Running head: EFFECTS OF SVS AND V-CAS ON SINGLE PILOT PERFORMANCE

Effects of a Velocity-Vector Based Command Augmentation System and Synthetic Vision System Terrain Portrayal and Guidance Symbology Concepts on Single-Pilot Performance

Dahai Liu

Embry Riddle Aeronautical University

Kenneth Goodrich

NASA Langley Research Center

Bob Peak

Cogent Corporation International

Abstract

This study investigated the effects of synthetic vision system (SVS) concepts and advanced flight controls on the performance of pilots flying a light, single-engine general-aviation airplane. We evaluated the effects and interactions of two levels of terrain portrayal, guidance symbology, and flight control response type on pilot performance during the conduct of a relatively complex instrument approach procedure. The terrain and guidance presentations were evaluated as elements of an integrated primary flight display system. The approach procedure used in the study included a steeply descending, curved segment as might be encountered in emerging, required navigation performance (RNP) based procedures. Pilot performance measures consisted of flight technical performance, perceived workload, perceived situational awareness and subjective preference. The results revealed that an elevation based generic terrain portrayal significantly improved perceived situation awareness without adversely affecting flight technical performance or workload. Other factors (pilot instrument rating, control response type, and guidance symbology) were not found to significantly affect the performance measures.

Nomenclature

ANOVA = analysis of variance

BSBG = blue sky brown ground (terrain portrayal concept)

df = degrees of freedom for analysis of variance

EBG = elevation based generic (terrain portrayal concept)

FBW = fly-by-wire

FTP = flight technical performance

F-value = ratio of the model mean square to the error mean square

GSC = guidance symbology concept

HITS = highway in the sky (guidance symbology concept)

IFR = instrument flight rules

IV = independent variable

p = p-value (ANOVA significance level)

PFD = primary flight display

PRFD = pitch roll flight director (guidance symbology concept)

RMSE = root mean squared error

RNP = required navigation performance

SA = situation awareness

SART = Situation Awareness Rating Technique

SD-HDD = Symbology Development for Head-Down Displays

SVS = Synthetic Vision System

TLX = Task Load Index

TPC = terrain portrayal concept

TWS = time within standard

V-CAS = velocity vector augmentation system

Introduction

Single-pilot operations in low-visibility conditions can be extremely challenging and less forgiving of human-error than multi-pilot operations. On average, the workload is higher and without the ability to cross-check decisions and actions with an independent crew member, slips and lapses have an increased risk of propagating into hazardous situations. At the same time, many single-pilot operations are conducted by pilots with less training, total experience, recent experience, and oversight than pilots typically conducting multi-pilot, commercial transport operations. Finally, full access to the future national airspace is likely to require high flight-technical performance while performing more complex procedures such as curved, radius-to-fix legs, and the ability to self-separate during some flight phases (JPDO, 2007). Meeting these future requirements may be particularly challenging for single-pilots and may, more than crewed-operations, depend on the careful integration of advanced technologies. The demands of single-pilot operations put increased emphasis on technologies that, beyond performing their intended function, are easily learned and remembered, minimize adverse workload additions or peaks, and support robust error resistance and/or recovery. Two technologies that may be particularly beneficial in this context are synthetic vision and highly-augmented, manual flight controls.

Synthetic Vision Systems (SVS) are designed to improve pilot performance by enhancing situation awareness (SA) and control precision without increasing mental and physical workload significantly. SVS typically refers to a primary flight display (PFD) that, in addition to the traditional control, performance, and navigation indicators, includes an egocentric, perspective rendering of the external environment

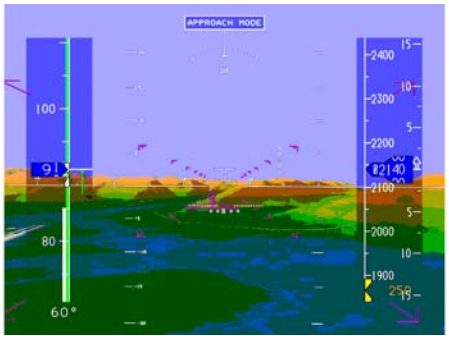

Figure 1 – Example of a SVS based PFD

(e.g. terrain, obstructions, and cultural features) as shown in figure 1. This rendering often includes a visualization of the desired flight path, usually in the form of a pathway or "highway in the sky" (HITS, Arthur, Prinzel, Kramer, Parrish, & Bailey, 2003). A HITS provides easily interpreted visual cues indicating the position and orientation of the aircraft relative to the desired flight path. To further enhance the usefulness of the HITS, a flight path marker (FPM) symbol showing the actual or near future (i.e. quickened or predicted) direction of travel of the aircraft is typically displayed as well. The expectation is that the naturalistically presented information of an SVS can be assimilated more rapidly and robustly than conventional presentations. Previous studies such as Glaab and Takallu (2002), Uenking and Hughes (2002), Comstock, Glaab, Prinzel, and Elliott (2001), and Hughes and Takallu (2002), support this expectation.

A potential concern regarding SVS is that much of the terrain and pathway information is not essential for immediate control and guidance of the flight and can be visually complex and cognitively compelling, possibly interfering with the perception of other critical information (e.g. Wickens, Alexander, Horrey, Nunes, & Hardy, 2004). Wong, Takallu, Hughes, Bartolone, and Glaab (2004) conducted a simulation experiment to partially investigate this potential. They compared flight technical performance (FTP), workload, and situation awareness for a range of SVS symbology concepts ranging from relatively simple terrain and guidance presentations to potentially more informative but also more complex presentations. Their study found no interaction between terrain portrayal concepts and FTP and no significant interaction between guidance symbology and terrain portrayal complexity. These results suggest that designers can independently choose a preferred terrain portrayal and guidance symbology concept without excessive concern regarding adverse interactions. Our investigation examines key findings from Wong, et al. (2004) by evaluating a sub-set of their display concepts in a flight environment.

