Multi-Dimensionality of Synthetic Vision Cockpit Displays: Prevention of Controlled-Flight-Into-Terrain

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ABSTRACT

NASA's Synthetic Vision Systems (SVS) project is developing technologies with practical applications that will help to eliminate low visibility conditions as a causal factor to civil aircraft accidents while replicating the operational benefits of clear day flight operations, regardless of the actual outside visibility condition. The paper describes experimental evaluation of a multi-mode 3-D exocentric synthetic vision navigation display concept for commercial aircraft. Experimental results showed the situation awareness benefits of 2-D and 3-D exocentric synthetic vision displays over traditional 2-D co-planar navigation and vertical situation displays. Conclusions and future research directions are discussed.

INTRODUCTION

A "synthetic vision system" is an electronic means of displaying the pertinent and critical features of the environment external to the aircraft through a computer-generated image of the external scene topography using on-board databases (e.g., terrain, obstacles, cultural features), precise positioning information, and flight display symbologies that may be combined with information derived from a weather-penetrating sensor (e.g., runway edge detection, object detection algorithms) or with actual imagery from enhanced vision sensors. What characterizes the Synthetic Vision Systems technology is the intuitive representation of visual information and cues that the pilot or flight crews would normally have in visual instrument conditions; Synthetic vision is not simply an aid or adjunct to human visual perception, but rather integrates many technologies that together meet, or exceed, human capabilities found during visual rules flight. A significant research issue, however, concerns the optimal display format for synthetic vision displays to best support local guidance and global situation awareness.

3-D Synthetic Vision Displays

Past research has shown that both 2D and 3D exocentric terrain renderings are useful for portraying a three-dimensional environment, and that the most appropriate cockpit display for a given context is generally dictated by the nature of the tasks at hand (Alexander & Wickens, 2005; St. John, Cowen, Smallman, Oonk, 2001; Wickens, 2000). Three-dimensional displays have been found to best support integration of information across several spatial locations into one display source so as to reduce the amount of visual scanning and mental integration required (e.g., Wickens, Merwin, & Liu, 1994). Another advantage of 3-D displays relates to the concept of "pictorial realism" through the presentation of a view that is similar to what the pilot would expect to see if he or she was looking outside the cockpit window. The design advantages of integration and realism with 3-D displays, however, are limited by perceptual issues, such as line-of-sight ambiguity, foreshortening, and resolution loss (McGreevy & Ellis, 1986; Wickens, Todd, & Seidler, 1989; Wickens et al., 1994).

Experimental Objective

Alexander and Wickens (2004) reported greater vertical position estimation error, higher mental workload ratings, and higher number of unexpected tower collisions (obstacles only visible out-the-window) with the 3-D exocentric display suggesting that the format would not be suitable as a stand-alone display for a synthetic vision display. The objective of the present experiment was to evaluate whether the limitations of 3D display formats could be mitigated through a multi-mode display concept that provides pilots with **rotatable** 2D coplanar and split-screen view options, supporting motion parallax as a depth cue. Another objective was to evaluate the additive effects of cockpit display formats for both ego- and exocentric views because synthetic vision technology will most likely be developed for the primary flight display (PFD) and PFD/Navigation Display (ND) combination (e.g., Schnell et al., 2004; Stapleton & Cieplak, 2004; Williams et al., 2000).

METHOD

Pilot Participants

Twelve transport pilots, who fly for major commercial airlines, participated in the experiment. All participants were head-up display (HUD) experienced and were type-rated in the B-757. The HUD requirement was to ensure familiarity with a velocity vector and guidance symbology. All participants also had logged flight time in "glass cockpits" (e.g., A-320; MD-11).

Simulation

The experiment was conducted in the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III simulator at NASA Langley Research Center. The B-757-200, fixed-based simulator consists of a 144° by 30° out-the-window (OTW) scene and head-down high-resolution research display. The OTW scene was presented with unlimited visibility during simulation training and was reduced to ¾ nm for the experimental runs. The synthetic terrain database for all SVS concepts was 95 nautical miles (nm) by 95 nm in area, centered at the Eagle-Vail Regional County Airport (EGE) airport in Colorado (see Kramer et al., 2005). All scenarios were flown with moderate turbulence and autothrottles engaged.

Experimental Display Concepts

Six display concepts were evaluated from the full-factorial combination of two primary flight displays and three navigation displays. The primary flight displays were: (1) baseline "blue sky/ brown ground" PFD, or (2) synthetic vision PFD. The navigation displays were: (1) baseline 2-D co-planar navigation display, (2) 2-D co-planar SVS navigation display; or, (3) multi-mode SVS navigation display. Each of the display concepts are described below.

