Ecological Synthetic Vision Display to Support Pilot Terrain Awareness

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A Synthetic Vision Display is generally believed to support pilot terrain awareness. Many studies have shown, however, that perspective views are biased, which can cause pilots to make judgment errors regarding the relative location, height, and ultimately the avoidance of terrain obstacles. Therefore, this system is usually backed by terrain avoidance systems that provide explicit resolutions to circumvent conflicts. They are, however, far from optimal regarding terrain awareness as they fail to present the rationale of the automation. This paper presents an extension to a Synthetic Vision Display that promotes pilot terrain awareness by means of overlays that reveal the functional meaning of the terrain. It is designed to effectively deal with terrain conflict situations while preserving the freedom of maneuvering as much as possible. An experiment showed that the overlays improved pilot situation awareness and decision-making (in unanticipated events) as compared to a command-based interface counterpart.

Since the introduction of the glass cockpit and the technological advances in computing and sensing, the designers of aviation human-machine interfaces can almost freely create the pilot interface that should support situation awareness (SA). Traditional approaches to system and interface design have the tendency to either 1) show as much information as possible on single interfaces in a way that corresponds to a pilot's mental model (Spitzer, 2001), or, 2) to automate and hide the reasoning behind decision-making by showing pilots explicit resolution commands (Pritchett, 2003). From these technology-driven approaches to interface design two systems have emerged in the field of terrain awareness: the Synthetic Vision Display (SVD) the Terrain Awareness Warning System (TAWS).

An SVD shows pilots a perspective view on the surrounding terrain overlaid with primary flight status data. Although it presents data in an intuitive way, perspective views are biased which can cause pilots to make judgment errors regarding the relative location, height, and ultimately the avoidance of terrain obstacles (Wickens, 2002). Therefore, an SVD is usually backed by a TAWS that provides terrain collision warnings and escape maneuver commands. This system, however, is far from optimal regarding pilot terrain awareness as it fails to present the rationale of the automation that could help pilots to understand the nature of the issued alerts and commands (Bisantz & Pritchett, 2003).

Recent studies in SA and interface design claim that the Ecological Interface Design (EID) framework has the potential to support SA and improve decision-making, even in unanticipated situations (Flach, Mulder, & Van Paassen, 2004; Burns, Jamieson, Skraaning, & Kwok, 2007). Previous research in terrain awareness and EID revealed that showing the 'internal' (aircraft performance) and 'external' (terrain) constraints to flight is effective in promoting SA and decision-making (Borst, Suijkerbuijk, Mulder, & Van Paassen, 2006; Borst, Sjer, Mulder, Van Paassen, & Mulder, 2008). Although these designs and the results of pilot-in-the-loop experiments were promising, it was not always clear whether the improved pilot performance and SA could be fully attributed to the ecological interface. The experiment designs compared the ecological interfaces to conventional pilot interfaces, which were not always designed for the same purpose.

This paper describes the design and evaluation of an Ecological Synthetic Vision Display (ESVD) that extends an SVD with functional overlays that show pilots how their maneuvering possibilities are constrained by their own aircraft performance and surrounding terrain. Additionally, an experiment design will be presented that aims to make a fair SA comparison between the ESVD and a viable design alternative.

Enhancing the SVD

A work domain analysis for terrain awareness has been conducted in earlier work (Borst et al., 2006, 2008). The analysis showed that terrain awareness can be achieved by appropriately dealing with the external constraints, imposed by the terrain, and the internal constraints, imposed by the aircraft's climb and turn performance. Analysis showed that in order to effectively promote terrain awareness, an SVD should be enhanced with the following constraints: aircraft maneuvering performance, aircraft energy management, and aircraft-terrain separation.

Requirements

In general, the features on an ecological interface represent the constraints of the work domain. To map the constraints of the work domain into a visual form, EID provides guidelines for an interface design process rather than an interface blueprint. When enhancing an existing interface, however, the design of the visual form is also constrained. The designer is limited to create enhancements that are compatible with the interface "template". The template of a perspective display enables pilots to perceive relative distances, heights and locations between objects by means of relative angles (with respect to a horizon line), occlusion, and the relative size of objects (Wickens, 2002). To enable pilots to effectively relate the internal aircraft performance constraints to the external terrain constraint on a perspective display, the aircraft performance constraints need to be translated into angular descriptions whenever possible. In the following, the constraints of a Cessna Citation 500 aircraft, of which a non-linear, 6 degree-of-freedom mathematical model was available, will be explored. The content of all plots and figures in this paper are based on that model. Note that for other aircraft the method will be exactly the same.