While SVS by itself has the potential to enhance FTP and pilot awareness, the underlying task of flying the airplane remains essentially unchanged. For a typical, unaugmented airplane, the pilot must monitor the primary flight instruments nearly full-time, particularly when operating in turbulence. Pennington (1979) reported that proficient pilots using conventional, electro-mechanical flight instruments allocate approximately 70-80% of their visual attention to monitoring the attitude indicator and directional gyro. This high allocation severely limits the time available for other important cockpit tasks. While large-format attitude and SVS displays should reduce this allocation, the basic flight characteristics of an aircraft require constant, high-frequency attention and brief inattention can result in an unusual attitude and possible loss of control (Newman & Greeley, 2001).

Current autopilots offer a means of addressing this concern but create additional complexity and potential hazards by introducing multiple, dissimilar modes of control, and in more complex systems, potentially confusing temporal shifts between command inputs and the response of the airplane. In addition, autopilots encourage detachment from the basic "aviate" task by eliminating the pilot's physical involvement (Billings, 1997). While the pilot is expected to monitor the situation, there is generally no immediate feedback or consequence if this responsibility is not diligently performed.

An alternative to current autopilot systems is to integrate active control elements directly into the manual control system such that the short and long-term responses of the aircraft follow appropriate performance indices. A "Fly-by-wire" (FBW) control system in which the pilot's inceptors, for example the control yoke, issue commands to a flight control computer rather than being linked directly to the control effectors underlies, perhaps, the definitive mechanization of such an approach. Although currently considered too expensive and high-risk for light aircraft, FBW technology has recently migrated from military and large commercial aircraft to lower cost commuter and business jets and technologically

similar “drive-by-wire” systems are also beginning to appear on production automobiles. These trends suggest that FBW may become economical for small aircraft in the foreseeable future.

The application of FBW opens up a range of design options as to what the pilot commands through the control inceptors and how the aircraft responds to these commands and other factors of flight such as staying within the operating envelope. Depending on the goals of the design and practical constraints in its realization, for example, consideration of failure effects, FBW offers potential performance, training, workload, and safety benefits. By creating a direct, proportional relationship between operational parameters of interest (e.g., vertical speed, turn rate, and airspeed) and the airplane’s response to the pilot’s control inceptors, the effort to learn and preserve low-level perceptual-motor skills can be reduced, as can operational workload. Automatic disturbance rejection may also reduce workload and improve performance when the pilot’s attention is diverted from the immediate control task. Finally, integrated envelope protection features may improve safety by preventing unintentional departures from the design flight envelope and by simplifying the piloting technique needed to achieve and maintain maximum performance (Rogers, 1999).

The design space of potential FBW realizations is large and relatively unexplored outside the perspective of traditional flying qualities for skilled pilots with undivided attention on a control task. The design of the system in this study was directed toward enabling training, workload, performance, and safety benefits, particularly for low-time and ab-initio student pilots. Since there are few detailed guidelines for achieving these objectives, the specific system implementation used in this study should be considered exploratory and not necessarily the optimum design relative to these goals. Extensive research would be required to propose any such recommendations and is far beyond the scope of this study. It should also be noted that while the system used in the study was developed with the goal of

demonstrating the full range of benefits, this study focuses on assessing workload and performance impacts during manual control.

The research FBW system provided the evaluation pilots with direct control over the velocity vector of the aircraft and can be classified as a velocity-vector command augmentation system (V-CAS). The longitudinal position of a 2-axis side-stick commanded the vertical, air-mass referenced, flight-path angle. Lateral side-stick position commanded bank angle (effectively turn-rate and turn radius at constant airspeed). A separate, single-axis lever commanded airspeed (figure 2). It should be recognized that these response characteristics are quite different from an unaugmented airplane. For example, when the pilot applies no force to the stick, allowing it to return to neutral, the bank angle and flight-path angle commands are zero and the aircraft promptly returns to and maintains straight and level flight. In comparison, neutralizing the inputs of an unaugmented airplane simply returns the control effectors to a neutral position, nulling their respective control moments and nothing can be directly inferred about the attitude or trajectory. The current implementation was developed for ease of learning by ab initio pilots with no flight experience but highly experienced operating ground vehicles in which inceptor inputs (e.g. steering wheel deflection) typically correspond to the rate of change of the trajectory (e.g. turn rate). As would be expected, the unconventional response characteristics introduced transition issues for the experienced pilots used in this study. The transition issues were recognized during the development of the system but considered acceptable based on earlier research (e.g. Bergman, 1976).

Figure 2 - Control inceptors for FBW system

In simulation (Stewart, 1994; Lam, Mulder, van Paassen, & Mulder, 2006) and limited flight experiments (Bergman, 1976), similar V-CAS implementations show improved FTP

while reducing workload. Stewart also demonstrated that minimal training is needed to use a properly functioning V-CAS system (i.e. effects of potential failures have not been investigated). This study examines the general findings from these earlier studies in a flight environment and in the context of emerging airspace procedures incorporating curved flight segments. In addition, this study investigated potential interactions between the SVS and V-CAS concepts. Previous research (e.g. Stewart, 1994 and Lam, et al., 2006) suggests that the control-display concurrence of a path-based HITS and the path-based control provided by the V-CAS is particularly beneficial.

Since the motivating context of this evaluation is small-aircraft operations, the flight task scenario and evaluation pilot pool were selected accordingly. The flight task, explained in detail later, consisted of a challenging, multi-segment approach procedure intended to be representative of what might be implemented in the future using required navigation performance (RNP) concepts. Such a procedure might be needed to support access to a terrain challenged airport or an urban airport with demanding noise and/or obstacle clearance concerns. The evaluation pilot pool consisted of current, licensed pilots and included both instrument rated and non-instrumented rated subjects. The investigators initially planned on including flight-naive subjects, but time limitations prevented this participation.

