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Despite the fact that modern cockpits present an abundance of information to pilots, Controlled Flight Into Terrain (CFIT) accidents continue to occur. The introduction of terrain awareness and warning systems, like the Enhanced Ground Proximity Warning System (EGPWS), has led to a considerable reduction of terrain incursions. EGPWS predicts the aircraft motion relative to terrain and, based on a rule-base of advanced reasoning logic, informs pilots on how to react appropriately. Common to all terrain warning systems, is that all cognition is ‘hidden’ in the EGPWS logic, and pilots are required to respond rapidly to the system’s commands. We hypothesize that pilot decision making is accelerated and situation awareness is improved when the internal functioning of terrain awareness and warning systems is clarified, visualized on the interface. To test this hypothesis we developed two extensions to the EGPWS. In the first, the EGPWS flight path prediction was presented, to clarify the look-ahead function. In the second, also the potential escape trajectories were presented. A simulator experiment was conducted where twelve general aviation pilots were brought in close encounter with terrain, with the three EGPWS variations. Results show that when the EGPWS internal reasoning is visualized to pilots, situation awareness significantly improved.

Introduction

Alerting systems have been developed to prevent Controlled Flight Into Terrain (CFIT) accidents that direct the attention of the pilot to the terrain-threatening situation (Pritchett, 2001). An example is the Enhanced Ground Proximity Warning System (EGPWS) which presents nearby terrain and obstacles and, when flying too close, provides an alert (Honeywell, 2000). Based on a prediction of the aircraft motion relative to the terrain, the ‘look-ahead’ function, internal reasoning logic evaluates the situation. Dependent on the moment when terrain is predicted to be encountered, bright colored terrain is shown on the Terrain Awareness Display (TAD), and an aural alert is given.

Despite the fact that these systems have shown to reduce the number of terrain incursions, some problems remain. The main problem is that all cognition is ‘hidden’ in the alerting system’s logic. Pilots are not supported at all in diagnosing the threat themselves (Abeloos, Egging, Mulder, Van Paassen and Pritchett, 2003), and as a consequence, pilots do not always have time to understand what exactly is going on, and often simply follow the alert system commands. Especially in bad weather conditions or when pilots are distracted, the time to make a decision is short, which deteriorates performance considerably (Pritchett, 2001).

We investigated how a conventional EGPWS can be improved upon through providing more meaningful information that helps the pilot in better understanding the reasoning of the EGPWS. The exploration is done for general aviation aircraft, manually controlled by pilots without the aid of flight management systems and air traffic control.

Two improvements were considered. First, the constraints encountered by the ‘the look-ahead function’ are visualized, revealing the internal functioning of this EGPWS capability. Second, the resolution advisories, both in the vertical plane as well as in the lateral plane, are presented on a Vertical Situation Display (VSD) and Horizontal Situation Display (HSD), respectively. An experiment was conducted to investigate the potential benefits of these EGPWS enhancements on pilot situation awareness, manual control performance, safety, and workload. This paper summarizes the EGPWS enhancements and the experimental results. For more details the reader is referred to (Lenaerts, 2006).

Enhancing terrain awareness warning systems

Most CFIT accidents are attributed to the short reaction time provided by alerting systems after the pilot’s attention is directed (Moroze and Snow, 1999). The pilot needs more time to react than the alerting system’s algorithm has foreseen. Situation awareness of the pilot is too low to be able to react immediately. They do not know their position with respect to terrain and do not readily understand where the alert comes from.

The main problem is that terrain awareness systems do not clearly enough explain what happens. They do a poor job in clarifying the meaning of the hazard in terms of *why* the pilot should do *what*, *how* and *when* to avoid the threatening terrain. Furthermore, the alerting system is a safety system, the role of which does not evolve through day-to-day operations, but is only experienced by the pilot when a hazard appears. The judgment of the alerting system is based on its sensors, its algorithms and decision thresholds, i.e. on information that is normally not accessible to the pilot. It is important to decrease the gap between these judgments of the human and the machine in order to enable a quick, corrective action in a critical situation.

Ideally, the situation display must "explain" the internal logic of the terrain awareness system. Furthermore, the system and its situation display must be consonant, i.e., they must promote the same action. This poses not only a requirement on the situation display to provide alerting system awareness, but also a limitation on the alerting system: in order to communicate its functioning, the alerting system's logic must be communicable, limiting its allowable complexity (Bainbridge, 1983).