Exploring the Constraints

Maneuvering In the vertical plane, the aircraft's optimal climb performance is important for terrain avoidance (Asselin, 1997). The steepest climb angle relative to the air is function of the altitude, weight, roll angle, aircraft configuration, and aerodynamic efficiency. The steepest climb angle relative to the terrain (γ_k^{OC}) can be obtained by adding the influence of wind speed and wind direction to the aerodynamic climb (Asselin, 1997). The turn dynamics of an aircraft, expressed in terms of the ground-referenced turn radius, in coordinated level turns is a function of the airspeed, roll angle, wind speed and wind direction. An important constraint on the turn radius is the maximum allowable vertical load factor n_z, which determines the maximum allowable roll angle. In wind conditions, the ground track of a level turn performed at a constant bank angle will be deformed (Figure 1(b)).

Energy Management The total energy state of an aircraft determines the opportunities for maneuvering. On a perspective display, pilots can perceive the rate of energy exchange by means of the Total Energy Angle (Amelink, Mulder, Paassen, & Flach, 2005). At a constant total energy level, the rate of energy exchange indicates how much potential energy an aircraft is gaining at the cost of kinetic energy and vice versa. Increasing the total energy of an aircraft is done by adding thrust to the system.

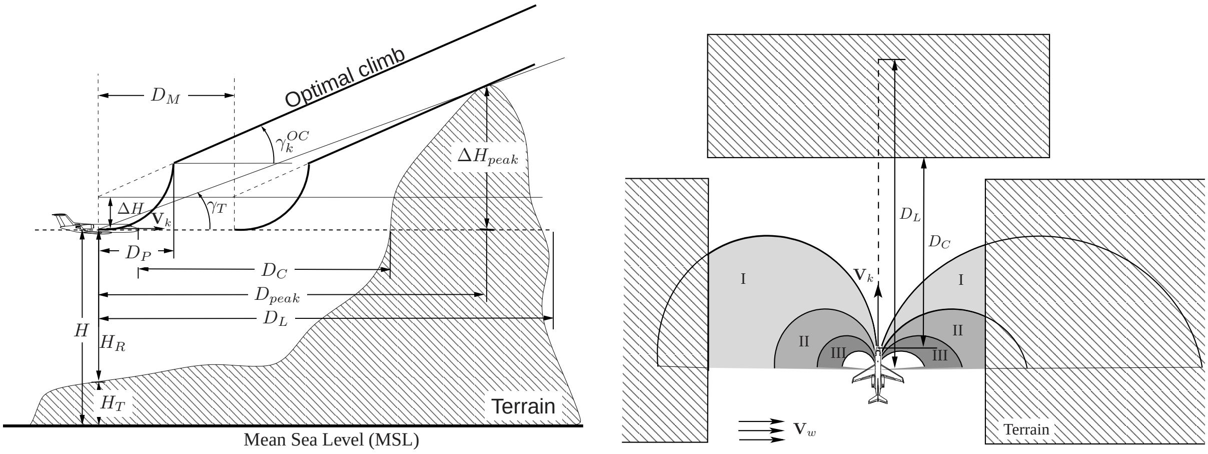
Separation The vertical terrain separation (Figure 1(a)) is expressed by the radio altitude H_R, whereas the forward terrain separation is expressed by the distance-to-collision D_C, which is defined as the distance between the aircraft's current position and the intersection of the line extending along the current ground-referenced flight direction with a terrain point. For the forward terrain separation, however, the distance-to-maneuver D_M would be more meaningful to the pilot than D_C. Using geometric relations, D_M can be interpreted as the cotangent of the maneuver angle γ_M: $\cot \gamma_M = \cot \gamma_T - \cot \gamma_k^{OC}$, where γ_T is the terrain peak angle. If $\gamma_T < \gamma_k^{OC}$, then $D_M > 0$, meaning that a climb over the terrain would be possible. Assuming a circular pull-up trajectory, D_P is the horizontal distance traveled needed to reduce the current kinematic velocity to the optimal climb velocity during the pull-up.

