JOURNAL OF AIRCRAFT
Vol. 45, No. 1, January–February 2008

Ecological Approach to Support Pilot Terrain Awareness After Total Engine Failure

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DOI: 10.2514/1.30214

Terrain awareness enhancing avionics, such as Synthetic Vision Systems and the Enhanced Ground Proximity Warning System, have been developed to reduce the number of controlled flight into terrain accidents. The protection these systems offer, however, is far from optimal. Synthetic Vision Systems only provide pilots with perceptual data, and leave all cognition and interpretation of data to the pilot. With Enhanced Ground Proximity Warning Systems the opposite is true. Here, pilots are only confronted with compelling advisories and commands without the underlying data and rationale. This paper presents a display system, the Emergency Landing Guidance System, that visualizes the functional meaning of surrounding terrain, adopting an ecological interface design approach. The potential benefits of this approach are demonstrated with the case of locating and approaching a suitable landing area after sudden complete engine failure. To evaluate the effect of the new display on pilot terrain awareness, an experiment was conducted in a fixed-base flight simulator. Results show that the new display supports pilot terrain awareness much better than present terrain avoidance systems, i.e., pilots better understand the "meaning" of the terrain in relation to their goals and constraints. However, pilots also operated more closely to the limits of performance, thereby negatively affecting the metrics for safety.

Nomenclature

C_D	=	drag coefficient, –
C_L	=	lift coefficient, –
C_L/C_D	=	glide ratio/aerodynamic efficiency, –
D	=	drag, N
E_{kin}	=	kinetic energy, J
E_{pot}	=	potential energy, J
E_{sp}	=	specific energy, m
E_{tot}	=	total energy, J
g	=	gravitational acceleration, $\mathrm{m/s^2}$
H	=	altitude, m
n_z	=	normal acceleration
R	=	pull-up radius, m
S	=	wing area, $\mathrm{m^2}$
T	=	thrust, N
W	=	weight, N
γ	=	vertical flight-path angle, deg
δ_e, δ_a	=	elevator, aileron control surface deflections, deg
δ_T	=	throttle handle deflection, deg
ρ	=	air density, $\mathrm{kg/m^3}$
φ	=	roll angle, deg
χ	=	track angle, deg

I. Introduction

WITH today's technologies for computing and sensing, the designers of aviation human–machine interfaces (HMI) can almost freely create the pilot interface to support situation awareness (SA) [1,2]. That is, there are fewer constraints on the type and quantity of information or on the display format. Two examples of modern displays that profited from these technological advances are the Enhanced Ground Proximity Warning System (EGPWS) and the Synthetic Vision System (SVS) [2–8]. The goal of the EGPWS is to prevent controlled flight into terrain (CFIT) accidents by aurally and visually warning pilots about rising terrain. The aim of the SVS is to improve the pilot terrain awareness by showing a computer-generated three-dimensional perspective view of the outside world.

Several independent research studies have shown, however, that although such systems have proven to yield significant improvements in terms of safety [9,10], the lack of communication between those systems still requires the flight crew to mentally integrate information from different sources. This can lead to insufficient terrain awareness considering the three levels of SA as defined by Endsley [11], namely perception, comprehension, and projection. On the one hand, an SVS supports the perception level of terrain awareness, but lacks properties to communicate the meaning that could support pilot comprehension and projection [2,6,7,12–14]. On the other hand, a terrain warning system attaches meaning to the environment, but communicates this to the pilots without the underlying data and rationale [15,16].

To improve pilot terrain awareness, the preceding systems could be enhanced by overlays that fill in the missing links between them and, ultimately, support all levels of terrain awareness. Improving the comprehension and projection levels of terrain awareness can be realized if pilots can sense what aircraft performance characteristics and flight condition allow them to do in relation to the terrain. Hence, we hypothesize that interface enhancements should include aircraft performance overlays that inform pilots of their climb, glide, and/or turn capabilities [17]. Then, comparing these internal aircraft constraints with external constraints imposed by the terrain may allow a pilot to more easily detect potential threats to safety and find the correct maneuvers to circumvent these threats.

For this paper, a new display was developed and evaluated that aims to support all three levels of terrain awareness in case of a total engine failure. This new interface was designed using a relatively novel approach in aviation: ecological interface design (EID) [18,19]. EID is based on an analysis of the work domain, using a tool

Received 2 February 2007; revision received 19 July 2007; accepted for publication 28 July 2007.

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called the abstraction hierarchy (AH), which helps to obtain a hierarchical description of the functional means–end relationships between the system and the operator objectives and the many ways to achieve these objectives [20–22]. The work domain analysis (WDA) also helps to identify the constraints on different levels of abstraction, defining the "safety margin" within which the aircraft can be operated without violating the objectives. This design approach resulted in a prototype of an Emergency Landing Guidance System (ELGS), as an extension to the existing EGPWS, that enables a pilot to locate suitable off-airport landing locations and provides guidance strategies on how to reach them.

General aviation (GA) was chosen as the application domain. The GA community is using technologies such as the SVS and EGPWS to increase pilot SA and, more importantly, safety [23–26]. CFIT accidents occur most frequently in GA operations, comprising 17% of all GA fatal accidents [27], where at least 32% of all CFIT accidents in GA occur in Instrumental Meteorological Conditions [27]. This indicates the need for systems such as the SVS and the EGPWS in GA. The case study of a total engine failure was chosen based on 1) several NTSB accident reports that showed that awareness about the terrain and aircraft capabilities is critical in this situation [28]; and 2) the fact that 70% of all GA CFIT accidents occur with single engine aircraft [27].

This paper is structured as follows. First, a brief description of EID and a WDA for terrain awareness in the situation of a total engine failure will be provided. The WDA results in a definition of the information content and structure of the ELGS. Second, the mapping of these findings on the EGPWS display is described. Finally, the results of a pilot-in-the-loop experiment, conducted in a fixed-base simulator, are discussed. The goal of this experiment was to study the levels of terrain awareness and safety obtained by the ELGS as compared with conventional terrain awareness interfaces.

II. Ecological Interface Design

EID is a theoretical framework for designing human–machine interfaces for complex socio-technical systems [20–22]. It gives priority to the worker's environment and concentrates on how the environment imposes constraints on the worker [21,22]. Rasmussen and Vicente argued that by revealing the work domain constraints to the operators, they are better able to cope with situations not foreseen by system designers.

An interface is typically characterized by its content, structure, and form. In EID, two different analyses are used to determine these interface features. First, the content and structure of the work environment are analyzed through a WDA, usually in the form of an abstraction hierarchy. Second, the form that the interface will have is a result of design guided by the three levels of the skills, rules, and knowledge (SRK) taxonomy [29].

A. Work Domain Analysis

In EID, the abstraction hierarchy will serve as a representation of the work domain. The abstraction hierarchy ranges from, top to bottom, the most abstract level of purpose to the most concrete form of material [21,30]. A typical abstraction hierarchy consists of five levels: functional purpose, abstract function, generalized function, physical function, and physical form [20–22,29]. The relation between the levels is described as a "means-ends" relation [29].

A WDA for terrain awareness and its resulting abstraction hierarchy have been presented in earlier work [17], where pilot terrain awareness was believed to be achieved by "appropriately mapping the 'internal' aircraft constraints onto the 'external' terrain constraints." The abstraction hierarchy for terrain awareness is shown in Fig. 1, and a brief description of the WDA is summarized in the following.

