

Preliminary Effect of Synthetic Vision Systems Displays to Reduce Low-Visibility Loss of Control and Controlled Flight Into Terrain Accidents

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ABSTRACT

An experimental investigation was conducted to study the effectiveness of Synthetic Vision Systems (SVS) flight displays as a means of eliminating Low Visibility Loss of Control (LVLOC) and Controlled Flight Into Terrain (CFIT) accidents by low time general aviation (GA) pilots. A series of basic maneuvers were performed by 18 subject pilots during transition from Visual Meteorological Conditions (VMC) to Instrument Meteorological Conditions (IMC), with continued flight into IMC, employing a fixed-based flight simulator.

A total of three display concepts were employed for this evaluation. One display concept, referred to as the Attitude Indicator (AI) replicated instrumentation common in today's General Aviation (GA) aircraft. The second display concept, referred to as the Electronic Attitude Indicator (EAI), featured an enlarged attitude indicator that was more representative of a "glass display" that also included advanced flight symbology, such as a velocity vector. The third concept, referred to as the SVS display, was identical to the EAI except that computer-generated terrain imagery replaced the conventional blue-sky/brown-ground of the EAI. Pilot performance parameters, pilot control inputs and physiological data were recorded for post-test analysis. Situation awareness (SA) and qualitative pilot comments were obtained

through questionnaires and free-form interviews administered immediately after the experimental session. Initial pilot performance data were obtained by instructor pilot observations. Physiological data (skin temperature, heart rate, and muscle flexure) were also recorded.

Preliminary results indicate that far less errors were committed when using the EAI and SVS displays than when using conventional instruments. The specific data example examined in this report illustrates the benefit from SVS displays to avoid massive loss of SA conditions. All pilots acknowledged the enhanced situation awareness provided by the SVS display concept. Levels of pilot stress appear to be correlated with skin temperature measurements.

INTRODUCTION

The ability of a pilot to ascertain critical information through visual perception of the outside environment can be limited by various weather phenomena, such as rain, fog, snow, etc, and darkness typical of night operations. Since the beginning of flight, the aviation industry has continuously developed various devices to overcome low-visibility issues, such as attitude indicators, radio navigation, instrument landing systems, and many more. Recent advances include moving map displays, incorporating advances in navigational accuracies from the Global Positioning System

(GPS), and enhanced ground proximity warning systems (EGPWS). All of the aircraft information display concepts developed to date require the pilot to perform various additional levels of mental model development and maintenance and information decoding in a real-time environment when outside visibility is restricted.

Better pilot situation and spatial awareness during low visibility conditions can be provided by SVS displays. SA can be defined as the pilot's integrated understanding of the factors that would contribute to the safe flying of the aircraft under normal or non-normal conditions. Spatial awareness (an individual component of SA) can be defined as the pilot's knowledge of ownship position relative to its desired flight route, the runway, terrain and other traffic as well as the aircraft's orientation.

GA aircraft compromise 85 percent of the total number of civil aircraft in the United States of America (USA). In a report of the National Transportation Safety Board (NTSB) accident database (Reference 1), of all aviation accident/incident reports from 1983 to 1999, GA accounted for 85 percent of all accidents and 65 percent of all fatalities. For GA fatal accidents, LVLOC and CFIT greatly outnumber all other types of fatal accidents.

LVLOC accidents involve pilots becoming spatially disorientated losing the ability to accurately judge the aircraft's pitch and bank. LVLOC style accidents begin from nominal controlled flight and can proceed into a tight spiral or into an unrecoverable stall or stall and spin combination. Based on previous work, Spatial Disorientation (SD) has been identified as a primary cause in LVLOC accidents. During the course of training associated with instrument ratings, pilots are trained to increasingly rely on the visual orientation cues provided by the cockpit instrumentation and to progressively manage their vestibular sense of orientation.

While previous studies have been conducted regarding the understanding of SD, only relatively minor progress has been achieved towards reducing it (see references 2 through 10). Currently, pilots still require substantial training to become instrument rated, and even at that level of training, LVLOC accidents still occur at an unacceptable rate. CFIT accidents involve a massive loss of SA resulting in the aircraft

actually flying in a much different area than the pilot perceives. In CFIT style accidents, pilots are totally unaware of the proximity to terrain prior to impact. Both accident scenarios involve limited visibility conditions as a causal factor.