The distance D_L represents a finite look-ahead distance over which a terrain intersection point can be found. Parameters such as time-to-collision, time-to-maneuver, look-ahead time, etcetera can all be obtained by dividing the above distance parameters with the aircraft ground speed.

The sideward separation constraints are formed by the turn performance of the aircraft and the surrounding terrain. The sideward distance-to-collision is the intersection distance of the aircraft's predicted curved trajectory. Assuming level turns with a 180-degree heading change at the current airspeed and at a constant roll angle in constant and uniform wind, collision points to the left and to the right can be found using three turn regions (Figure 1(b)): I) all turns with roll angles between 15 and 30 degrees, II) all turns with roll angles between 30 and 45 degrees, and III) all turns with roll angles between 30 and 45 degrees.

Display Mapping

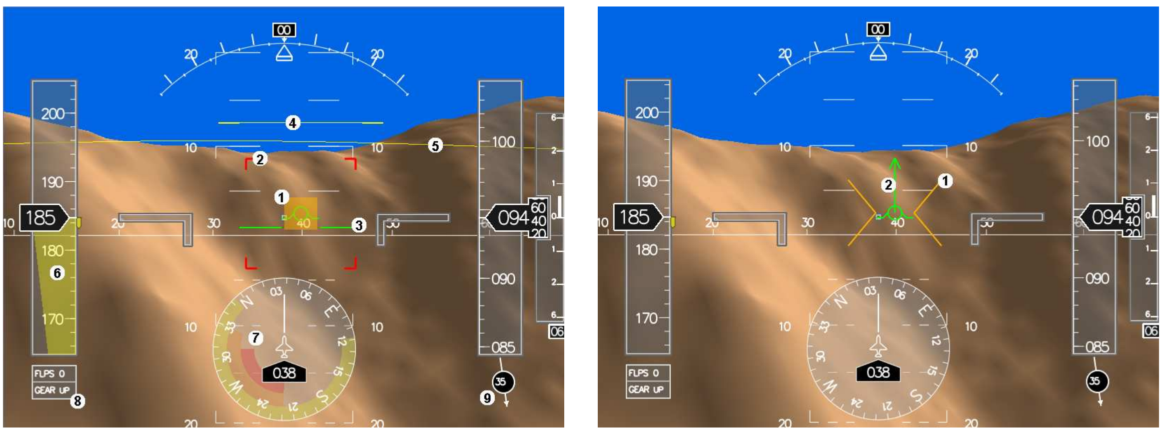
Mapping the above explored constraints resulted in the ESVD as shown in Figure 2(a). For the ESVD, the optimum climb constraint of the aircraft can be projected on the pitch ladder ④. The optimum climb while turning with a 45 degree bank angle is represented by ⑤. All optimum climb angles are computed using an aircraft performance database. By comparing the terrain angle perceived on the ESVD with the steepest climb angle, a pilot would be able



(a) Longitudinal separation (b) Lateral separation

Figure 1: The longitudinal and lateral separation parameters between the aircraft and the terrain.

to see if climbing over the terrain is possible. In Figure 2(a) it can be seen that the aircraft would be able to climb over the mountain. The energy angle is represented by ③. The cue from the energy angle and terrain angle is that the pilot would need to add energy to the system to be able to reach the optimum climb performance. To indicate how much distance and time are left to initiate an escape maneuver, a so-called distance-to-maneuver square was shown (①). As the aircraft approaches the terrain, the inner square will expand to the corner points of the outer square (②). The expansion rate depends on the ground speed at which the aircraft is approaching the terrain. From this a relative time-to-maneuver can be estimated. Furthermore, the inner square changes color from yellow to red, representing "enough" and "little" distance-to-maneuver, respectively. This color-coding corresponds to the caution and warning colors of a TAWS. The yellow area on the speed tape (⑥) indicates that the aircraft has excess speed that can be exchanged into additional altitude. The sideward terrain separations are represented on the compass rose in the form of left and right heading band constraints (⑦). The turn regions described above are used to check terrain intersections, which are color-coded as follows: constraints (or obstacles) in region I are colored yellow, in region II orange, in region III red. In Figure 2(a) it is shown that making any left turn will result in a terrain collision at some point, whereas making a right turn with a bank angle of at least 30 degrees circumvents the collision. Furthermore, pilots could also opt for making a straight climb over the mountain ahead.