The functional purpose level describes what the system was designed for. It also contains criteria that can be used to determine whether the system is functioning correctly [22]. Here, the purpose of the aircraft and its crew in the environment is to provide air transportation in a productive, efficient, and safe way.

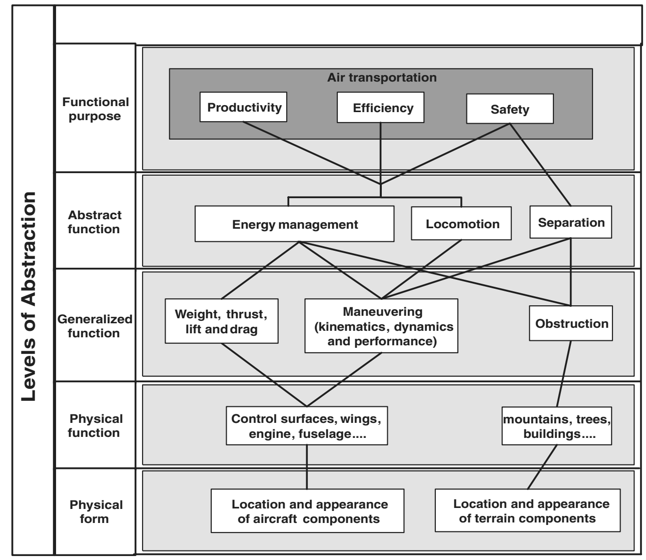


Fig. 1 Abstraction hierarchy with means-ends links for terrain awareness [17].

The abstract function level describes the underlying causal relationships and priority measures that are necessary to meet the purpose of the system. In general, the laws of physics are described at this level. In the present context, the energy laws that govern the aircraft's motion in the vertical and lateral plane and the separation between the aircraft and the terrain are necessary to satisfy the system's purpose. Energy management can be seen as an abstract representation for locomotion in terms of speed and altitude [31]. Energy management in flight can be defined as controlling the aircraft's total energy E_{tot} and the distribution between kinetic energy, $E_{\mathrm{kin}} = (1/2)mV^2$, and potential energy, $E_{\mathrm{pot}} = mgH$. The energy constraints of an aircraft are described by the minimal kinetic energy E_{kin} of the aircraft, which is related to the minimal airspeed (stall speed), and the minimal potential energy E_{pot} that the aircraft should have to avoid collision into terrain. Together, these constraints determine the minimal total energy required for an aircraft to avoid terrain collision:

$$E_{\mathrm{tot}_{\min}} = \underbrace{E_{\mathrm{pot}_{\min}}}_{f(\mathrm{terrain})} + \underbrace{E_{\mathrm{kin}_{\min}}}_{g(\mathrm{aircraft})} \tag{1}$$

The generalized function level explains how the laws and priority measures described at the abstract function level can be achieved, independent of the physical implementation of the system. Here, the lift, weight, drag, and thrust functions of the aircraft determine the (internal) constraints on the aircraft's energy management. They describe the aircraft maneuver functions in terms of kinematics, dynamics, and performance, which determine how fast an aircraft can exchange kinetic for potential energy and vice versa. Also the obstruction function of the terrain, the external constraint to locomotion, can be found on this level of abstraction, which determines how the aircraft energy must be managed to avoid terrain collisions.

At the physical function level of abstraction, the states of system components and their capabilities are described. Each of the components is used in a process described at the preceding level. Here, the states and configuration of the wings (flaps and slats), control surfaces (elevator, ailerons, rudder and speed brakes), fuselage, and engine serve the ends of lift, drag, thrust, weight, and maneuvering. The mountains, trees, buildings, protrusions, and undulations define the obstruction function of the terrain.

The physical form level contains the appearance, condition, and location of each component that forms the aircraft geometry and the specific shape of the terrain profile.

B. Case Study: *Total Engine Failure*

In the situation of a total engine failure, the engine thrust force, which is a constraint on the generalized function level, is zero. Hence, with this altered constraint, some of the goals defined in the abstraction hierarchy cannot be achieved. Whereas the abstraction hierarchy itself does not change in the situation of a total engine failure, the constraints of this work domain will be different than in a situation where all aircraft systems are appropriately functioning. From a pilot's perspective, two important questions to answer after a total engine failure are 1) "What are the relative positions of possible landing locations within reach?" and 2) "How can I safely fly toward that landing location?" Identifying the goals and constraints in terms of energy management, aircraft performance, and terrain separation could help to answer those questions.

1. *Functional Purpose*

In the work domain of a total engine failure, the focus will be on the safety aspect, because an emergency landing needs to be conducted for which productivity and efficiency are relatively less important. The purpose is to land as safely as possible on suitable and safe terrain.

2. *Abstract Functions*

Energy management is one of the abstract functions; how a total engine failure affects energy management will be explained here. The total energy rate of an aircraft is described as follows [32]:

$$\dot{E}_{\mathrm{tot}} = (T - D)V \tag{2}$$

where T is the thrust, D is the drag, and V is the airspeed. In the case of a total engine failure, the thrust T will be zero, reducing Eq. (2) to

$$\dot{E}_{\mathrm{tot}} = -DV \tag{3}$$

Equation (3) shows that, after engine failure, the total energy rate is controlled by means of the drag and speed. Another way of describing the total energy of an aircraft is by the specific energy, that is, the energy per unit weight [32]:

$$E_{\mathrm{tot}_{\mathrm{sp}}} = \frac{E_{\mathrm{tot}}}{W} = H + \frac{1}{2}\frac{V^2}{g} \tag{4}$$

The specific total energy has units of altitude and is sometimes referred to as the energy height. Differentiating Eq. (4) results in the specific energy rate:

$$\dot{E}_{\mathrm{tot}_{\mathrm{sp}}} = \dot{H} + \frac{V}{g}\dot{V} \tag{5}$$

Substituting $\dot{H} = V \sin\gamma$ into Eq. (5) yields

$$\dot{E}_{\mathrm{tot}_{\mathrm{sp}}} = V \sin\gamma + \frac{\dot{V}}{g}V \tag{6}$$

where the specific potential and kinetic energy rates are

$$\dot{E}_{\mathrm{pot}_{\mathrm{sp}}} = V \sin\gamma \tag{7}$$

$$\dot{E}_{\mathrm{kin}_{\mathrm{sp}}} = V\frac{\dot{V}}{g} \tag{8}$$

In case of a total engine failure, pilots are likely to try to maximize the aircraft's range, thereby maximizing the number of places where an emergency landing can be conducted. For this purpose, the drag and speed need to be controlled in such a way that the absolute value for $\dot{E}_{\mathrm{tot}}$ is minimized. Assuming that an optimum gliding flight with maximum range is conducted at a constant speed, minimizing the total energy rate reduces to minimizing the potential energy rate or, equivalently, the descent rate [see Eq. (7)]. This, however, only holds up to the moment where the pilot has chosen the suitable emergency landing location. After the choice has been made, the required total energy rate to arrive exactly at the chosen emergency landing location is likely to be different from the minimum absolute value. For example, if the distance to the landing location is much smaller than the maximum glide range, the energy rate must be higher than the minimum absolute value. Therefore, pilots will have to determine what this required total energy rate is to prevent overshooting (too much total energy) or not reaching the desired landing location at all (too little total energy). While doing so, both the potential and kinetic energy impose an important constraint. The minimal potential energy corresponds to safe terrain *separation* and the minimal kinetic energy corresponds to the aircraft's touchdown speed.