Recent technological developments in navigation performance, low-cost attitude and heading reference systems, computational capabilities, and displays present the prospect of SVS displays, in various capacities, in virtually all aircraft. SVS display concepts employ computer-generated terrain imagery to create a three dimensional perspective presentation of the outside world, with necessary and sufficient information and realism, to enable operations equivalent to those of a bright, clear, sunny day, regardless of the outside weather conditions.

Limited visibility is the single most critical factor affecting both the safety and capacity of worldwide aviation operations. The SVS project of the National Aeronautics and Space Administration's (NASA) Aviation Safety Program (AvSP) is striving to eliminate poor visibility as a causal factor in aircraft accidents as well as enhance operational capabilities of all aircraft.

The objective of the SVS project is to develop cockpit display systems with intuitive visual cues that replicate the safety and operational benefits of flight operations in clear day VMC. One part of SVS project is the General Aviation element (SVS-GA). As an initial investigation, the SVS-GA team conducted a study that focused on determining the associated benefits of SVS displays towards reducing LVLOC and CFIT accidents for GA pilots.

DESCRIPTION OF THE EXPERIMENT

EXPERIMENTAL OBJECTIVES - This experiment was performed to establish the benefits of baseline SVS displays towards eliminating LVLOC and CFIT accidents as well as augmenting the knowledge-base regarding SD. In addition, the incorporation of an EAI display enables the value of advanced symbology and terrain to be assessed independently.

EXPERIMENTAL THEORY - It was theorized that a VFR pilot in normal flight acts as a feedback controller who makes control inputs based on visual and vestibular information to correct for deviations from the desired aircraft state. When non-instrument rated pilots process information solely from the aircraft instruments, the additional processing time increases feedback lag time creating an unstable situation. The presence of computer-generated terrain on the primary flight display will enable low-time GA pilots to maintain superior mental models of the outside world while operating in IMC, enhancing spatial and situation awareness, and eliminating LVLOC and CFIT accidents.

TEST SUBJECTS QUALIFICATIONS - A total of 18 pilots participated in the study. All subjects held a valid Private Pilot-Single Engine Land (SEL) license and had no instrument training beyond what was required for the license. In addition, all pilots had less than 400 hours total time with no substantial simulator experience.

EXPERIMENTAL SETUP - The experiment was conducted in the GA Work Station (GAWS) at NASA LaRC. GAWS has 5 primary components. One part of GAWS was the Precision Flight Control's PC-based Aviation Training Device (PCATD) Model PI-142 instrument procedure trainer. The model PI-142 includes controls typical of general aviation aircraft for left- and right-seat pilots. Instrument panel displays and gauges are created using photo-realistic computer graphics and displayed on a 17" LCD. Modifications performed to the PCATD to support this experiment included moving the radio stack to be below the PCATD, replacing the 17" LCDs with 15" LCDs, and using custom imagery from the SVS display software.

Another component of GAWS was the Initiative Computing (IC) Elite Electronic IFR Training Environment Version 6.2 software hosted on a Pentium-3 class PC. The Elite software provided the aircraft dynamic responses to pilot control inputs, control of the out the window weather, post-run data for analysis, as well as data required by the SVS research display software to generate the research display imagery. Various aircraft simulation models were provided by the Elite software. For the current study, a Cessna-172 was selected. Modifications performed to the Elite software included provisions to pass the required data to

the SVS display software via TCP Socketman interface.

The third component of GAWS was the out-the-window imagery that was provided by the Elite GenView software hosted on a Pentium-3 class PC. Aircraft position and orientation information were relayed to this computer from the primary Elite computer via an Ethernet interface. The Elite GenView software provided a generic out the window view for this study. Asheville, NC, was the area selected for this work.