Summarizing, the specific objectives of the study were two fold:

1. Evaluate the benefits and issues of SVS displays and a V-CAS for a single pilot conducting advanced airspace procedures by providing comparative results of SVS and V-CAS versus conventional interfaces.
2. Examine key findings from a previous simulation experiment (Wong, et al., 2004) in flight. Specifically, investigate the interactions between Guidance Symbology Concepts (GSC) and Terrain Portrayal Concepts (TPC) as part of a PFD.

Method

Based on the objectives of the study, the following hypotheses were tested:

Hypothesis 1: SVS/HITS significantly improves the flight performance of both IFR and non-IFR pilots.

Hypothesis 2: V-CAS has a significant improvement on both IFR and non-IFR pilots' flight performance.

Hypothesis 3: With SVS/HITS and V-CAS, non-IFR pilots can achieve the flight performance of an experienced IFR pilot with conventional controls.

Hypothesis 4: FTP will not be significantly affected by the 2 terrain portrayal concepts of the SVS display for both IFR and non-IFR pilots.

Hypothesis 5: Pilots will have a significant subjective preference for elevation based generic (EBG) over blue sky, brown ground (BSBG) terrain portrayal.

Due to limitations on the availability of suitable test subjects when the flights were conducted, the final mix of evaluation pilots was 8 Non IFR pilots and 4 IFR rated pilots. Also, while not a requirement for participation, all the evaluation pilots were male.

To test these hypotheses with the small subject pool, a mixed factorial design was conducted on the following variables:

Independent Variables (IVs): There were four independent variables with each variable having two levels:

IV-1: Terrain portrayal concepts [1. Blue sky, brown ground (BSBG); 2. Elevation based generic (EBG)]

IV-2: Guidance and position awareness symbology concepts [1. Pitch / roll flight director (PRFD); 2. The preferred HITS symbology from Wong, et al., 2004 (e.g. the "NASA Ghost format")]

IV-3: Control system response types [1. Conventional aircraft controls; 2. V-CAS]

IV-4: Pilot Rating [1. Non IFR pilots; 2. IFR pilots]

Among these variables, IV-1, IV-2, IV-3 are within-subject variables and IV-4 is the only between-subject variable. There are 8 treatments for each pilot skill type: 4 symbology and terrain portrayal combinations x 2 the two control system types. Figures 3 and 4 illustrate the 4 different combinations of the symbology and terrain portrayal types. Since changing the control system configuration took approximately one day to perform, it was necessary to evaluate one control system configuration at a time and keep this configuration until all other necessary runs had been made. For this reason, the control system presentation was counterbalanced with half the participants flying first with the V-CAS and the other half flying first with the conventional controls. Treatment presentation was randomized at a group level. This design should prevent practice effects from masquerading as treatment effects. That said, any practice effects will still reduce the sensitivity of the experiment.

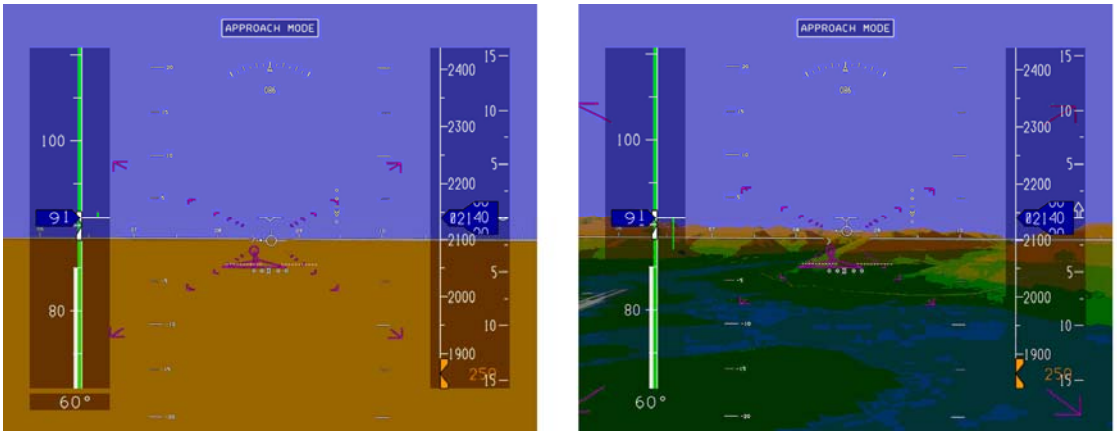

Figure 3. Terrain portrayal. Left: Blue Sky Brown Ground (BSBG)/NASA Tunnel (HITS); Right: Elevation Based Generic Terrain/ NASA Tunnel (EBG/HITS)

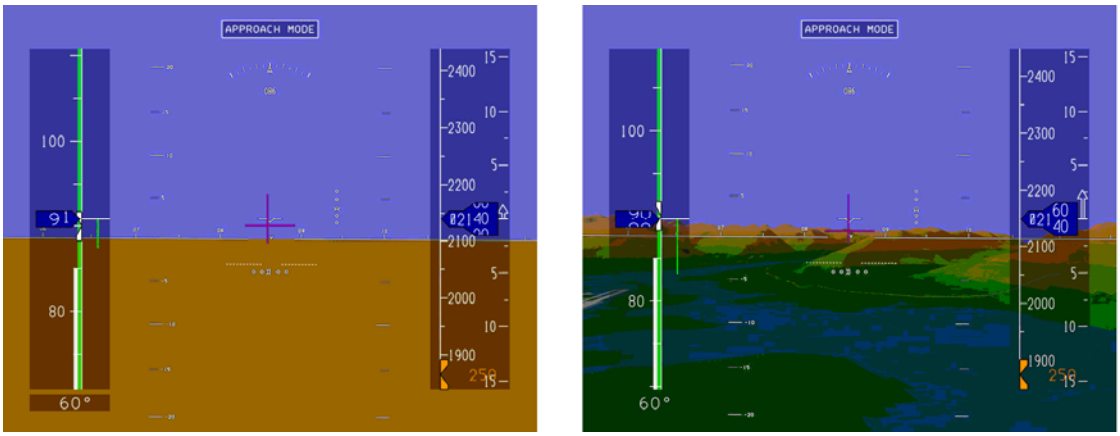

Figure 4. Illustration of symbology. Left: Blue Sky Brown Ground/ Pitch Roll Flight Director (BSBG/PRFD); Right: Elevation Based Generic Terrain / Pitch Roll Flight Director (EBG/PRFD)