3. *Generalized Functions*

To maximize the number of places where an emergency landing can be conducted, the aircraft needs to be controlled in such a way that the range is maximized. This maximum range can be described by the optimum glide of an aircraft, in which the minimum glide path angle is as follows[32,33]:

$$\gamma_{\min} = -\arctan\left(\frac{1}{(C_L/C_D)_{\max}\cos\varphi}\right) \tag{9}$$

where $(C_L/C_D)_{\max}$ is the maximum glide ratio and φ is the roll angle. The airspeed at which the optimum glide is performed is [32,33]

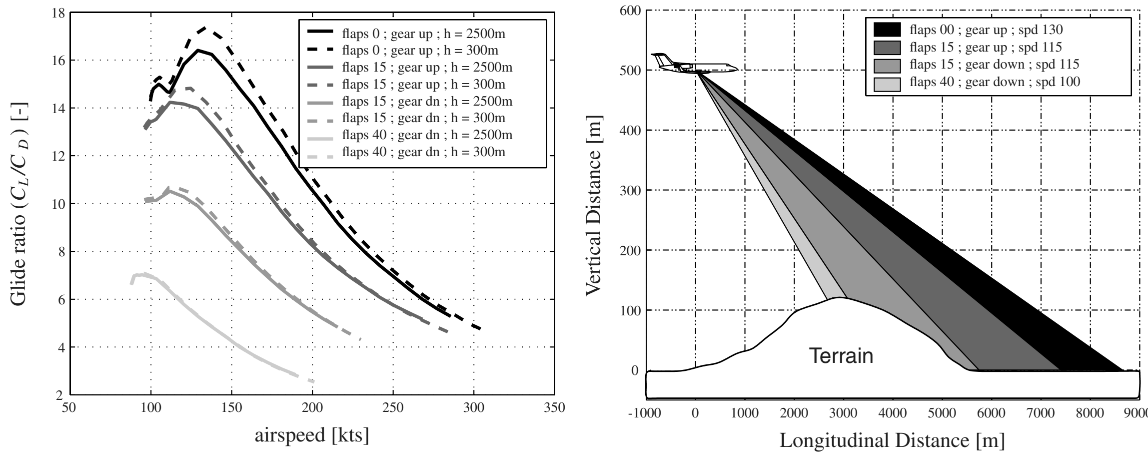
$$V_{\mathrm{opt}} = \sqrt{\frac{2W\cos\gamma_{\min}}{S\rho(C_L)_{(C_L/C_D)_{\max}}\cos\varphi}} \tag{10}$$

with the wing area S and the air density ρ. From Eqs. (9) and (10) it can be seen that, for a certain glide ratio and airspeed, the minimum glide path angle decreases with an increasing roll angle. Hence, the maximum range in a gliding flight is obtained when performing a *straight* gliding flight. To reach a landing area, however, it may be required to make one or more turns.

Furthermore, the maximum range also depends on the aircraft configuration, such as the flap setting and the landing gear position. This induces higher drag than a clean configuration and, therefore, affects the glide ratio or aerodynamic efficiency C_L/C_D. To determine how the glide ratios will be affected by the aircraft configuration, off-line simulations were done with a nonlinear 6 degrees of freedom mathematical model of the Cessna Citation 500 [34]. In Fig. 2a the glide ratios are shown as a function of indicated airspeed, at 300 and 2500 m, for different configurations of the Cessna Citation 500. To find the ratios for different heights, the values are either interpolated or extrapolated. The maximum glide ratios for each configuration shown in Fig. 2a are given in Table 1. In Fig. 2b the maximum ranges of the Citation, starting from an altitude of 500 m, are shown for different flap and landing gear settings. Each range region is limited on the right-hand side by the optimum glide ratio that corresponds to that specific configuration. The left-hand side of a range region is limited by the optimum glide ratio of the subsequent configuration. All glide paths in between these boundaries can be flown by choosing a different airspeed than the indicated value in Table 1. The left boundary of the region that corresponds to flaps 40 and gear down represents the glide path at the maximum allowable airspeed with flaps 40, that is, 176 kt.

At the time a total engine failure occurs, the airspeed is likely to be different from the airspeed at which the optimum glide is conducted. If the airspeed is higher than the optimum airspeed of the glide, a pull-up maneuver is conducted to exchange the excess in kinetic energy for potential energy. If the airspeed is lower than the optimum airspeed of the glide, a push-over maneuver is initiated to exchange altitude for kinetic energy. The pull-up/push-over maneuver can be approximated by a circle with a radius of [33]

$$R = \frac{V^2}{g(n_z - 1)} \tag{11}$$



a) Glide ratios versus the airspeed **b) Maximum ranges**

Fig. 2 The glide ratios and maximum ranges as a function of airspeed and aircraft configuration for the Cessna Citation 500.

with n_z the vertical load factor. A constraint for the pull-up/pull-down maneuver is the maximum load factor.

The generalized terrain obstruction function again serves the ends of energy management, where now the *lack* of obstructions provides a possible landing area. On the other hand, the terrain also influences the maximum glide range and corresponding configuration of an aircraft. For example, in Fig. 2b, flaps 0 and flaps 15 with gear up allow the aircraft to reach the landing location, whereas with flaps 15 and flaps 40 with gear down a terrain collision cannot be avoided.

4. Physical Functions

At this level of abstraction, the flap setting and landing gear position are important to control the aircraft drag and, hence, the glide performance. The terrain's physical function remains the same as in Fig. 1, however, now the *lack* of rocks, trees and buildings defines a possible landing area.

5. Physical Form

This level remains the same as in Sec. II.A.

C. Skill-, Rule-, and Knowledge-Based Behavior

The SRK-based mental constraints a pilot may use in the situation of a total engine failure can be identified with a control task analysis, where the decision ladder can be regarded as a modeling tool for control tasks [29,35], see Fig. 3. In general, after a total engine failure a GA pilot will first trim the aircraft for optimum glide. This can be regarded as a rule-based shortcut that directly leads to a procedure. After that, pilots use the out-of-the-window view to identify suitable landing areas. This visual identification can be categorized as skill-based behavior (SBB), but is known from practice to be unreliable and to be affected by atmospheric visibility conditions. In terms of rule-based behavior (RBB), pilots will use the altimeter, the speed indicator, navigational maps, etc., to determine their own state and possible states within the situation constraints. Based on that information, a pilot will choose and eventually apply a strategy to reach a selected landing area. The process of scanning maps, scanning primary flight information, and mentally calculating landing locations within reach may lead to high levels of workload. Within the time frame of looking for suitable landing areas and figuring out how to get there, there may be little time left for knowledge-based behavior (KBB), which requires the pilot to complete all eight information-processing steps (Fig. 3).