The fourth part of the GAWS apparatus was the SVS research display software system. Hosted on an SGI Intergraph Zx10 computer equipped with an Intense-3D Wildcatt 4210 video board, the SVS research display software generated the imagery presented to the evaluation pilots on the left-side 15" LCD. Aircraft state data, such as pitch, roll, heading, position, airspeed, etc, were transmitted to the SVS research display software from the Elite computer. The research terrain database employed to generate the SVS imagery was created for the Asheville, NC, area using 3-Arcsec Digital Elevation Model (DEM) data. Texturing applied to the terrain database was colored based on the absolute altitude ranging from dark green for altitudes from 0 to approximately 800 ft MSL, to white for altitudes greater than 9,000 ft MSL.

The fifth part of GAWS was the control room area where the test was monitored. Only the evaluation pilot was located in the GAWS cockpit simulation area during the experiment.

Figure 1 shows the GAWS configured to support the current study. The evaluation pilot occupied the left seat. Research display imagery was presented to the evaluation pilot on the left-side LCD. The right-side LCD was turned off for formal evaluations.

RESEARCH DISPLAYS - A total of three displays were employed for the current study. One display concept, referred to as the Attitude Indicator (AI), replicated instrumentation common in today's GA aircraft. Illustrated in figure 2, the AI display included the basic 6 gauges (airspeed, attitude, altitude, turn coordinator, directional gyro, and vertical speed indicator) along with a tachometer gauge that are typical of current GA aircraft. All gauges for the AI display concept were 3" in diameter.

The second display concept, referred to as the Electronic Attitude Indicator (EAI), featured an enlarged attitude indicator that was more representative of a "glass display" that also included some advanced flight symbology, such as a velocity vector. Enlarging the attitude indicator to approximately 4" by 4" provided the ability to evaluate the effect of attitude indicator size as well. In order to limit the number of displays evaluated for this study, some advanced symbology was added to the EAI display. Basic symbology included on the EAI display was a horizon line, a pitch grid, a roll scale with sideslip wedge and a digital heading. Advanced symbology included a velocity vector with sideslip flag. It was considered that all of the symbology elements employed for the EAI concept would be present since the systems required to generate them are considered to be parts of glass cockpit systems, such as Air Data, Attitude, and Heading Reference Systems (ADAHRS). The symbology was presented on top of a blue-sky brown-ground background.

The third concept, referred to as the SVS display, was identical to the EAI except that computer-generated terrain imagery replaced the conventional blue-sky/brown-ground background of the EAI. In order to keep the symbology identical to the EAI display concept, a 50-degree Field of View (FOV) was employed for the SVS imagery. The conformal (non-minified) FOV is about 10.3 degrees. Thus, for this SVS display concept, a minification factor of approximately 4.8 was created. The minification factor is the amount the image is minified to fit onto the display device.

TEST SCENARIOS - Four scenarios were developed based on low time pilot's options. For a VFR pilot to avoid an area of IMC, the pilot may execute one of the following 4 basic maneuvers. The pilot may stay on course and continue the level flight into IMC, he/she may execute a 180-degree turn to reverse the course, or he/she may initiate a climb or a descent, to get back to VMC. All four scenarios were initiated at 2,500 AGL with a speed of 100 kts and a heading of 20 degrees. For all scenarios, the pilots were briefed to use out the window pilotage as much as possible. Upon entering IMC, the pilot was instructed to execute one of the four scenarios.

Scenario 1: Straight and Level - The pilot's task was to fly straight and level until the flight was

ended while maintaining airspeed, altitude and heading.

Scenario 2: 180° Turn - The pilot's task was to make a 180° turn with a 20° bank upon entering IMC while maintaining altitude and airspeed.

Scenario 3: Descent - The pilot's task was to descend 1,000 feet upon entering IMC while maintaining heading and airspeed.

Scenario 4: Climb - The pilot's task was to climb 1,000 feet upon entering IMC at 80 kts while maintaining heading.

TEST PROTOCOL - All subject pilots received a pilot briefing that detailed the experiment they were participating in. Included in the briefing was information regarding research displays and the GAWS facility.

All subjects were trained on the experimental equipment using a set of standardized training scenarios that were similar to the actual experimental flight scenarios. Structured practice time was provided to train subjects to an acceptable level of competency prior to formal evaluations. Once the subjects were fully trained, the physiological data sensors were attached to the subject's body.