Apparatus

Figure 5 - Flight Deck of Test Aircraft

Test airplane was a modified 1978 Model F33C Bonanza, S/N CJ-144. Figure 5 provides a picture of the modified cockpit. The right side of the cockpit served as a safety pilot's station and retained conventional, certified instruments, avionics, and controls. During flight operations, a safety pilot was the legal, pilot in command. The left side of the cockpit was modified to serve as a flexible, evaluation pilot's station and was equipped with reconfigurable controls and displays. When evaluating the V-CAS, a side-stick control inceptor and airspeed command lever were installed. In response to the pilot's inputs, these devices generated signals sent to a flight control computer in the rear of the aircraft. For conventional control evaluations, a standard dual-yoke control column was installed. The evaluation pilot's station was configured with two high-brightness 8 x 10 inches liquid crystal displays with resolutions of 1024 x 768 pixels. The left display was used to display the PFD concepts while the right display was used to present a complimentary navigation display. This

navigation display provided a real-time, planform view of the approach procedure and terrain in a track-up, exocentric format. Two personal computers mounted in the rear of the aircraft drove the two displays. Both of these computers received position and state information from an air-data, attitude and heading reference system installed in the aircraft. The computer driving the PFD also functioned as the data acquisition system, recording the performance parameters used later in the paper.

Procedures

Training

All the evaluation pilots participated in the previously conducted "Symbology Development for Head-Down Display" (SD-HDD) simulation experiments described by Wong, et al. (2004) and Takallu, et al. (2004) and received extensive training and practice with the terrain portrayal and guidance symbology concepts. See Takallu, et al. (2004) for more details on this training. Since control system response type was not a factor in the SD-HDD experiment, subjects did not have prior training on the V-CAS. Prior to the conduct of the current flight experiment, subject pilots received a refresher briefing on the terrain portrayal and guidance symbology concepts as well as an introduction to the V-CAS. Subjects were also provided with sufficient flight time in the aircraft to become comfortable with the symbology and control concepts prior to the collection of relevant data.

Evaluation tasks

The Juneau approach procedure from the SD-HDD experiment was used in this study as the flight task. As Figure 6 illustrates, the approach consists of four different segments presenting the pilot with differing levels of difficulty. The procedure begins with an easy segment (straight and level) followed by a transition to a straight segment with a three degree descent angle typical of current procedures. This is followed by constant radius, curved

segment with a steep descent angle (6 degrees). At the approach speed of the test aircraft (90 knots) the radius of curvature corresponds to a nominal bank angle of 10 degrees. The approach ends with a final straight segment having a 4 degree glide slope angle.

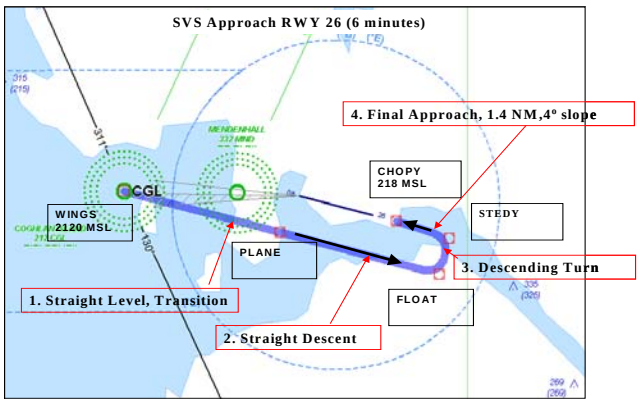

Figure 6. Flight Approach

Flight operations

Flights originated from Beech Field in Wichita Kansas and the evaluation approaches were conducted nearby, in an area selected to avoid other air traffic. The research system allowed the measured position of the aircraft to be biased such that from the perspective of the SVS displays, the aircraft appeared to be operating in the Juneau, Alaska, area.

Each evaluation pilot flew two separate flights corresponding to the two control system configurations. Individual flights lasted approximately 60 minutes including transit time to and from the test area. Within a flight, the pilots experienced the 4 display treatments with the order of presentation being randomized. During the conduct of the evaluation scenarios, subject pilots wore a view-limiting hood that prevented use of outside visual cues. At the completion of an evaluation approach, the safety pilot would take back control of the aircraft and set up for the next approach. During this period, the evaluation pilot completed the workload and SA questionnaires described in the next section.

Variables and Measurements (Dependent Variables)

FTP measures how a pilot performs in terms his flight path and airspeed control relative to the desired path and airspeed. FTP was measured using two types of metrics: root mean square error (RMSE) and time within standard (TWS). Since RMSE is the square root of the averaged mean square of the deviation from standard (i.e., airspeed, vertical and lateral deviation) it should be noted that it cannot be negative. Given this lower bound of zero, the distribution of RMSE is not likely to be normal, which is a basic requirement for most inferential statistic procedures. To address this issue, RMSE data were transformed using the natural logarithm function, and this will usually result in a normal distribution of RMSE data. TWS is computed as the percentage of time during an approach during which the pilot remained within the specified performance tolerances. The tolerances used were airspeed within ± 10 knots of 90 kts, lateral deviation ≤ 200 feet, and vertical deviation ≤ 150 feet.