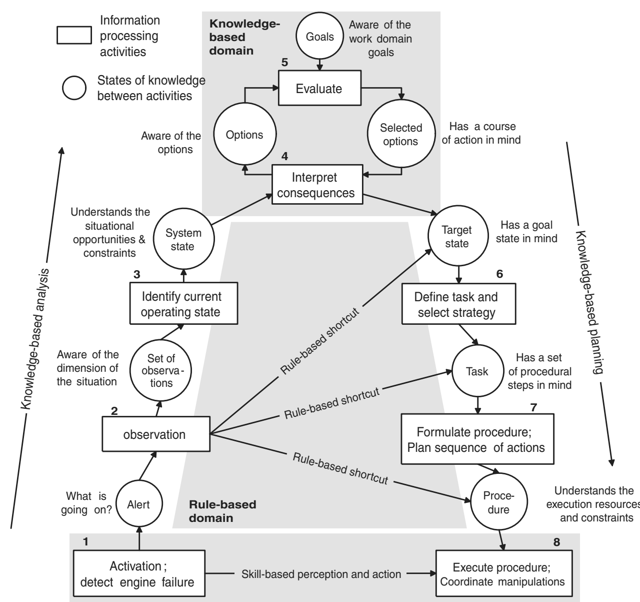


Fig. 3 The decision ladder as a modeling tool for identifying skill-, rule-, and knowledge-based behavior [29,35].

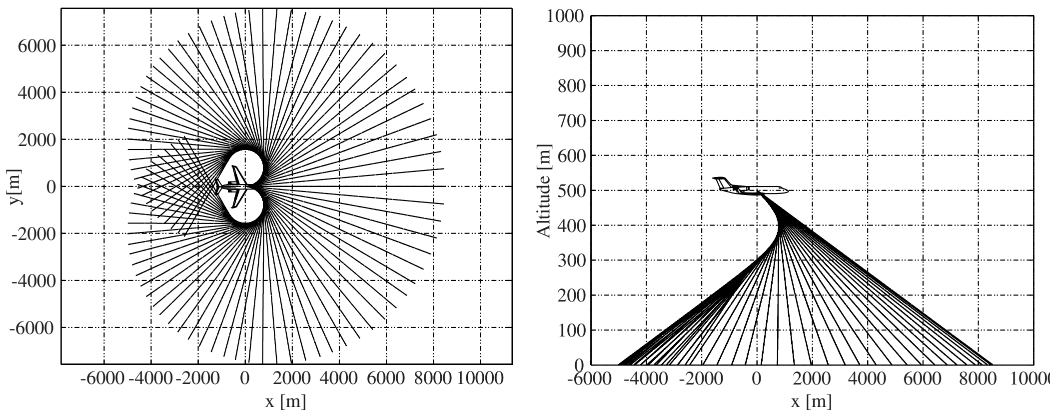
Table 1 Flight conditions and corresponding maximum glide ratios, Cessna Citation 500

Flight condition			Glide ratio	
Flaps, deg	Gear	Airspeed, kt	At 300 m	At 2500 m
0	Up	130	17.2	16.4
15	Up	115	14.7	14.2
15	Down	115	10.7	10.4
40	Down	100	6.97	6.92
40	Down	176	3.21	3.24

III. Interface Design

In general, the features in an ecological interface are a result of visually mapping the goals and constraints of the abstraction hierarchy guided by the SRK taxonomy [22]. Instead of designing a completely new interface, it was chosen to map the goals and constraints as overlays on an existing EGPWS terrain awareness display (TAD). Enhancing existing interfaces is important in a domain such as aviation, where one cannot simply replace all current displays without taking previous training of pilots with these displays and systems into account.

Current EGPWS systems do not incorporate aircraft performance in their look-ahead flight-path prediction [26]. A new system, the terrain and traffic collision avoidance system (T^2CAS), does take the



a) Top view b) Side view

Fig. 4 A three-dimensional mesh of optimum glide paths for a clean aircraft configuration.

climb performance into account in its collision avoidance algorithms, but it does not support the selection of and guidance to a suitable landing location after a complete engine failure [36].

The present design of the ELGS interface overlay is aimed at leaving the pilot in the decision making loop. This is different from an EGPWS, which tells the pilot what decision to make without presenting the rationale. Based on the visual information the ELGS provides about the terrain in conjunction with the aircraft's capabilities, along with the pilot's expertise and experience, pilots can perceive the alternatives for action that the work domain provides and decide for themselves what the best resolution is. We hypothesize that this will induce improved terrain awareness.

A. Information Content and Structure

1. Aircraft Performance

To map the aircraft performance limitations in the situation of a complete engine failure, a three-dimensional glide path mesh was projected on the terrain plan view. Equations (9) and (10) may be used to construct the glide path mesh in a 360-deg heading range (see Fig. 4). The glide path mesh uses optimum glide paths with a clean aircraft configuration, that is, gear and flaps up. The curved parts of the glide path mesh are turns with a maximum roll angle of $\varphi = 45$ deg. The intersection of the glide mesh and the terrain indicates the aircraft maximum range for the particular configuration. Landing areas within the mesh are those that can be reached. The 45-deg roll angle turns serve as a safety margin in case a turn is needed to fly toward a certain landing location. Turning with a roll angle of less than 45 deg increases, of course, the aircraft's range, but turns with higher roll angles have the opposite effect.

If the aircraft velocity at the time of engine failure is larger than the ideal airspeed for the optimum glide, a pull-up maneuver should be initiated to exchange the excess in kinetic energy. This means that the glide mesh actually starts at vertical offset ΔH_g and horizontal offset ΔX, see Fig. 5. If an aircraft was able to instantaneously exchange its excess in kinetic energy into altitude, the law of conservation of energy describes the altitude difference ΔH as follows [17]:

$$\Delta H = \frac{1/2(V^2 - V_{\text{opt}}^2)}{g} \tag{12}$$

Next, the actual offsets ΔH_g and ΔX, defining the starting point of the glide mesh, can be calculated:

$$\begin{aligned} A &= (R - \Delta H)\sin\gamma_{\min} \\ &\quad + \sqrt{(R-\Delta H)^2 \sin^2\gamma_{\min} - ((R-\Delta H)^2 - R^2)}, \\ \Delta H_g &= \Delta H - A\sin\gamma_{\min}, \qquad \Delta X = A\cos\gamma_{\min} \end{aligned} \tag{13}$$

where the radius R is calculated using Eq. (11). Hence, the offset of the glide mesh is a cue for the pilot to pull up first to lose the excess

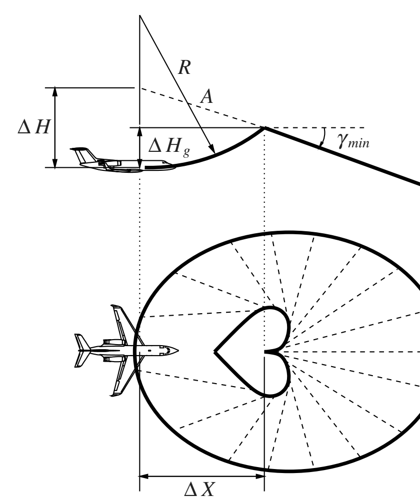


Fig. 5 Pull-up maneuver support for the ELGS.

speed. As soon as the aircraft reaches V_{opt} [Eq. (10)], the glide mesh is located at the aircraft's present position (see Fig. 4).

2. Terrain Separation

The present and future height above the terrain may be indicated by presenting the vertical spacing between the glide mesh and the terrain in terms of color coding, as shown in Table 2. The color coding was kept similar to the EGPWS color coding, making it easier for pilots to distinguish hazardous from safe terrain areas. The meaning of the ELGS color codes, however, differed from the EGPWS color codes. In ELGS mode, the red color indicates where the terrain rises above the glide mesh instead of indicating terrain that is 2000 ft above the current aircraft altitude. The color codes of the landing locations were chosen arbitrarily.