The presentation of the research display configurations was counterbalanced to eliminate training effects. Experimental scenario presentation sequences were grouped into 24 possible combinations. The experimental combination was selected at random for each subject pilot and not re-used. Subject pilots would perform the 4 evaluation maneuvers for each display configuration before proceeding to the next display configuration.

DEPENDENT VARIABLES - Objective measures for this study included aircraft state and position data along with pilot control inputs. Subsequent data analysis for this study, pilot performance parameters of heading, altitude, airspeed, and bank angle will be analyzed. Private pilot performance standards were employed for the interpretation of the data. Private pilot test standards require pilots to maintain airspeed within +/-10 kts, altitude within +/-100 ft, and heading within +/-10 degrees. A loss of control of the aircraft was considered to be when either pitch angle was greater than +/-

30 degrees and bank angle was greater than +/- 60 degrees. Massive loss of situation awareness was defined as altitude errors greater than 1,000 feet and heading errors greater than 45 degrees. Frequency analysis of the pilot control inputs was also conducted.

Physiological measurements included heart rate, skin temperature on the left (flying) hand, as well as muscle flexure on the left forearm. Subjective measures included the NASA TLX and a Stress-Arousal Checklist (SACL) after each run and responses to post-test questionnaires.

PRELIMINARY RESULTS AND DISCUSSIONS

At the time this paper was written, data analyses were still being conducted. Results presented herein are included to illustrate initial findings and to present the methods.

During the course of this study, subject pilots were instructed to maintain certain performance criteria appropriate for the evaluation maneuver. While no pilots experienced a loss of control event as defined by this study, one example of massive loss of SA was encountered and will be the focus of discussion for these preliminary results.

Real-time data for the massive loss of SA example is presented in figure 5. Figure 5 presents heading, bank angle, altitude and airspeed errors, visibility, roll and pitch commands for this example. In this experimental setup, IMC was considered to exist for visibilities less than 3 miles. In this example, the subject pilot performed a 360-degree turn instead of the desired 180-degree turn while using the AI display. As shown in figure 5, the massive loss of SA occurred for the baseline AI display, which was the last display configuration presented to this pilot. For this example, the subject pilot employed a bank angle of 40 degrees, instead of the nominal 20 degrees, lost 150 feet of altitude, and increased airspeed by almost 15 kts. While the bank angle, altitude, and IAS deviations were not considered extreme, the fact that the subject pilot was 180 degrees off of course could lead to serious safety of flight hazards, especially if hazardous terrain were in the vicinity.

Figure 6 presents altitude error vs. roll angle for the entire 180-degree turn maneuver for the massive loss of SA example. The significant observation from this figure is that a substantial altitude error was produced during the banked turn portion of the maneuver for the AI and EAI concepts. The subject pilot was able to control altitude better for the SVS display concept.

Preliminary qualitative results are presented in figure 7, which illustrates the results of all subject pilot responses to a series of questions. Pilots were asked to rank the displays in three areas; 1-which display concept would be best in IMC, 2-which display concept would be the best for SA, and 3-which display concept would be best for Spatial Awareness. From figure 7, it can be seen that the large majority of the subject pilots ranked the SVS display concept as best in all three areas. Only one pilot ranked the AI display as best in IMC and spatial awareness reflecting a preference for what he was accustomed to.

Specific pilot comments recorded indicate that the SVS display provided superior SA. Positive comments such as "it just makes it easier to fly" and "I felt the display gave a very realistic situation awareness" were received. Negative comments such as "I think it (the terrain) distracted me more than helped" were also noted.

Preliminary physiological data is presented in figure 8. This figure shows average subject pilot skin temperatures during the entire descent maneuver for all three display concepts. Lower skin temperatures can indicate increased levels of stress. From figure 8, it can be seen that skin temperatures varied depending on which display concept was being evaluated. It can be seen that lower skin temperatures were recorded for the AI concept than for the EAI and SVS concepts during both VMC and IMC. Also, lower skin temperatures were recorded for IMC than for VMC operations for the display concepts evaluated. While the analysis of these data are preliminary, the data in figure 8 could indicate that pilots felt less stress while operating with the SVS display concept.

FUTURE WORK

Future analysis of the data will include a segmentation of all of the scenarios to provide a detailed comparison across display concepts.