(a) The ESVD interface (b) The SVGCAS interface

Figure 2: The interfaces used in the experiment.

Experiment

To evaluate the ESVD, relevant CFIT situations were created and simulated in a pilot-in-the-loop experiment in a fixed-base flight simulator using the Cessna Citation 500 model. The ESVD system was compared to a viable design alternative.

Design Alternative

The F-16 has a so-called auto-GCAS, which takes over the aircraft to prevent a terrain collision. In literature, research has been conducted on using guidance symbology on the HUD such that pilots can manually restore the aircraft to a safe flight condition by following commands (Billingsley & Kuchar, 2001). It was chosen to use these overlays on an SVD, because they have the same safety purpose as the ESVD and they were not designed using EID. This command system will be called SVGCAS (Figure 2(b)). The functionalities of command symbols, however, were tailored to fit the purpose of this experiment and to make a fair comparison between the ESVD and the SVGCAS.

The SVGCAS shows two symbols on the SVD: ① chevrons (><), representing the distance-to-maneuver (and time-to-maneuver), and, ② the ideal evasive maneuver command arrow. The computation of the command is based upon the same look-ahead algorithms and constraints as present in the ESVD.

Subjects

In the experiment a total number of 16 professional glass-cockpit airline pilots participated, with an average age of 29 years and an average experience of 3,000 flight hours. The subjects were instructed to avoid a terrain collision by performing one of the following five escape maneuvers: straight climb up, left climbing turn, right climbing turn, level left turn, or a level right turn.

Independent Variables

The independent variables in the experiment were the display configuration (DISP) and the experiment scenarios (SCENE). DISP (within-subjects) had two levels (ESVD and SVGCAS), SCENE (within-subjects) had 7 levels. The scenarios used to test the effects of the independent variables on the dependent measures are such that in each scenario one escape maneuver is optimal to escape an impending collision. The possible escape maneuvers in the first 5 scenarios were: straight climb up, climbing turn to the left, climbing turn to the right, level left turn, and level right turn. Each of these scenario had two variants (A and B) which featured slightly different terrain, initial aircraft conditions (positions and trim settings), and wind conditions to prevent pilots from recognizing the scenarios. Scenarios 6 (total engine failure) and 7 (flaps retraction failure) were system failure scenarios unanticipated by both the ESVD and the SVGCAS. Hence, pilots could not rely on the information they perceived from the interfaces to avoid a collision and should therefore make a suitable decision based on their knowledge and intuitions.

Dependent Measures

The dependent measures in the experiment were: 1) The decision (escape maneuver choice) and 2) the situation awareness (SA). The decision was rated 0 for non-optimal maneuvers and rated 1 for optimal maneuvers. The SA was measured using a query with simulation freeze which probed the levels of perception (level 1), comprehension (level 2), projection (level 3) and metacognition (self confidence of pilots about their query answers). SA was graded in conjunction with the metacognition as shown in Table 1.

Table 1: *Grade determination of the SA query answers.*

	Query answers	
Metacognition	*Incorrect*	*Correct*
Sure	0	3
Unsure	1	2

Design

In the measurement phase of the experiment, the five anticipated and two unanticipated scenarios (6 and 7) were balanced between two groups of 8 pilots. In the training phase, each group of pilots only flew the two variants of the 5 anticipated scenarios in a different terrain database.

Results

The analysis of the decision and the SA levels was done using repeated-measures Analysis of Variance (ANOVA). The anticipated and unanticipated situations were separately analyzed.