3. Landing Location Detection

At the time of designing the interface, only a terrain elevation database was available, without information on trees and cultural

Table 2 Ground proximity colors of the ELGS

Color	Ground proximity interval, ft
Red	≥ 0
Yellow	$[-500, 0)$
Brown	$[-1000, -500)$
Green	$[-1500, -1000)$
Dark green	$[-2500, -1500)$
Black	< -2500

Table 3 Landing location colors indicating the aircraft configuration

Color	Flaps, deg	Gear	V_{IAS}, kt
Bright red	0	Up	130
Bright orange	15	Up	115
Bright green	15	Down	115
Bright light blue	40	Down	100
Bright blue	Turn needed	——	——

data, such as roads, fences, buildings, airports, etc.. Therefore, the landing locations in the terrain elevation database are only detected by the elevation rate or "terrain roughness." An area suitable for landing, that is, a relatively smooth and flat area in the terrain database, is indicated on the TAD. The area can be reached as long as it lies within the aircraft's glide range.

Pilots do not yet know, however, how much altitude they need to lose to arrive at the landing location without overshooting it. Therefore, the landing locations are given specific colors that correspond to a certain aircraft configuration (Table 3). Landing locations that are too close are indicated in bright blue, meaning that the excess in total energy is too large. Therefore, additional turns are needed to lose the excess energy. The energy management (or aircraft configuration) strategy is based on the difference between the total energy of the aircraft at the time of engine failure and the total energy required to reach the landing area, that is, the total energy that must be lost during the glide to landing. Assuming a gliding flight with constant speed, the energy difference will be lost by opting for a specific potential energy rate $\dot{E}_{pot_{sp}}$. This corresponds to a glide path angle (or descent rate) that depends on the aircraft configuration. For example, in Fig. 6, to arrive in the center of the landing location, a flaps 15 with gear up and 115 kt configuration must be selected.

B. Visual Form

The ELGS interface overlay consists of two layers projected on top of the terrain: 1) the glide path mesh with ground proximity colors and 2) the color-coded landing locations. Salience is used to distinguish the two layers, in which the landing locations are colored more brightly than the ground proximity colors. A screenshot and a conceptual representation of the ELGS overlay are shown in Fig. 7. How to use the ELGS interface overlay can best be explained by an example situation shown in Fig. 7b.

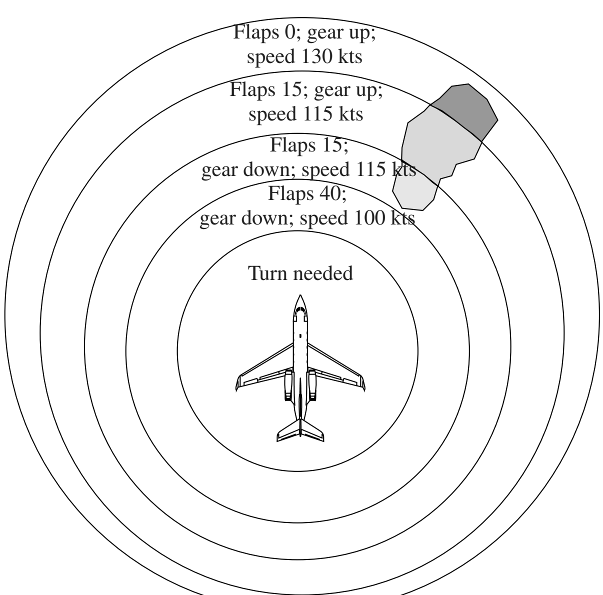


Fig. 6 Landing location color coding, where each color represents an aircraft configuration to lose the total excess in energy between the aircraft and the landing area.

In this figure, the ground proximity areas (a result of mapping the glide path mesh on top of the terrain) are indicated by I, II, III, and IV, where I shows where the terrain rises above the glide mesh and is colored in red (see Table 2). This defines the safety margin within which the aircraft can safely fly without colliding with terrain. As the aircraft descends, the safety margin gets smaller. From Fig. 7b it can also be seen that inside the safety margin there are two reachable landing locations, A and B. Landing location C lies outside the safety margin and therefore cannot be reached. With two reachable landing locations, A and B, the pilot has to make a decision which one is preferable. Landing location B lies closest to the aircraft, but the excess in energy is so large that the pilot has to make additional turns to lose the excess in potential and kinetic energy. If the pilot chooses to land on B, making a turn to the left will result in a terrain collision. Landing location A, however, can be reached by a straight gliding flight with a flaps 15 and gear down configuration. Based on that information, a pilot would best opt for a straight gliding flight toward landing location A.

C. EID-Related Properties

An ecological interface should support the operator on the three levels of cognitive processing. How these levels of cognitive processing are supported by the ELGS is shown in Fig. 8 and will be described in the following sections.

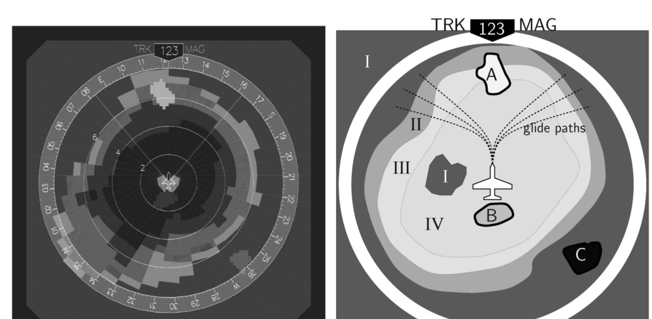
1. *Skill-Based Behavior*

SBB requires very little or no conscious control to perform an action and can be developed after sufficient training of the pilots with the displays during familiar events. The ELGS interface mainly supports SBB during the approach-to-landing phase. In this phase, (skilled) pilots use their automated sensorimotor patterns for controlling the aircraft to keep the target landing location aligned with the aircraft symbol (both are shown on the ELGS).

2. *Rule-Based Behavior*

At the rule-based level, the ELGS interface supports pilots in observing the engine failure situational elements in terms of showing the glide range, terrain separations, and nearby landing locations. Other observations, such as determining the cause for the engine failure, are not supported by the ELGS. These cues must be perceived from other interfaces, for example, the engine status display.

The ELGS also supports identifying the constraints of the current aircraft operating state in relation to the terrain by means of color coding the landing locations and terrain proximities. Hence, the geometry and color coding of the constraints mediates the rules that are required to obtain a situational understanding and finally select a strategy. The remaining information-processing activities on the rule-based level are currently not supported by the ELGS. It is assumed that skilled pilots will know how to perform an ideal gliding flight. In Fig. 8 the text in between parentheses indicates interface features that could be added for novice pilots to support the remaining information-processing activities.



a) Screenshot **b) Conceptual representation**

Fig. 7 A screenshot and a conceptual representation of the ELGS interface overlay.