Enhanced Ground Proximity Warning and Avoidance System (EGPWAS)

Inspired by the work presented in (Borst, Suikerbuik, Mulder and Van Paassen, 2006) and (Amelink, Mulder, Van Paassen and Flach, 2005), our team developed the Enhanced Ground Proximity Warning and Avoidance System (EGPWAS).

EGPWAS logic

The logic of the EGPWAS is based on relating 'internal aircraft constraints', i.e., the aircraft performance characteristics in terms of its capability to turn and climb, to the 'external terrain constraints', i.e., the limits to moving in space imposed by the terrain. In other words, the EGPWAS presents information about what the capabilities of the aircraft are with respect to the threatening terrain, through a visual interface that consists of a conventional Horizontal Situation Display (HSD) and Vertical Situation Display (VSD).

In the context of avoiding terrain, the main aircraft performance limit in the vertical plane is its ability to perform a steep climb. As discussed in detail in (Borst et al., 2006), the climb contains of two parts: a pull-up, where excess in speed is exchanged into height, followed by a quasi-stationary climbing flight. In the lateral plane, avoiding terrain implies turning, and here the aircraft turning capability is the primary constraint. The radius of the turn depends on the aircraft speed (for higher speeds the radius is larger) and the roll angle of the aircraft (for higher roll angles the radius is smaller). In both the lateral and vertical plane, the aircraft load factor should remain within limits (< 1.4), limiting the aircraft roll angle to approximately 45 degrees.

Similar to the conventional EGPWS, the EGPWAS provides provides an envelope of protection through its 'look-ahead function', based upon approximate time-to-impact of the aircraft with terrain. Using the aircraft current states in terms of position, attitude and speed, the EGPWAS predicts the aircraft future position and checks it with the terrain database. The algorithms of the EGPWAS look down, and keeps a vertical safety margin of 500 ft; ahead, based on the aircraft ground speed, up to 60 seconds ahead; aside, based on the aircraft bank angle (maximum 45 degrees); and up, based on maximum climb path angle.

EGPWAS interface

The interface of the EGPWAS consists of the HSD and VSD displays, and an aural alert. When no threatening terrain lies within 60 seconds ahead of the aircraft, terrain is displayed on the HSD and VSD, using conventional EGPWS color coding. The color coding and aural alerts in case threatening terrain lies within 60 seconds ahead is also similar to the conventional EGPWS.

Furthermore, together with the aural alert, the least tight possible turn is shown on the HSD by means of a solid arc symbol. The size of the arc depends on the aircraft ground speed and the terrain profile which imposes constraints on the bank angle required. The color of the arc indicates the required bank angle of the escape turn maneuver, where a yellow arc indicates a bank angle of 15 degrees, an orange arc indicates a bank angle of 30 degrees, and a red arc indicates a bank angle of 45 degrees. If turning away from the threatening terrain is not possible anymore, the arc is colored black.

At the time an aural alert is given, a possible escape maneuver is also displayed on the VSD as well. In the longitudinal plane, only the steepest climb is analyzed. The first part of the climb symbol, the pull-up arc, depends on the current ground speed. The color of the steepest climb symbol is consistent with the warning and caution alert color coding of the EGPWS. Again, a black climb symbol means that it is not possible anymore to escape the threatening terrain by performing the steepest climb.

In Figure 1 the layout of the HSD and VSD, corresponding with the EGPWAS, is presented. In the top figure ❶ is the compass with the current heading in degrees; ❷ is a zoom level on the display; ❸ is the EGPWS color coding for terrain which is not in the

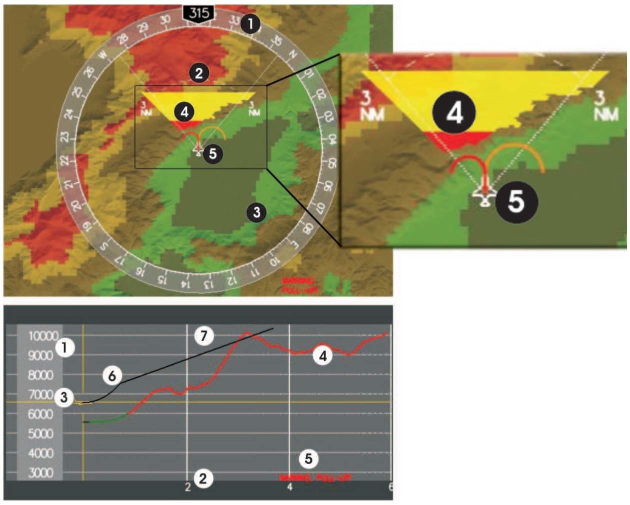


Figure 1: EGPWS display layout: HSD (top) and VSD (bottom) presentation.