For example, the 180-degree turn maneuver will be broken into 5 segments (pre-IMC straight and level, IMC turn entry, IMC level turn, IMC roll-out, and IMC straight and level). Figure 9 presents heading versus time for an example maneuver. The dots in figure 9 indicate the automatically selected segment breakpoints. Analysis of the data for each segment will include max/min and RMS values of errors from the target parameters and frequency analysis of the pilot control inputs for segments greater than 30 seconds. Private pilot's test standards will be employed for the interpretation of the resulting data. While initial analysis of the physiological data indicate increased stress levels for the AI display as compared to the EAI and SVS display concepts, subsequent analysis of the physiological data will include accounting for the subject's pre-exposure levels for heart rate, skin temperature, and muscle flexure. A statistical analysis will be performed on the resulting pilot performance and physiological data.

tested. Many pilot comments were recorded indicating that the SVS display concept provided an enhanced level of SA.

Results from the current study will be extended by subsequent simulation work in the GAWS as well as flight-testing at NASA LaRC. The follow-on study, referred to as Terrain Portrayal for Head-Down Displays (TP-HDD), will endeavor to establish requirements for terrain depiction for SVS displays. A total of 15 terrain portrayal concepts, created from variations in DEM and terrain texturing concepts, will be evaluated by at least 20 subject pilots. Following the simulation portion of TP-HDD, a 12-pilot flight test is planned, employing NASA LaRC's Cessna-206. The flight test will be conducted to extend the results of TP-HDD and the current simulation experiments to an actual flight environment.

CONCLUSIONS

Preliminary results from the current study indicate that SVS displays provide benefits compared to AI and EAI display concepts. For the data example discussed herein, the ability for the subject pilot to perform the 180-degree turn maneuver in IMC conditions was superior for the SVS display concept. The massive loss of SA, as indicated by the 360-degree turn instead of the nominal 180-degree turn, was observed for the baseline AI concept. Qualitative results of pilot preferences heavily favor the SVS display with it being ranked as best for IMC, best for SA, and best for Spatial Awareness out of the three display concepts

Figures



Figure 1. GAWS configured to support the current study.



Figure 2. The baseline AI research display.



Figure 3. The EAI research display.

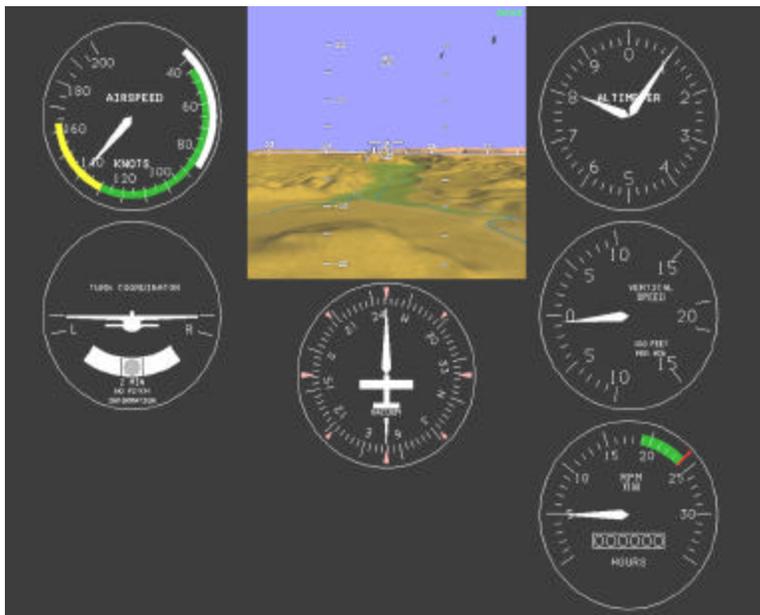


Figure 4. The SVS display.