Decision

In anticipated situations, DISP and SCENE had no significant effect on the decision about the escape maneuver. However, from Figure 3 it can be seen that the ESVD resulted in slightly less optimal decisions than SVGCAS. This can be explained due to the fact that the ESVD shows multiple candidate escape solutions, thereby increasing the likelihood that suboptimal escape maneuvers can be chosen. The SVGCAS always showed one escape solution, that is, the optimal escape. In unanticipated situations, however, DISP had a significant influence on the decision ($F(1, 14) = 11.065, p = 0.005$), as well as SCENE ($F(1, 14) = 27.512, p < 0.01$). From Figure 3 it can be seen that in the unanticipated situations pilots made much better decisions about their evasive maneuver when using the ESVD than when using the SVGCAS. Furthermore, flying with the ESVD did not result in any terrain crash, whereas the SVGCAS resulted in 3 crashes.

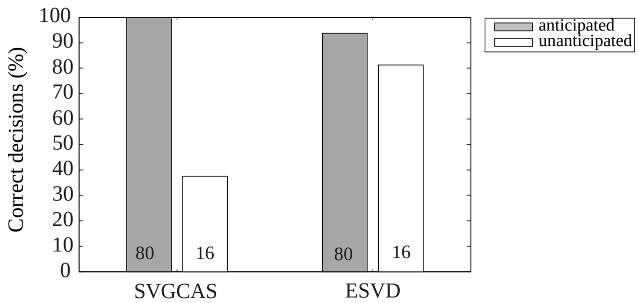


Figure 3: The pilots' decisions in terms of the chosen escape maneuvers. The number of runs are shown below in each bar.

Situation Awareness

In Figure 4(a) the average overall SA grades (anticipated and unanticipated situations combined) are shown, which indicate that pilots could much better comprehend and project the situations when flying with the ESVD than when flying with the SVGCAS. In Figure 4(b) it is shown that pilots were also much more confident about their answers in anticipated as well as unanticipated situations when using the ESVD. In anticipated situations, DISP had a significant effect on SA level 2 ($F(1, 14) = 221.5, p < 0.01$) and SA level 3 ($F(1, 14) = 464.8, p < 0.01$). In unanticipated situations, DISP had also a significant effect on SA level 2 ($F(1, 14) = 115.3, p < 0.01$) and SA level 3 ($F(1, 14) = 478.4, p < 0.01$).

Conclusions

The goal of the ESVD was to improve pilot terrain awareness and decision-making by using EID. The experiment results showed that pilots were more aware of the terrain situations in both anticipated and unanticipated scenarios when using the ESVD as opposed to a command-based display counterpart, the SVGCAS. The ecological approach resulted in an interface that clearly supported the higher levels of cognition and promoted pilot reasoning. The decision-making, however, only significantly improved in the unanticipated events. Despite this result, none of the pilots crashed when using the ESVD.

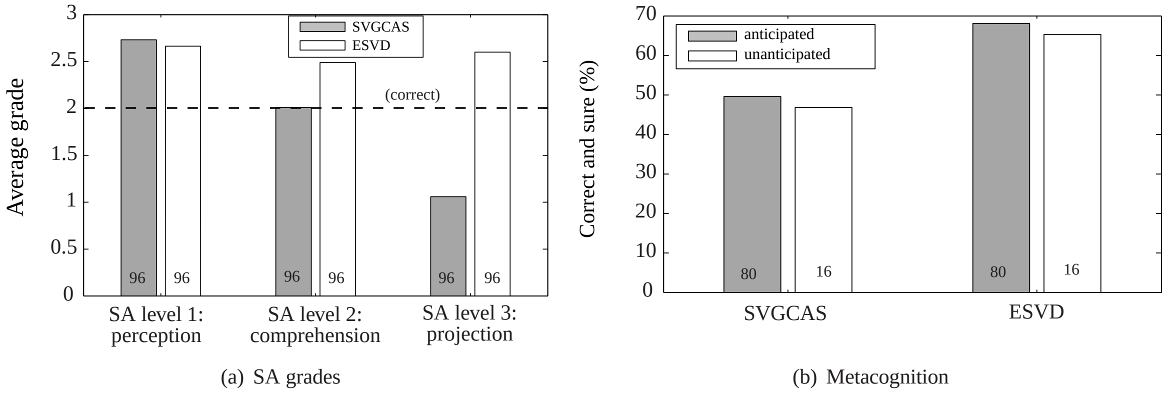


Figure 4: The SA grades and the metacognition, expressed in the percentages of correct answers for which pilots were confident. The number of runs are shown below in each bar.

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