Subject pilots completed questionnaires after each evaluation approach (the run questionnaire), flight (the block questionnaire), and at the conclusion of a subject's participation (the exit questionnaire). The run questionnaire focused on subjective evaluation of workload and SA using the NASA Task Load Index (TLX) and Situation Awareness Rating Technique (SART) respectively. Using the TLX, evaluators rated seven different workload factors: mental demand, physical demand, temporal demand, effort, performance, frustration, and stress level. Evaluators indicated their ranking by making a pencil mark along a continuum (indicated by a horizontal line segment) running from "low" to "high" for each factor. During the data analysis process, the placement of the marks was recoded into a quantitative value between 0-100 based on its position along the line segment. The raw rating of the "performance" factor was also subtracted from 100, so that like the other factors, a lower rating value generally indicates improved performance. This consistency allowed a composite workload rating to be obtained from an average of the factor ratings. Similar to

the TLX questionnaire, the SART survey assesses different aspects of pilot situation awareness, including demand on attention resource, supply of attention resource, level of aircraft situation awareness, level of terrain awareness, and level of guidance information awareness. As with the TLX, the SART was administered with paper and pencil with evaluators placing a mark for each factor along a continuum between low and high. Again, as part of the data analysis process, the placement of the marks was recoded into quantitative values between 0-100. For the SART responses, higher values typically indicate improved perceived awareness. Again, the average of the factor ratings was used to obtain a composite value.

The block questionnaire was administered after each flight to obtain a participant's subjective feedback regarding preferences towards different terrain portrayal and guidance symbology under each control type. After a subject completed both flights, he completed a questionnaire providing subjective feedback comparing the two control types.

Results

The twelve participants were scheduled to complete two flights for the study. Although all 12 participants completed all the planned evaluation approaches, there were some runs that had technical glitches and had to be repeated. Also, a data acquisition and recording system glitch resulted in the loss of lateral deviation data for one subject, so that that person's data was dropped from the data analysis. In order to identify the significant factors, in depth statistical analyses were carried out by performing repeated measures ANOVA on each of the flight performance metrics. A significance level of 5% was used to identify the significant factors. The results are presented in the following sections.

Lateral Path Deviation

The ANOVA results for lateral flight path deviation are presented in Table 1. The results indicate that none of the main factors significantly influence lateral flight path deviation. Thus, based in this lateral path control, hypotheses 1, 2 and 3 are rejected and hypothesis 4 is accepted.

Two interaction factors, however, were found to be significant. A further look at these interactions (Figure 7) shows an interaction between the control type and instrument rating.

Table 1 - Results of ANOVA on horizontal deviation RMSE

Source	*Design type*	*df*	*Sum of Square*	*Mean Square*	*F-value*	*Significance p-value*
Pilot Rating	Between subjects	1	.417	.417	.235	.639
Control Type	Within Subjects	1	1.046	1.046	1.184	.305
Terrain Portrayal	Within Subjects	1	1.251	1.251	1.486	.254
Guidance Symbology	Within subjects	1	5.418	5.418	3.932	.079
Control × Rating	Within subjects	1	4.686	4.686	5.302	**.047***
Control × guidance symbology × rating	Within subjects	1	4.895	4.895	5.491	**.044***

* Significant factor

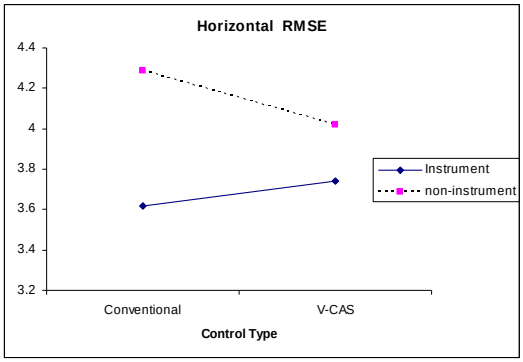

Figure 7 -- Mean horizontal RMSE for pilot rating and control type

That is to say, for instrument rated (IFR) pilots, their performance on maintaining lateral position using V-CAS was degraded compared to conventional control, while for non-

IFR pilots, V-CAS improved this performance. This effect can be further investigated by using a 3-way interaction plot. The results show that with guidance symbology 1 (baseline PRFD), the interaction between control type and pilot rating is positive. For the PRFD guidance, the non-IFR pilots had larger lateral deviations than IFR rated pilots. For this symbology, both groups had increased deviation with the V-CAS. With the HITS symbology, the interaction between control type and pilot rating become negative, that is compared to the IFR rated pilots, the non-IFR rated pilots had higher deviation with the conventional control and lower deviation with the V-CAS. The above finding (negative interaction effect) results in rejecting hypothesis 2, which states that V-CAS will improve flight performance for both pilot groups. The results also suggest that the effect of V-CAS (positive or negative) on pilot performance relies on other factors, such as the guidance symbology.

Vertical Path Deviation

The ANOVA results for vertical flight path deviation are presented in Table 2:

Table 2 - Results of ANOVA on vertical deviation RMSE

Source	*Design type*	*df*	*Sum of Square*	*Mean Square*	*F-value*	*Significance p-value*
Pilot Rating	Between subjects	1	2.041	2.041	2.192	.173
Control Type	Within subjects	1	.297	.297	.940	.383
Terrain Portrayal	Within subjects	1	.081	.081	.154	.703
Guidance Symbology	Within subjects	1	5.597	5.597	22.580	**.001***

* Significant factor

The only factor found significant for vertical deviation RMSE is the guidance symbology. The HITS symbology resulted in less vertical error than the baseline PRFD symbology across all other conditions. So in terms of vertical flight errors, hypothesis 1 can be accepted, as can hypothesis 4. Hypotheses 2 and 3 are rejected. It can also be noted that overall, across all conditions, IFR pilots performed better than non-IFR pilots in terms of controlling the glide slope of the aircraft, although not at a significant level.