vicinity of the aircraft; ❹ is the EGPWS caution and warning color coding for threatening terrain; finally, ❺ are the turn symbols, a 30 degree bank angle turn to the right and a 45 degree bank angle turn to the left are both an option to escape from the threatening terrain. The bottom figure shows: ① the altitude tape in feet; ② the look ahead distance [nm] along the aircraft's flight path; ③ the aircraft's symbol; ④ EGPWS colored terrain in the vicinity of the aircraft, this EGPWS color coding is clarified by ⑤, the EGPWS warning ⑥ represents the pull-up maneuver to obtain ⑦, the steepest climbing flight.

Experiment

METHOD

Apparatus The experiment was conducted in a fixed-base flight simulator with an hydraulic side stick, rudder pedals, pedestal controls (two throttle levers, flap lever and a speed brake lever) and two 18" LCD panels for the instrument displays.

Subjects and instructions Twelve Instrument Flight Rules (IFR) rated general aviation pilots were invited, all males, and with 200-1500 flying hours.

The subjects were asked to observe a specific frozen unexpected emergency situation and answer some questions about it. Afterwards, they were instructed to escape from the threatening situation, by executing only the following four maneuvers: full climb at 92% power, turn at a bank angle of 15, 30 or 45 degrees. Combinations of these maneuvers were not allowed.

Aircraft and weather model A non-linear Cessna Citation 500 aircraft model was used. The aircraft was trimmed for a straight level flight at 8250 ft at a velocity of 150 *kts* IAS. An ISA standard atmosphere was used and no wind or turbulence was simulated.

Independent variables Two independent variables were defined: display format and terrain layout. Three display formats, for both the HSD and VSD, were used (see Figure 2), where each of the displays was accompanied by the conventional Primary Flight Display (PFD), engine display and the conventional EGPWS color coding and aural alerts:

- Baseline (BASE) - current EGPWS. This display was the conventional display of the currently used EGPWS, presenting terrain in specific colors corresponding to terrain elevations, defined by Honeywell. The VSD only showed the terrain profile with EGPWS color coding and flight path vector.
- Clarified EGPWS (c-EGPWS). The baseline, extended with a visual representation of the predicted flight path 60 seconds ahead to clarify the underlying principle of the EGPWS to the pilots. This flight path was also shown on the VSD. This allowed pilots to estimate the time to collision with the threatening terrain.
- EGPWAS. The display format with extra indications about escape possibilities, in the lateral (HSD) and longitudinal plane (VSD), to avoid terrain.

The terrain layout consisted of six different existing North-American terrains. For each terrain a CFIT situation was created by positioning the aircraft in such a way that it will collide with the terrain when the pilot does not perform an escape maneuver. The scenarios were defined as follows:

- Aspen: threatening terrain lies around 30 seconds away. To escape, only a steep climb maneuver is possible.
- Eagle: threatening terrain lies between 0 and 30 seconds away. To escape, tight turns to the left and the right with a bank angle of at least 45 degrees are the only possibilities.
- Colorado Springs: threatening terrain lies between 0 and 30 seconds away. To escape, the following maneuvers are possible: a steep climb and a turn to the right with a bank angle of at least 30 degrees.

(a) Baseline (BASE)

(b) Clarified EGPWS (c-EGPWS)

(c) EGPWAS

Figure 2: Display formats

Reno: threatening terrain lies between 0 and 30 degrees away. To escape, two maneuvers are possible: a turn to the right with a bank angle of at least 30 degrees or a tight turn to the left with a bank angle of at least 45 degrees.

Truckee-Tahoe: no threatening terrain will be encountered within 60 seconds. Here no escape maneuver is necessary, although the alert is given. It is a false alarm.