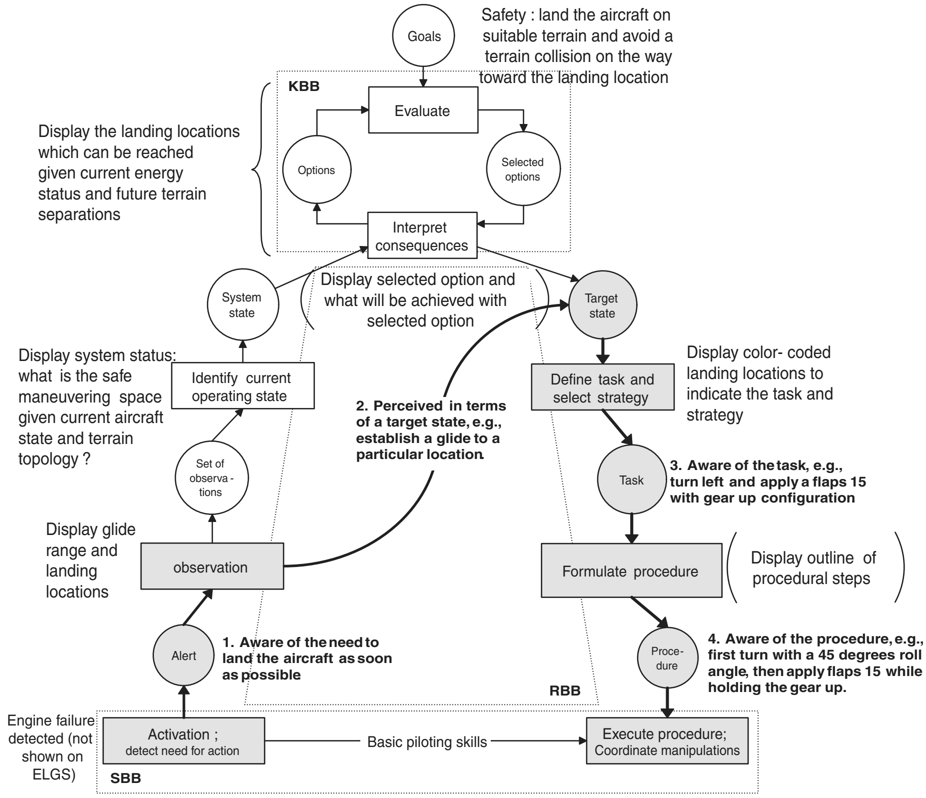


Fig. 8 Supporting skill-, rule-, and knowledge-based activities with the ELGS interface.

The ELGS also allows pilots to make rule-based shortcuts. For example, for a pilot who is familiar with the terrain area and aware of nearby landing locations, an engine failure, the observation of the glide range, and the reachable landing locations may directly be perceived in terms of a target state (heading toward a landing location, an appropriate speed, and flight configuration) followed by a suitable action (Fig. 8).

3. *Knowledge-Based Behavior*

The ELGS mainly supports the knowledge-based analysis of the situation, ranging from noticing a need for action to the behavior of evaluating the different options and their consequences. More specifically, the ELGS shows all the nearby landing locations along with their color coding, the future terrain separations, and the aircraft maximum glide range. This enables a pilot to choose a suitable solution that satisfies the work domain goals and develop new rules.

For example, a pilot may want to fly to landing location A (see Fig. 7b) with an advised flaps 15 and gear down configuration. The pilot, however, will note relatively high terrain surrounding the landing location, which will result in small terrain clearance margins during the approach. It is also possible to opt, however, for a flaps 0 and gear up configuration to increase the terrain clearance farther ahead. This will result in a landing location color change and, consequently, a final flaps 40 and gear down configuration is advised to compensate for the smaller energy dissipation during the clean configuration.

D. Final Remarks on the ELGS Design Considerations

The prototype of the ELGS interface overlay was simplified by means of assumptions to test the concept. Regarding the terrain database, it was assumed that a suitable off-airport landing location is only a function of the terrain elevation rate. For a final design, an accurate database is recommended such that the landing-location detection algorithm includes data on cultural obstructions (buildings) and landscape characteristics (for example, forests, lakes, and open fields).

However, suitable landing locations could include nearby airports. In this case, to safely land, the aircraft has to line up with the runway. This would require the aircraft to make more turns than initially indicated by the glide mesh and, hence, decrease the glide range. For the prototype design, this additional constraint was not yet included. It was assumed that all landing locations on the terrain could be approached from every direction.

Furthermore, the wind influence on the glide performance was not regarded. The deformation of the glide mesh in strong winds will be substantial [37]. The wind also affects the preferred aircraft heading at the landing. This can easily be included in the display, but it was not considered for the present research.

IV. Experiment

To evaluate the prototype of the ELGS interface overlay, it was tested in a pilot-in-the-loop experiment. For the experiment, relevant emergency landing situations were created and simulated, in which the ELGS was hypothesized to support all levels of terrain awareness. The ELGS display was analyzed with both objective and subjective measures.

A. Method

1. *Subjects and Instruction to Subjects*

Nine licensed GA pilots participated in the experiment. They were all males with an average age of 25 years and an average experience of 489 flying hours. In Table 4, the age, flight experience, and experience with EGPWS of the pilots are listed. None of the pilots had any prior experience with an SVS.

To make the situation as real and relevant as possible, the pilots were positioned above mountainous terrain. After approximately half a minute, a complete engine failure occurred. The terrain topologies used in the experiment were defined in such a way that three emergency landing locations were always shown. Pilots were instructed to perform an emergency landing on one of the three locations. They were also instructed to touch down with the correct landing speed and with as much roll-out margin in front of them as possible.

Table 4 Characteristics of the pilot subjects in the experiment

Pilot	Age	Hours	Aircraft types	EGPWS hours
1	26	410	G Glider, SEP	——
2	25	412	General aviation, B737	50
3	28	251	P28A/34, C150, C172, TB206, TB20, B747	212
4	24	1300	AVRO, PA28/38/34	48
5	28	245	Piper 28/44, C150/172R	110
6	24	256	C150/152/172, PA28/38A, AC114, BE78	——
7	24	255	C172, P28A/38A, B76/58, Purtenauia	20
8	28	295	Single engine, P34A	——
9	22	977	BE99, TB200, C152/172, PA28/34/44	——

2. *Apparatus*

The experiment was conducted in a fixed-base flight simulator, consisting of a cabin mock-up, situated in a darkened noise-free room. The cabin had two 18-in. liquid crystal display (LCD) monitors. One was situated in front of the pilot and was used to display the SVS. The other display was situated to the left of the pilot and showed the horizontal situation display (HSD) and the engine instruments. The outside view was projected by means of an LCD beamer onto a white wall in front of the cockpit. The aircraft model was controlled by a right-handed, control-loaded side stick and rudder pedals on which fixed mass, spring, and damper settings were selected. Furthermore, gear, throttle, and flaps were used. The elevator trim was controlled by a lever located to the left of the throttle levers.

3. *Aircraft Characteristics and Experiment Conditions*

The aircraft model used in the simulation was a 6 degrees of freedom nonlinear Cessna Citation 500 model. The aircraft model was trimmed at an altitude of 2500 m with a velocity of 150 kt calibrated airspeed in an International Standard Atmosphere [33] without wind and turbulence. The model was extended with a total engine failure block, that could switch the engines on and off at any point in time. To enable the aircraft to land, a landing gear model was present, which simulated both the aerodynamic drag force and ground impact on the landing gear.

4. *Independent Variables*

There were two independent variables in the experiment: the display configuration and the experiment terrain. The display configuration had 3 levels and the experiment terrain had 9 levels, creating a total of 27 experiment conditions.

a. Display Configurations. Three display modes were configured: MAP, EGPWS and ELGS. The display configurations were set up as follows:

1) MAP: This configuration featured a primary flight display (PFD) and a top view of the terrain on which a color map illustrated the elevations of the terrain on the HSD. The landing locations were indicated on the map.