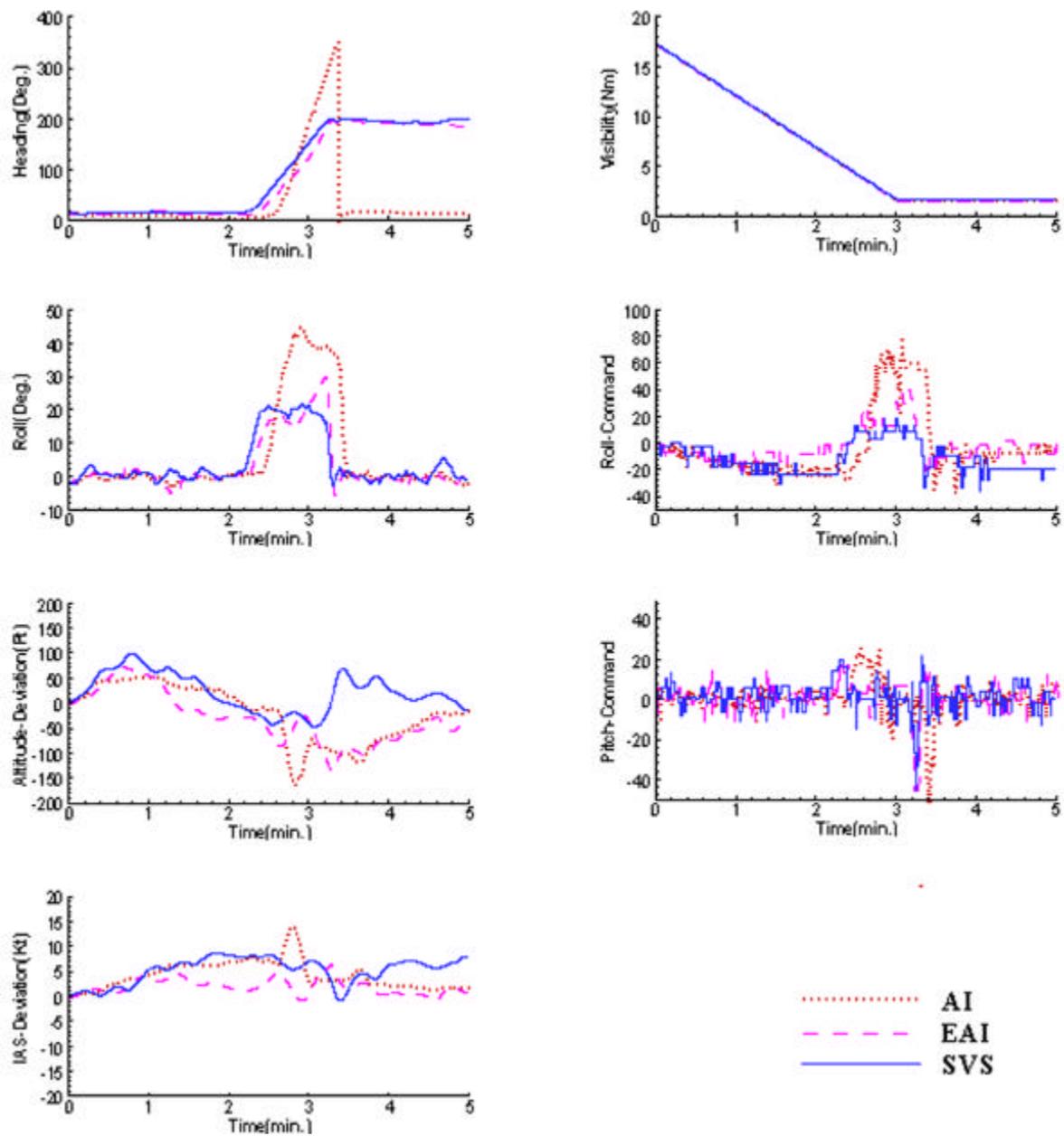


Figure 5. Real-time data for one subject pilot for the 180 degree turn maneuver for AI, EAI, and SVS display concepts. In the left column, from top to bottom, are heading, bank angle, altitude, and indicated airspeed. In the right column from top to bottom are visibility, roll (lateral) command, and pitch (longitudinal) command.