Yampa: threatening terrain lies between 30 and 60 seconds away. To escape, all maneuvers are possible: steep climb, soft turn with a bank angle of at least 15 degrees to the right or the left. In this scenario, it would be wise to turn away from the threatening terrain, to avoid further difficulties.

Experiment design The six terrain scenarios, in combination with a specific display format, were each used only once by each pilot. In total 72 runs were done (6 scenarios $\times$ 12 pilots), which were organized in a Latin Squares design.

Dependent measures The dependent measures were: 1) situation awareness, 2) subjective symbology ratings, 3) performance and safety, and, 4) pilot workload.

Situation Awareness. SA, in terms of perception, comprehension, projection and metacognition (McGuinness, 1999), was measured using questions about the current situation, which were different for each run, and a post-run questionnaire. The questionnaire consists of 9 questions, 3 for each level. Examples of questions for first, second and third level of SA are respectively "What is your indicated airspeed?", "What is the level of risk?" and "Is it possible to escape the terrain threat by performing a horizontal 45 degree bank angle turn to the right?". To quantify these first three levels, a model was created to specify whether pilots were incorrect, far off, almost correct or correct. These levels were graded with 0, 3, 6 or 9, respectively. The thresholds between the levels to which the given answer was to be directed, were partly determined by expert subjects and partly by comparing the correct answer to a question. The fourth level of terrain awareness metacognition, was measured through a confidence interval. Next to each question the pilots indicated on this interval their self-confidence, with a number ranging from 0 to 10, 0 being very unsure and 10 being very sure. Of the indicated values a z-score was taken, with which the pilots were graded 0, 1, 2, 3, 6 or 9 for the metacognition. The determination of the metacognition grade was done through a combination of the self-confidence interval and the grade obtained for the question itself. With these two numbers Table 1 was used.

Symbology. The measurement involved questions related to the symbology of a specific display format. Pilots gave their opinion, by using a 10 point Likert-scale, about each of the following three

Table 1: Score system to measure metacognition.

	Correct	Incorrect
Very sure ($z > 0.33$)	9	0
Fairly sure ($0.33 > z > -0.33$)	6	1
Unsure ($z < -0.33$)	3	2

statements: “I knew exactly how much time was left before collision”, “I knew exactly when to perform a maneuver”, and, “I knew exactly which maneuver would be the best to escape safely.” The z-scores of the subjective ratings on each statement are examined.

Performance and safety. The performance of the pilot was evaluated by measuring the longitudinal and vertical separation with terrain. Safety is analyzed by counting the number of intrusions and crashes. Four categories of intrusions into a safety margin above the terrain surface are defined: Very soft intrusions (1000ft-750ft), soft intrusions (750ft-500ft), hard intrusions (500ft-250ft).

Workload. The workload was measured by means of a NASA TLX rating scale.

Experiment procedure The experiment consisted of two phases: training and measurement. In the measurement phase, pilots were confronted with a frozen situation and could observe all displays in this situation for 12 seconds. Then, the simulation was briefly interrupted and the pilot was asked to answer 9 situation awareness-related questions. Next, the simulation was started and the pilots had to escape from the threatening terrain. After completing the evasive maneuver, pilots were asked to complete a NASA TLX rating sheet. Finally, at the end of an experiment run, symbology related questions were asked.

Results and discussion

For a detailed discussion, see (Lenaerts, 2006).

Situation awareness

Considering each level of SA separately (Figures 3(a)-3(c)) indicates a borderline effect at the ‘perception’ level, no effect at the ‘comprehension’ level, and a highly-significant effect ($F_{2,125} = 6.705$, $p \leq 0.01$) at the ‘projection’ level. Metacognition (Figure 3(d)) is significantly higher with the enhanced systems as compared to BASE ($F_{2,413} = 3.459$, $0.01 < p \leq 0.05$), indicating that pilots are more confident about their understanding of the situation.

Subjective symbology measures

The z-scores of the subjective ratings of statement 1, “I knew exactly how much time was left before collision”, (Figure 4(a)) are higher for c-EGPWS and EGPWAS than BASE, a borderline effect. The z-scores of the subjective rating of statement 2, “I knew exactly when to perform a maneuver”, (Figure 4(b)) are higher for EGPWAS as compared to BASE and c-EGPWS (not significant). The z-scores for statement 3, “I knew exactly which maneuver would be best to escape safely”, (Figure 4(c)) are much higher for EGPWAS, a highly-significant effect ($F_{2,18} = 7.003$, $p \leq 0.01$).