Primary Flight Displays

The two PFDs were identical to one another with the exception that synthetic vision terrain information was shown on the SVS PFD. Both PFDs had symbology typical of integrated PFDs (See Prinzel et al., 2004 for details). In addition to the standard PFD symbology, the displays had a flight path marker with acceleration along the flight path indicator and reference airspeed error indicator; a pitch/roll guidance cue (Merrick & Jeske, 1995); and pathway angular deviation indicators. The field-of-view was 30° and display size was 16.0 cm X 16.0 cm (ARINC Size "D" cockpit display).

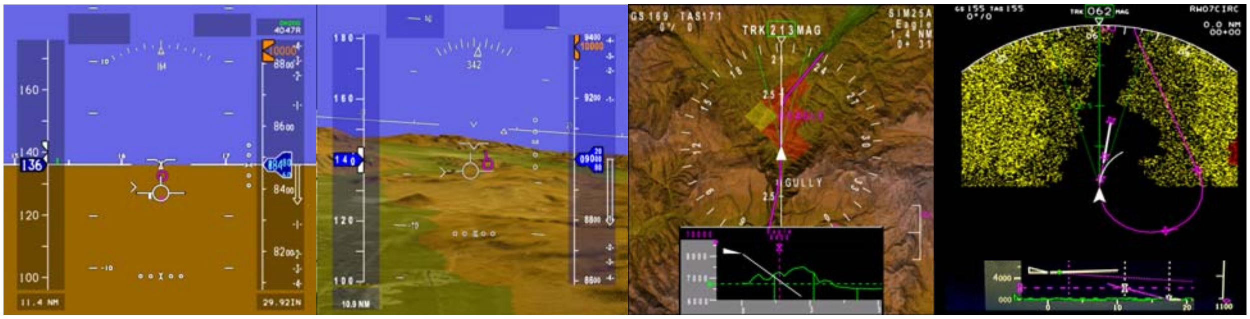

Figure 1. Ego- and Exo-Centric Cockpit Displays

Navigation Display Concepts

Three ND concepts were evaluated: (a) baseline ND w/ Terrain Awareness and Warning System (TAWS) and vertical situation display (VSD), (b) SVS ND w/ TAWS and VSD, and (c) multi-mode SVS ND w/ TAWS and VSD. The baseline ND concept simulated present-day commercial aircraft equipage presented as a co-planar display in map-centered mode. The SVS ND was identical to the baseline ND concept with additional hybrid terrain information. The multi-mode navigational concept was identical to the 2-D SVS ND concept with the exception that the pilot could initiate additional viewing modes that changed the display frame-of-reference from a 2-D co-planar view to either of two dynamic 3-D exocentric perspective views: "Animate" or "Perspective" modes (see Figs 2 and 3, respectively). An important feature of the Multi-Mode display concept was that these 3-D exocentric views would "time out," or go back to the SVS 2D coplanar mode, to preclude the possibility that a pilot might leave the ND in a 3D exocentric mode and attempt to use it for primary navigation; the 3D exocentric modes were designed for "situation awareness" use only.

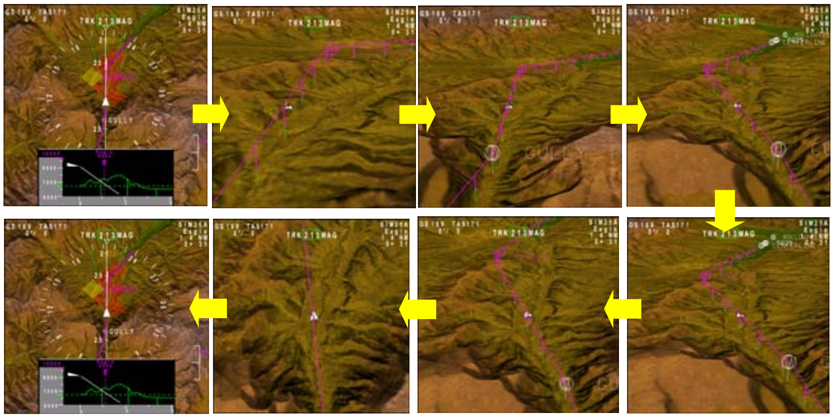

Figure 2. **Static Screenshots of Dynamic "Animate" Mode Sequence**

Figure 3. **Static Screenshots of "Perspective" Mode Sequence**

Experimental Tasks & Design

Each pilot flew thirteen Localizer DME (LDA/DME RWY 25) approach and six departure (KREMM) tasks for a total of nineteen runs. The experimental runs combined one of eight initial starting positions with one of five pre-entered flight management system (FMS) flight paths (3 approach paths, 2 departure paths). Pilots were asked to fly twelve nominal (i.e., non-CFIT) approaches that varied in initial stating position and flight path flown. A thirteenth approach task consisted of an initial starting condition and flight path that guided the aircraft toward significant terrain on approach to the airport. Pilots flew five nominal departure tasks and a "rare event" CFIT departure scenario.