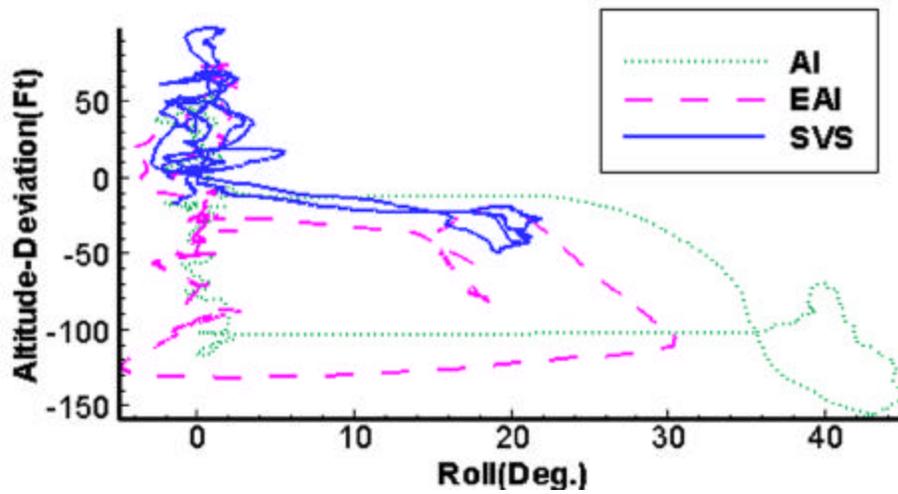


Figure 6. Altitude deviation plotted against bank angle for the entire 180-degree turn maneuver for the massive loss of SA example.

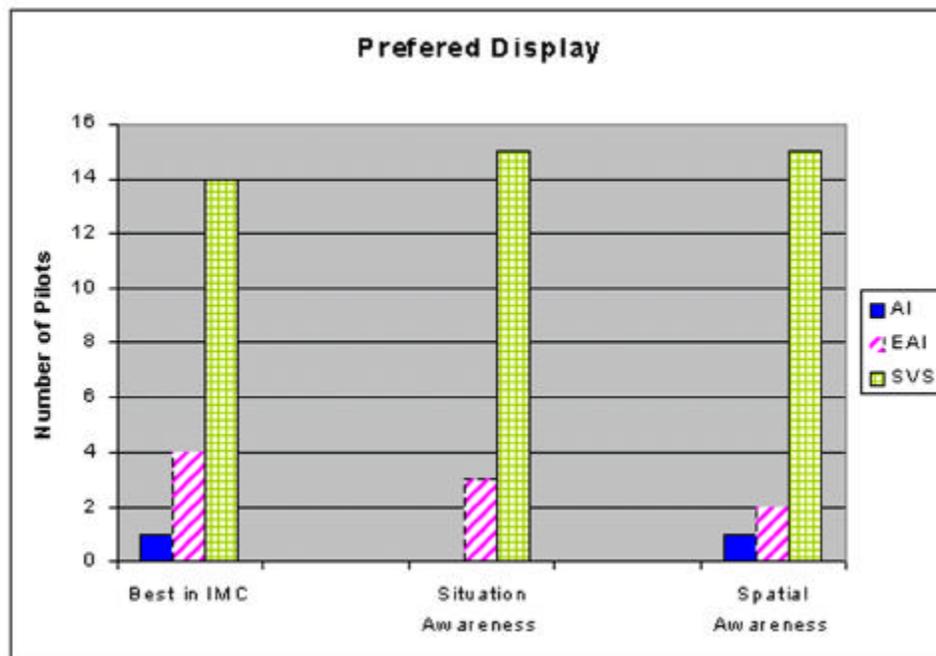


Figure 7. Results from questionnaires regarding which concept was preferred for IMC operations, Situation Awareness, and Spatial Awareness.