2) EGPWS: This configuration featured an SVS and an HSD overlaid with EGPWS colors. Besides EGPWS color coding, this display configuration also included an EGPWS forward-looking flight-path prediction along with aural and visual caution/warning messages. The relative positions of the landing locations were also indicated on this plan view.

3) ELGS: This configuration also featured an SVS and an HSD with the ELGS logic and color coding defined in Section III.

The display configurations, besides the ELGS, are shown in Fig. 9.

b. Experiment Terrains. Nine mountainous virtual terrains were created. Each terrain featured three landing locations. The positions and altitudes of the landing areas in the terrain database, with respect to the aircraft state at the moment of the engine failure, were chosen such that:

1) One of the locations is reachable by performing a single turn followed by a straight gliding flight. On the ELGS interface, this location lies inside the glide range and its color code indicates the appropriate aircraft configuration.

2) One of the locations is reachable but very close to the aircraft. On the ELGS, this location lies inside the glide range and its color code indicates that a large amount of excess energy needs to be lost through extra turns.

3) One of the locations is unreachable. On the ELGS interface, this location lies outside the aircraft's glide range.

Pilots should choose, based on the information that was provided, to conduct the emergency landing preferably on the first location. Apart from the location of the landing areas, all terrains were different to prevent pilots from recognizing the scenario. This introduced the experiment terrain as an independent variable into the experiment. The influence of the terrain was, however, of little interest for the research. Hence, to reduce the effect of this independent variable, two countermeasures were taken. First, the difficulty of each scenario was kept at an equal level as much as possible and, second, the scenarios were flown in each display configuration an equal number of times. It was, however, impossible to completely exclude the influence of the terrain from the results. Therefore, the effects of the terrain were analyzed to test their significance.

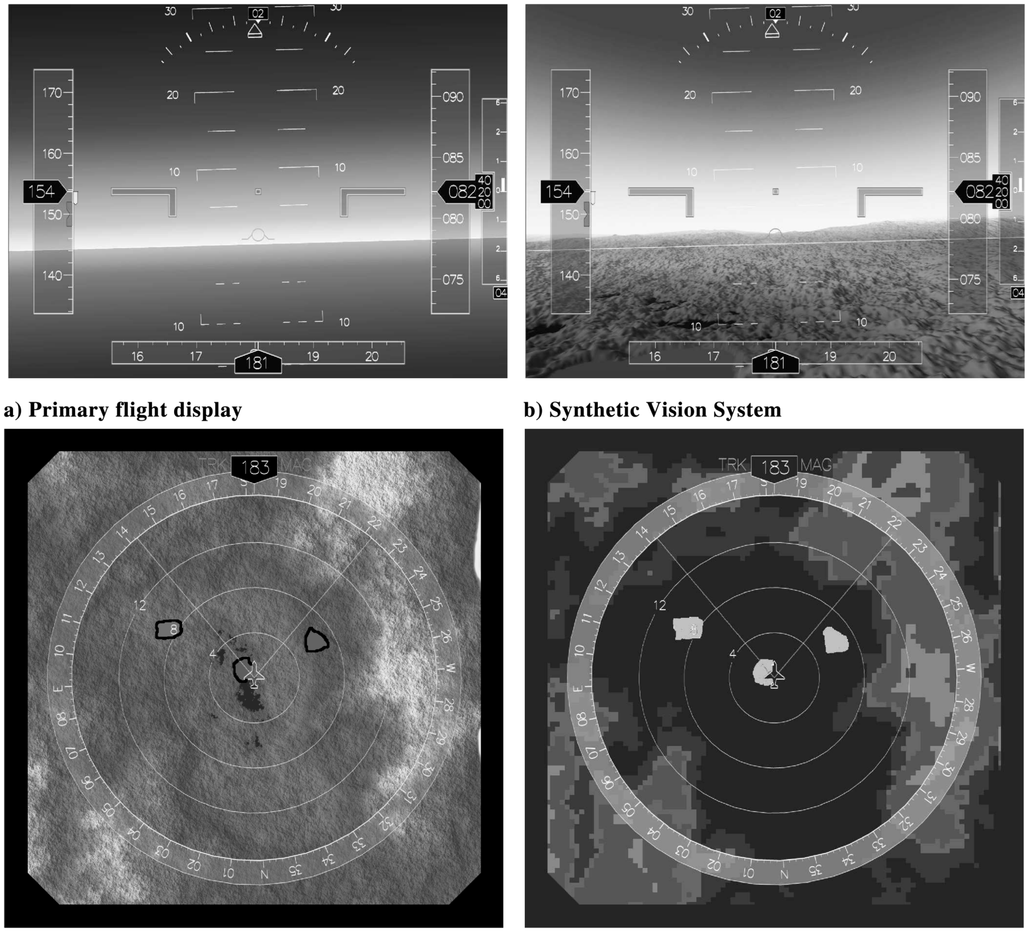
5. *Experiment Design and Procedure*

a. Experiment Design. The experiment consisted of two phases: training and measurement. The training phase started with a pilot briefing, followed by one general training run to get used to the controls and aircraft dynamics. During this run, pilots were asked to fly a track with which they practiced their instrument flight skills. The final phase of the training consisted of performing one emergency landing in each display mode, i.e., MAP, EGPWS, and ELGS.

The experiment phase, where the actual measurements took place, consisted of nine runs. Each display mode was used 3 times during the experiment. Each pilot flew three scenarios with each display mode. To reduce learning effects in the experiment results, the order of the displays was counter-balanced between the pilots using a 9×9 Latin Square [38], which was built up out of nine different 3×3 Latin Squares. Hence, for each group of three pilots, all experiment conditions were flown once, and each experiment condition was repeated 3 times.

b. Procedure. For each pilot, the experiment took half a day. The arrangement of the experiment activities was, in chronological sequence, an oral briefing and training, a series of five experiment runs, a series of four experiment runs, and a final questionnaire. All the experiment activities were interrupted by 10 min breaks. Each experiment run took approximately 12 min.

At the start of the run, pilots were asked to establish a steady, straight, and trimmed flight condition, with flaps and gear up. In the first 30 s of a run, pilots would fly in this flight trimmed condition. This was followed by an engine failure and the outside visual and displays would freeze for 5 s in which the pilots were asked to perform a post-engine-failure check. This meant scanning the engine display, the HSD, and the SVS or PFD. After these 5 s, the screens turned blank and the pilots started filling in a short questionnaire. After finishing the questionnaire, the run continued and pilots executed the emergency landing with the engines switched off. After the aircraft made its first contact with the ground, the operator would stop the experiment run and pilots completed a NASA Task Load Index (TLX) [39]. The short questionnaires, which interrupted the



a) Primary flight display b) Synthetic Vision System

c) Map view d) EGPWS TAD

Fig. 9 The display configurations, besides the ELGS, used in the experiment. The highlighting of the landing locations on the map-view and TAD is exaggerated for these pictures.

experiment runs, are a method to assess pilot SA, which will be elaborated on in the next section.