Airspeed regulation

The repeated measure ANOVA found no significant effect of any of the factors on the pilots' ability to maintain airspeed at the 90 knots reference value. As a component of FTP, this analysis partially tests hypotheses 1, 2, 3, and 4. Since none of the factors were found to be significant, based on airspeed control, hypotheses 1, 2 and 3 are rejected and hypothesis 4 is accepted.

Time Within Standard (TWS) Metric

A pilot was considered within standard if he was flying at the airspeed 90 ± 10 knots, with horizontal deviation less than 200 feet, and vertical deviation less than 150 feet. There were no significant factors or interactions identified for the TWS metric. Thus hypotheses 1, 2 and 3 are rejected and hypothesis 4 is supported. A further look at the mean TMS as a function of pilot rating and control response type (Figure 8) illustrates that overall, IFR pilots had better performance than non-IFR pilots in terms of TWS, although as already mentioned, the difference did not reach significant levels in this study.

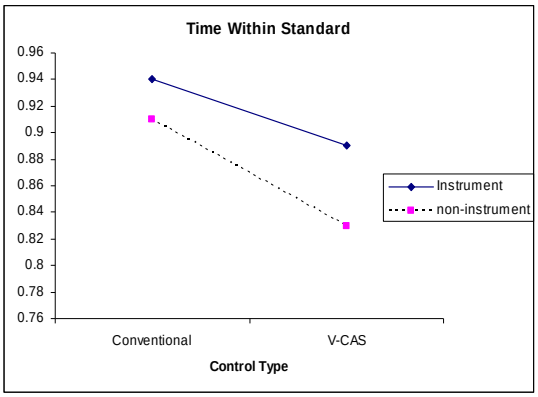

Figure 8 - Mean TWS for pilot rating and control type

Perceived Workload Assessment

A repeated measure ANOVA was carried out, with the average workload scores of all seven domains as the dependent measure. ANOVA results reveal that the between-subject factor (pilot rating) was not a significant factor for TLX workload scores (p value of 0.458)

and none of the within-subject factors were found significant (for control type, p=0.097; for terrain portrayal, p = 0.695; and for guidance symbology, p=0.101). The only factor found significant is the 3-way interaction among control, terrain portrayal, and pilot rating (with p = 0.011). A further investigation on this interaction found that under PRFD symbology, IFR pilots have higher workload scores for EBG while non-IFR pilots have higher workload scores for BSBG. With the HITS symbology, this interaction is reversed, that is, IFR pilots have a higher workload score for BSBG while non-IFR pilots have a higher score for EBG. The overall lowest score is IFR-BSBG-PRFD.

Perceived Situation Awareness Assessment

A repeated measure ANOVA analysis was carried out on the average SA score. Of all the factors, terrain portrayal was found as the only significant factor to affect SA ($p < 0.001$). The result strongly implies that under EBG terrain, pilots are more likely to maintain higher levels of situation awareness than BSBG.

Block and Exit Questionnaire Results

As described earlier, a block questionnaire was administered after each flight to obtain the participant's subjective feedback regarding preferences towards different terrain portrayal and guidance symbology under each control type. And, after both flights were completed, each participant was asked to complete an exit questionnaire eliciting subjective feedback on the two control types. Table 3 presents the results of the exit questionnaires.

Pilot rating	*Prefer Conventional (Percentage)*	*Prefer V-CAS (percentage)*	*Total*
Instrument Rating (IFR)	2 (66%)	1(33%)	3 (100%)
Non-instrument Rating(Non-IFR)	6(75%)	2(25%)	8(100%)

Table 3 - Summary of subjective preference on control types

From the exit survey results, it can be seen that regardless of pilot rating (IFR or Non-IFR), conventional control was preferred over the V-CAS control implementation. The reasons given by participants for this preference were often related to their familiarity with conventional control. Since all the pilots were trained using conventional flight control, this result is not unexpected given their comparatively limited exposure to the V-CAS. In general, the increased familiarity resulted in a greater sense of being in control. That said, the V-CAS does separate the pilot from the instantaneous activity of the control effectors, so in a real sense, there is a reduction in the pilot's authority over the lowest-level actions of the airplane. For instance, many pilots commented, with some concern, about interactions between flight path commands (i.e. longitudinal stick inputs) and changes to the engines power-setting. Representative pilot comments by those favoring conventional control include the following:

"I was in control with the conventional. Putting the nose down hard to reduce power is an uncomfortable means of control inputs";

"Conventional control is more responsive";

"I don't like holding the input (for V-CAS) as opposed to adding an input then neutralizing controls." ;

"Less control input seemed to be required when using conventional controls";

"I think I was more comfortable with the conventional, the VCAS was easy to fly but I felt I did a better job of anticipating the power changes necessary. That being said I seemed to track the guidance better while flying the VCAS".

Comments given by pilots who preferred the V-CAS mainly relate to workload reduction. Comments supportive of V-CAS included the following:

"(V-CAS) reduced my workload by keeping the aircraft on speed and coordinated

"The auto coordination was a tremendous help"

"VCAS increased the precision".

Participant's preference towards the guidance symbology and terrain portrayal within different control types was assessed using block questionnaires. These findings are presented in Table 4.