The experimental design was a 2 (experimental task) x 6 (display conditions) x 2 (nominal, rare event) x 12 (pilots) mixed-subjects experimental design. All pilots flew each approach and departure nominal scenario with all six display conditions. There was one replicate of each of the six nominal approach scenarios (2 runs each of nominal approach tasks). For the CFIT scenarios, each pilot experienced one approach and one departure CFIT scenario. Hence for each of the 6 display conditions, only 2 of the 12 pilots experienced the approach CFIT and departure scenarios for a particular display condition. All independent variables were randomly presented to participants across experiment trials.

RESULTS

Flight Technical Error

The flight path tracking data were examined in terms of vertical and lateral deviations from the point of path intercept to the 4.5 DME fix (IEGE) representing the visual descent point and decision altitude. There were no significant differences found for flight technical error for the conditions of display, path, or interactions (p > .05).

Situation Awareness & Workload

Subjective measures of situation awareness are shown in Table 1. There was a significant main effect for display conditions for SA (F(5, 55) = 17.8, p < .01). Pilots rated their SA significantly higher with the SVS PFD + SVS multi-mode ND compared to the other five display combinations. The baseline PFD + baseline ND was rated significantly lower in SA than all other display conditions. No other significant effects were found. This same pattern of effects was revealed with the SA-SWORD measure (F(5, 55) = 60.8, p < .01).

As shown in Table 1, an ANOVA revealed a significant main effect for Revised Workload Estimation Scale ratings for mental workload (F(5, 55) = 2.70, p < .05). The SNK showed that pilots rated the SVS PFD + SVS ND to be significantly lower in mental workload than the baseline PFD + baseline ND. No other displays were significantly different from each other. The SWORD analysis also found a significant effect for mental workload (F(5, 55) = 8.78, p < .05), revealing the same general pattern of effects.

Table 1. Situation Awareness and Mental Workload Ratings by PFD and ND Format.

	Post-Run Subjective Ratings[1]		Paired Comparison Ratings[2]	
Display Combination	Situation Awareness	Workload	Situation Awareness	Workload
Baseline PFD + Baseline 2D Coplanar ND	4.04	2.96	0.022	0.2523
Baseline PFD + SVS 2D Coplanar ND	4.69	2.81	0.042	0.249
Baseline PFD + SVS Multi-Mode ND	5.46	2.77	0.1245	0.2319
SVS PFD + Baseline 2D Coplanar ND	5.5	2.58	0.1369	0.0888
SVS PFD + SVS 2D Coplanar ND	5.88	2.54	0.2297	0.076
SVS PFD + SVS Multi-Mode ND	6.35	2.27	0.4438	0.1005

Note. PFD = primary flight display; ND = navigation display; SVS = synthetic vision system. [1] = 7-point Likert scale. [2] = Geometric means.

Controlled-Flight-Into-Terrain

All pilots avoided terrain for the approach CFIT scenarios, but there was a significant difference in reaction time in response to the non-normal event for both the approach and departure tasks (F (5, 11) = 26.6, p < .05), as shown in Table 2. Pilots responded significantly sooner with the multi-mode ND combinations, and of these, the display coupled with the SVS PFD produced the fastest reaction time. A similar pattern of data was observed with the departure data. The results showed that both pilots who saw the departure CFIT scenario with the baseline PFD + baseline ND concept had a CFIT "incident" and avoided the terrain by an average of 273 ft (83.2 m) vertically and 0 ft laterally.

Table 2. Time of Detection of Impending CFIT before Impact with Terrain

	CFIT Scenario	
Display Combination	Departure (sec)	Approach (sec)
Baseline PFD + Baseline 2D Coplanar ND	14	62
Baseline PFD + SVS 2D Coplanar ND	27	54
Baseline PFD + SVS Multi-Mode ND	184	168
SVS PFD + Baseline 2D Coplanar ND	85	138
SVS PFD + SVS 2D Coplanar ND	72	122
SVS PFD + SVS Multi-Mode ND	237	342

Note. PFD = primary flight display; ND = navigation display; SVS = synthetic vision system.

Mode Preference

Pilots initiated the perspective mode (M = 4.83) significantly more times than animate mode (M = 1.58) during the approach (z = -3.089, p < .05), but not significantly different during the departure (z = -1.406, p > .05) for animate (M = 2.25) and perspective (M = 1.16) modes. Pilots preferred the perspective mode (83%) if limited to one mode only.

DISCUSSION

The objective of the experiment was to evaluate multi-dimensionality of cockpit displays to mitigate the human factors issues of egocentric and exocentric display formats. The results evince that a synthetic vision 2-D coplanar exocentric display with 3-D exocentric option significantly enhanced situation awareness and CFIT prevention, particularly when combined with an egocentric synthetic vision primary flight display. Based on these results, future research will be directed toward design of added functionality (e.g., graphical rehearsal of nominal and off-nominal procedures; Synthetic Vision System electronic flight bags) to extend the tremendous potential of the display concept for accident prevention and increased operational capability.

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