Performance and safety

Less intrusions or crashes were found with EGPWAS (Table 2), a result that was not significant, however (Wilcoxon). Many intrusions were caused when pilots executed a turn and lost altitude. In the experiment only one crash occurred, in scenario 2 with BASE.

Table 2: Number of intrusions (I = BASE, II = c-EGPWS, III = EGPWAS).

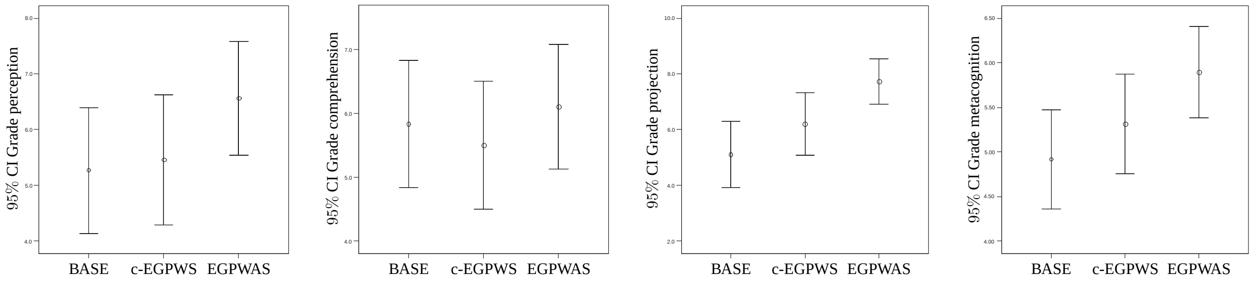
	very soft intrusion			soft intrusion			hard intrusion		
scenario	I	II	III	I	II	III	I	II	III
1	2	1	0	0	0	0	0	0	0
2	13	7	9	7	2	0	4	1	0
3	1	3	4	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
total	17	11	13	7	2	0	4	1	0

Workload

Workload (Figure 4(d)) remains the same for all display formats, although the (not-significant) trend is in favor of c-EGPWS and EGPWAS.

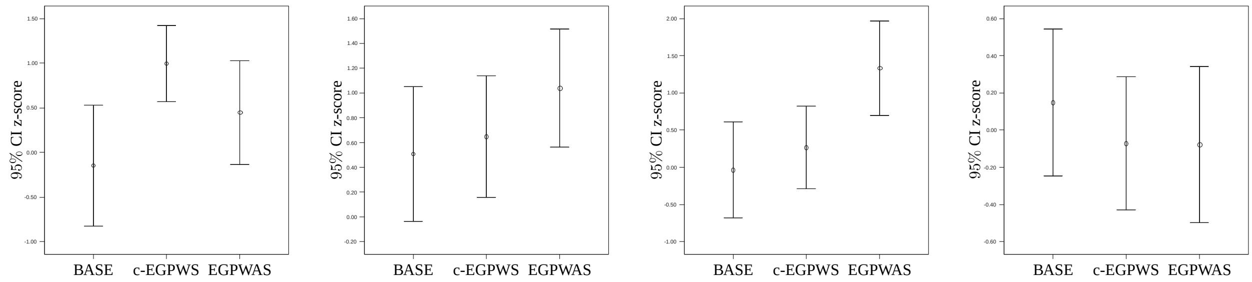
Concluding remarks

Clarifying the internal logic of a terrain warning system like the EGPWS, enhances pilot performance. Sharing cognition between the automation and crew yields a higher level of situation awareness, in particular at the highest level, ‘projection’. Pilots are more aware of *when* an evasive maneuver needs to be conducted, and also *what* maneuver (turn or climb) would be the most appropriate. They are better able to ‘connect’ the constraints on their flight as imposed by the terrain with the constraints on their flight that are due to the aircraft performance. As a result, the opportunities for action become much more clear, to the benefit of performance and safety.



(a) ‘perception’ (b) ‘comprehension’ (c) ‘projection’ (d) metacognition

Figure 3: Situation awareness scores with 95% confidence interval.



(a) statement 1 (‘time’) (b) statement 2 (‘when’) (c) statement 3 (‘what’) (d) workload (TLX)

Figure 4: Subjective ratings (z-scores with 95% confidence intervals) on symbology and workload.

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