Pilot Rating	*Control Type*	*Preference of Terrain*		*Preference of Guidance Symbology*	
		BSBG	*EBG*	*PRFD*	*HITS*
IFR	*Conventional*	0	4	3	0
	V-CAS	0	4	3	0
Non-IFR	*Conventional*	0	8	3	5
	V-CAS	0	8	3	5

Table 4 - Summary of Subjective Preference on Terrain and Guidance Symbology

IFR rated participants had a strong preference (100%) towards EBG and PRFD regardless of control type. For non-IFR participants, EBG is strongly preferred (100%); however, there is a split in preference of guidance symbology, about 38% of participants prefer the PRFD and the rest (62%) prefer HITS. These results are consistent with the SA results, in which EBG has a significantly higher score than BSBG across all pilot ratings. However, the difference in workload scores for these two terrain types was not significant. Finally, as all evaluation pilots had a subjective preference for the EBG terrain portrayal concept, hypothesis 5 is accepted.

Discussions and Conclusions

This study aimed to investigate, via flight evaluations, the effect of SVS terrain portrayal and guidance symbology and V-CAS control on pilot performance and perceived workload and situational awareness during the conduct of advanced approach procedures. From the preceding analyses, the following major findings are presented:

Flight technical performance

Surprisingly, pilot rating (IFR versus non-IFR) was not a statistically significant factor for the FTP metrics used this study. These FTP metrics included horizontal deviation RMSE,

vertical deviation RMSE, airspeed RMSE, and proportion of time within standards. Of particular interest in this study is the comparison of the advanced concepts relative to their baseline counterparts in regards to FTP. Comparing V-CAS versus baseline flight control; EBG versus BSBG terrain portrayal; and HITS versus PRFD, no significant differences were found except for the effect of guidance symbology on vertical path deviation. For vertical tracking, HITS resulted in less deviation than the PRFD across all other conditions. Two significant interaction effects were found relative to lateral path deviation. These interactions involved pilot rating and control type; and pilot rating, control type, and guidance symbology. For lateral tracking, V-CAS reduced the deviation of non-IFR pilots; while for IFR pilots, V-CAS had a negative effect. Considering the percentage of time the subjects maintained flight technical performance within the specified standards, the data showed no significant effects. In summary, based on the FTP results hypothesis 1 is accepted for vertical tracking but rejected for lateral tracking and airspace regulation. Hypothesis 2 and 3 cannot be accepted. We can accept hypothesis 4 which states that the terrain portrayal concept will not affect flight technical performance.

Workload and Situational Awareness

The subject's perceptions of workload did not differ significantly between the treatments. For situation awareness, the only significant factor found was the terrain portrayal, with the EBG concept having higher perceived SA than the BSBG concept. This result is not difficult to understand since EBG provides relatively detailed terrain information. It should also be recognized that this improved awareness was obtained without negatively impacting workload or FTP.

Factors Influencing Results

In this experiment, with the exception of improved perceived SA from the EBG terrain portrayal, the different concepts yielded only minor changes in FTP, workload, and SA. There are several important factors that probably influenced these results and these factors should be considered before applying the results beyond the context of the experiment.

The first factor is the effect of prior pilot experience and training. In general, the pilots had much more experience with the conventional or baseline concepts prior to the experiment. For example, all the pilots' previous training and operations would have been conducted using conventional control systems. While the subjects were given training and time to practice with the concepts until they demonstrated adequate proficiency and felt prepared to perform the evaluations, it is unlikely that they had reached maximal performance with the advanced concepts. In the case of the V-CAS, it is clear that significant negative transfer from previous experience and training was a factor. As mentioned previously, the original design user group for this system was ab-initio pilots and certain design features that would benefit this group such as lateral stick inputs commanding turn-rate (i.e. bank angle) rather than roll-rate as in a conventional aircraft were found to be distracting by a number of the evaluation pilots with their relatively brief exposure to the system. Had this system been designed for pilots already trained on conventional control systems, a different set of command responses may have minimized transition issues while retaining many of the benefits of the underlying technology.

A second factor is related to flight task itself. In this study, evaluation pilots were able to allocate their full attention to the task of flying the approach. In the context of typical GA operations and perhaps more so in future operations in which some traffic separation responsibilities may be delegated to the cockpit, pilots are required to share their attention between multiple tasks. It is possible that the isolated approach task used in this study was

not well suited to revealing the potential operational benefits of the advanced concepts. Evaluation scenarios in which the pilot must perform other tasks, in addition to flying the airplane, could well uncover significant differences not found in this study.

A final factor to consider is the implementation details of the systems used in this experiment versus the more general concepts. The advanced display and control concepts are the result of many low-level design and implementation details. A minor, easily remedied deficiency, in any of these details can color the evaluation of the entire concept. For example, strong winds aloft during some of the flights uncovered a previously unseen interaction between the V-CAS and the steep approach segment. At full-forward stick, the V-CAS commands a descent angle of 7 degrees relative to the air mass data from which the actual descent angle is derived. Pre-experiment trails had shown this limit to be adequate to track the 6 degree descent angle of the steep approach segment. Strong tail winds during some of the evaluation flights resulted in an inertial descent angle at full stick that was equal to or less than the 6-degree angle of the steep approach segment. Needless to say, pilots that could not follow the segment precisely because of this limit found the experience frustrating and these encounters affected both flight technical and subjective performance measures. A more mature or refined V-CAS design could maintain simplified control through a greater expanse of the physical flight envelope of the aircraft and may elicit different pilot reaction than seen in this study.

