on a potential collision course, as shown in Figure 3. This warning corresponds in function to a TCAS traffic advisory, alerting the pilot to the existence and direction of a potential collision. A second level, non-spatialized warning (equivalent to a TCAS resolution advisory) is also included that instructs the pilot to stop the aircraft, within a time frame calculated in terms of time-until-impact.

CONCLUSIONS AND SUMMARY

The 3-D audio GCAW system has recently been integrated into the T-NASA system and the full-complement version of T-NASA is undergoing evaluation in a high-fidelity part-task simulation. In 1997, the T-NASA system will be assessed in full-mission simulation and tested in a joint NASA Ames Research Center and NASA Langley Research Center flight test to be held at Atlanta's Hartsfield Airport.

To summarize, the goal of NASA's TAP/LVLASO subelement is to improve the efficiency of airport surface operations for commercial aircraft operating in weather conditions to CAT IIIB while maintaining a high degree of safety. Currently, surface operations are one of the least technologically sophisticated components of the air transport system, being conducted in the 1990's with the same basic technology as in the 1950's. Pilots are given little or no explicit information about their current position, and routing information is limited to air traffic control verbal communications and airport charts. In TAP/LVLASO, advanced technologies such as satellite navigation systems, digital data communications, advanced information presentation technology, and ground surveillance systems are being integrated into flight deck displays to enable expeditious and safe traffic movement on the airport surface. The T-NASA (Taxiway Navigation and Situation Awareness) system, described herein, has integrated three components:

- Scene-Linked HUD Symbology -- route/taxi information virtually projected via a HUD onto the forward scene;
- Perspective Moving Map -- track-up airport surface display with own-ship, traffic and graphical route guidance; and,
- 3-D Audio Ground Collision Avoidance Warning system -- spatially-localized auditory traffic and navigation alerts.

A recently completed piloted high-fidelity part-task simulation [12] evaluating two components of the T-NASA system with the scene-linked HUD symbology and an early version of the moving map display found that both of these displays independently aided low-visibility taxi -- reducing navigation errors and decreasing taxi time. More importantly, however, is that the two displays when used as an integrated system led to even larger taxi performance improvements than either display alone. These data are taken to support the efficacy of the integrated design of the T-NASA system.

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