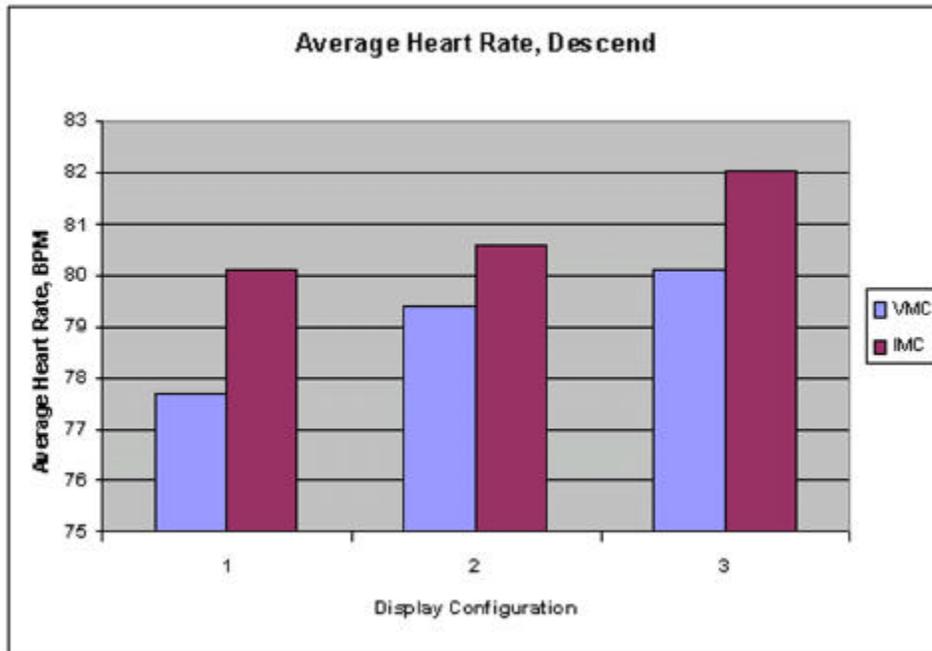


Figure 8. Example of preliminary physiological results. Average skin temperature for the entire descent maneuver for all pilots. Display configuration #1 is the AI, #2 is the EAI, and #3 is the SVS display concept.

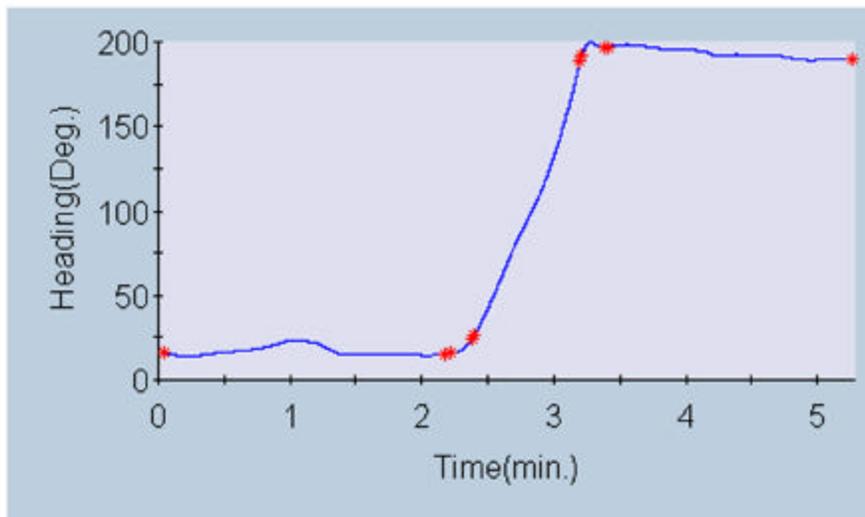


Figure 9. Example of automatic maneuver segmentation system to be used for subsequent data analysis.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADAHRS	Air Data, Attitude, and Heading Reference System
AI	Attitude Indicator display concept
AvSP	Aviation Safety Program
CFIT	Controlled-Flight into Terrain
EAI	Electronic Attitude Indicator
DEM	Digital Elevation Model
EGPWS	Enhanced Ground Proximity Warning System

FOV	Field of View
GA	General Aviation
GAWS	General Aviation Work-Station
GPS	Global Positioning System
IAS	Indicated Airspeed
IMC	Instrument Meteorological Conditions
LCD	Liquid Crystal Display
LVLOC	Low-Visibility Loss of Control
MSL	Mean Sea Level
NASA	The National Aeronautics and Space Administration
NTSB	National Transportation and Safety Board
PC	Personal Computer
PCATD	Personal Computer Aviation Training Device
SA	Situation Awareness
SACL	Stress and Arousal Checklist
SD	Spatial Disorientation
SEL	Single Engine Land
SVS	Synthetic Vision Systems
TLX	Task Load Index
TP-HDD	Terrain Portrayal for Head-Down Displays
USA	United States of America
VMC	Visual Meteorological Conditions