With these thoughts in mind, the results of this study should be seen as a contribution to the growing body of experience with advanced control and SVS display concepts. The study is relatively unique in that it provides an initial investigation into potential interactions between display and control concepts in a flight test environment. With the exception of the enhanced perceived awareness afforded by the EBG terrain portrayal relative to the baseline, the effects seen in this study were modest and in most cases, no significant differences

between conditions were observed. These results suggest several general observations. First, while the advanced guidance and control concepts may have the potential to improve flight performance, this improvement is likely to be limited when used by highly trained, proficient pilots with full attention dedicated to controlling the aircraft. Even the non-IFR rated pilots participating in this study could perform the challenging approach task with reasonable accuracy using the conventional, state-of-art displays and controls. That said, it should be recognized that the "conventional, state of the art displays" used in this study included a large format primary flight display with a flight director and also a separate, large format navigation display. While this combination has become the norm on many newly manufactured small aircraft, it is far beyond the "steam-gauge"(electro-mechanical round dials) panels found in the majority of the operational fleet. Also, while performance improvements are likely to be modest for fully attentive pilots, gains for pilots having to divide their attention with other responsibilities may be much more meaningful, particular in terms of error prevention, detection, and recovery. Future evaluations should include operationally representative scenarios requiring the evaluation pilots to divide their attention between the control task and other cockpit responsibilities.

Another observation is that achieving potential performance improvements depends on many details of the implementation. A minor deficiency in any of these details or their interactions may overwhelm the potential benefit of the integrated concept. The final observation is that transitioning concepts from simulation to flight or even expanding the flight envelope of "flight proven" concepts is likely to uncover previously unseen or unknown deficiencies, despite rigorous simulation and build-up. The flight evaluation schedule should provide sufficient time to thoroughly screen, and if necessary refine both technical concepts and experimental procedures prior to data collection runs. Even then, novel factors are frequently encountered during the formal flight evaluation process. While

these encounters may invalidate pre-flight expectations, they also afford the learning opportunities from which new knowledge and progress flow.

References

Arthur III J. J., Prinzel III, L., J., Kramer, L. J., Parrish, R. V., & Bailey, R. E. (2004). Flight simulator evaluation of synthetic vision display concepts to prevent controlled flight into terrain (CFIT), *NASA/TP-2004-213008*. Langley Research Center, Hampton Virginia.

Bergman, C. A. (1976). An airplane performance control system: a flight experiment. Human Factors, 18(2), 173-182.

Billings, C. E. (1997). *Aviation automation: the search for a-human-centered approach.* Mahwah, NJ: Lawrence Erlbaum Associates.

Comstock, J. R., Jr., Glaab, L. J., Prinzel, L. J. & Elliott, D. M. (2001). Can effective synthetic vision system displays be implemented on limited size display spaces? *Proceedings of 11th international symposium on aviation psychology*, Columbus, Ohio.

Duerksen, N. (2003). Advanced Flight Controls and Pilot Displays for General Aviation. AIAA, 2003-2647

FAA (2005). United States Standard for Required Navigation Performance (RNP) Approach Procedures with Special Aircraft and Aircrew Authorization Required (SAAAR), FAA Order 8260.52. Federal Aviation Administration, Washington D. C.

Glaab, L.J & Takallu, M.A. (2002). Preliminary effect of synthetic vision systems displays to reduce low-visibility loss of control and controlled flight into terrain accidents, SAE 2002-01-1550.

Hughes, M. F. & Takallu, M. A. (2002). Terrain portrayal for head-down displays experiment. *The Proceedings of international advanced aviation conference*, August, 2002. Retrieved online at URL http://avsp.larc.nasa.gov/pdfs/csrp33.pdf.

Hunn, B. P. & Camacho, M. J. (1999). Pilot performance and anxiety in a high-risk flight test environment, *The proceedings of the human factors and ergonomics society 43rd annual meeting*, September 27 - October 1, 1999, Houston, Texas, USA.

JPDO (2007). Operational Concept for the Next Generation Air Transportation System (NextGen), v2.0, Joint Planning and Development Office, Washington D.C.

Lam, T. M., Mulder, M., van Paassen M. M., Mulder, J. A. (2006) Comparison of Control and Display Augmentation for Perspective Flight-Path Displays. Journal of Guidance, Control, and Dynamics, Vol. 29, No. 3 May-June 2006.

Newman, R. L. & Greeley, K. W., (2001). *Cockpit Displays: Test and Evaluation*, Asgate Publishing Limited, Hants England.

Pennington, J. E. (1979). Single pilot scanning behavior in simulated instrument flight, *NASA Technical Memorandum 80178 (NASA-TM)*, Langley Research Center, Hampton Virginia.

Rogers, R. (1999). Flight Test Results of the Controlled Flight into Terrain Avoidance Maneuver in Fly-by-Wire Transports, Airline Pilots Association, Airworthiness Performance Evaluation and Certification Committee

Stewart, E. C. (1994). A piloted simulation study of advanced controls and displays for general aviation airplanes. NASA Center for Aerospace Information (CASI) *NASA-TM-111545; NAS 1.15:111545; 19th Congress of ICAS*, Anaheim, CA, United States, 18-23 Sep. 1994.

Takallu, M., Wong, D., Bartolone, A., Hughes, M., & Glaab, L.(2004). Interaction between various terrain portrayals and guidance/tunnel symbology concepts for general aviation synthetic vision displays during a low en-route scenario, *Proceedings of the 23rd digital avionics systems conference*, 2004.

Uenking, M. D. & Hughes, M. F. (2002). The Efficacy of using synthetic vision terrain-Textured images to improve pilot situation awareness, *2002 SAE World Aviation Congress and Display*. NASA Langley Research Center, 2002-11-5.

Wickens, C. D., Alexander, A. L., Horrey, W., J., Nunes A., & Hardy, T. J., (2004). Traffic and flight guidance depiction on a synthetic vision system display: the effects of clutter on performance and visual attention allocation, *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting*. Santa Monica: Human Factors and Ergonomics Society, 2004.

Wong, D., Takallu, M., Hughes, M. , Bartolone, A., & Glaab, L. (2004). Simulation Experiment for Developing the Symbology for the Approach and Missed Approach Phases of Flight of Head-Down Synthetic Vision Systems Displays, AIAA 2004-5440, Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit, 2004.