6. *Dependent Measures*

The dependent measures in the experiment were chosen such that they reflect the design hypotheses of the ecological ELGS interface. That is, by revealing the internal and external constraints to flight, pilots are more aware of the situation, they make better decisions, and fly more safely. The dependent measures in the experiment were:

Performance. The objective performance measures were as follows:

1) The landing location that was chosen. (Graded 1 for choosing the most suitable landing location and graded 3 for the least suitable.)

2) Touchdown point, that is, did the aircraft touch down at the start or at the end of the landing location. (Graded 1 for landing at the start of a location, a 2 for in the middle, and a 3 for at the end.)

Situation awareness. A common approach, also followed here, is to divide situation awareness into the following four cognitive levels: perception (level 1), comprehension (level 2), projection (level 3), and metacognition (level 4) [40]. In this experiment, these cognitive levels represent terrain awareness in the situation of a total engine failure as follows:

1) Perception: perception of the situational elements, such as flight status and landing locations.

2) Comprehension: understanding the meaning of the perceived variables, such as determining which landing locations can and cannot be reached.

3) Projection: planning and strategies, such as selecting a flight configuration to reach a chosen landing location.

4) Metacognition: the self-assessment of a pilot's own terrain awareness.

SA was measured by interruptive query probing [11,41,42]. The interruptive query probing was done in the form of short questionnaires of six questions that were aimed at the different levels of SA. Questions at the first level, that is, perception, were similar to, "What is your indicated airspeed?" or "Where are the landing locations with respect to your current heading?" At the second level, comprehension, questions such as, "Which landing location can be reached?" were asked. The third level, projection, was tested by questions such as, "What strategy is appropriate to reach your selected landing spot?"

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 given answers to the correct answer of the question.

The fourth level of SA, metacognition, was measured through a confidence interval. Next to each question, the pilots indicated on this interval their self-confidence, with an 11-point Likert scale, 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, 3, 6, or 9 for 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 5 was used. The total SA consisted of the grades of the four measured levels, averaged to one overall grade.

In the post-run questionnaire, pilots were asked to give their opinion on the display configurations in terms of symbology and overall usefulness in relation to reaching their goal, that is, to safely land the aircraft after a total engine failure. These opinions, however, were not part of the SA measurement.

Table 5 Grade determination of metacognition SA level

	Absolutely sure $z > 0.33$	Fairly sure $0.33 > z > -0.33$	Unsure $z < -0.33$
Correct: *grade* 9, 6	9	6	3
Incorrect: *grade* 3, 0	0	1	2

Workload. Workload was measured by a NASA TLX rating sheet [39]. Zero to hundred (0–100) scales were used to measure the mental demand, physical demand, temporal demand, performance, effort, and frustration.

Safety. Safety was quantified by measuring the number of intrusions into above ground level (AGL) margins during the flight trajectory after engine failure. The number of intrusions, excluding the intrusions made in the last 30 s of the landing phase, were counted using the following thresholds:

1) Soft intrusions (500–300 ft margin)
2) Hard intrusions (300–100 ft margin)
3) Number of "crashes" (<100 ft)
4) Number of real crashes, that is, landing location not reached

B. Experiment Hypotheses

Performance was hypothesized to be highest for ELGS and lowest for the MAP configuration. The performance for the EGPWS configuration was hypothesized to rate in between MAP and ELGS.

SA was hypothesized to be highest for ELGS and lowest for MAP. Especially at the level of "projection," the SA was expected to be higher for ELGS because of the extra information that relates the terrain to the aircraft's performance.

The workload was hypothesized to be the lowest for ELGS and the highest for MAP. In MAP, pilots had to do all the cognitive work themselves by making a mental model of the aircraft's glide performance and projecting this on the terrain to consider their possibilities.

Regarding safety, it was hypothesized that pilots would maintain higher ground clearance in EGPWS and ELGS with respect to MAP. Furthermore, the terrain was hypothesized to yield no significant influence on the dependent measures.

V. Results and Discussion

The analysis of the SA levels, landing location choice, touchdown point, and TLX workload, was done using analysis of variance (ANOVA). Because these dependent measures are expected to be correlated, a multivariate ANOVA (MANOVA) was done to protect against inflating the type I error rate. However, the ANOVA/MANOVA requirement that the data should be from a normally distributed population was not met. Several studies have shown, however, that ANOVAs can still be robust for data skewness as long as the sample sizes are equal and large enough (>20) and the outliers are removed from the data [43–46]. Furthermore, Pillai's trace tests are proven to be robust for normality violations [43,47]. After having met these criteria, multivariate tests showed the following effects on the dependent variables: a significant effect of the display (Pillai: $F_{14,98} = 7.694$, $p \leq 0.01$), no significant effect of the terrain (Pillai: $F_{56,378} = 1.014$, $p = 0.454$), and no significant effect of the display × terrain interaction (Pillai: $F_{112,378} = 0.991$, $p = 0.514$) on the dependent variables. Furthermore, display and terrain did not violate the sphericity assumption using Mauchly's test. The significance of the effects on the safety measure was analyzed using Wilcoxon [48] signed-rank tests. A more detailed discussion of the MANOVA and Wilcoxon results is provided in the following sections.

A. Results

1. Performance

The landing location choice and touchdown point both support the hypothesis that performance will be highest (lowest grade) for ELGS. Figure 10 shows that when pilots were flying with ELGS, they made significantly better landing location choices ($F_{2,54} = 28.304$, $p \leq 0.01$) and their touchdown point also significantly improved ($F_{2,54} = 42.056$, $p \leq 0.01$). Tukey-b's post-hoc analysis ($\alpha = 0.05$) showed that the difference between MAP and EGPWS was not significant.

2. Situation Awareness

The results of the SA measurements are shown in Fig. 11. Analysis showed that display had no significant effect on the perception level ($F_{2,54} = 0.911$, $p = 0.408$), a borderline effect on the comprehension level ($F_{2,54} = 15.737$, $p = 0.051$), and a significant effect on the projection ($F_{2,54} = 62.237$, $p \leq 0.01$) and metacognition ($F_{2,54} = 29.229$, $p \leq 0.01$) levels. In Fig. 11 the overall SA grade is shown, obtained by averaging the grades for the four levels of SA [40]. Tukey-b's post-hoc analysis showed no significant differences between MAP and EGPWS for all SA levels.

In general, the SA can be said to increase for ELGS with respect to MAP and EGPWS. The increase in SA cannot be seen at the level of perception, indicating that each display provides equal levels of perceived variables. Indeed, all displays allowed pilots to perceive nearby landing areas and their location and heading relative to their own aircraft. The increase in SA is, however, very clear for the projection and metacognition level. This supports our hypothesis and also the potential of the ecological approach to interface design.

3. Workload

Display had a significant effect on the pilot workload ($F_{2,54} = 25.097$, $p \leq 0.01$). In Fig. 12 the boxplot of the TLX z scores is shown. Tukey-b's post-hoc analysis showed that the difference between ELGS and both EGPWS and MAP is highly significant, whereas the difference between EGPWS and MAP is not significant. Although the difference between EGPWS and MAP is not significant, the trend suggests that pilots have experienced less workload when flying with EGPWS.

4. Safety

The number of intrusions and crashes is shown in Table 6. The average number of intrusions below 300 ft and 100 ft showed an increase from MAP to ELGS. This trend indicates that, in this respect, pilots performed the most unsafe flight in ELGS. A Wilcoxon signed-rank test analysis of the average number of intrusions per pilot and per display mode showed, however, that the differences between the display modes were not significant.

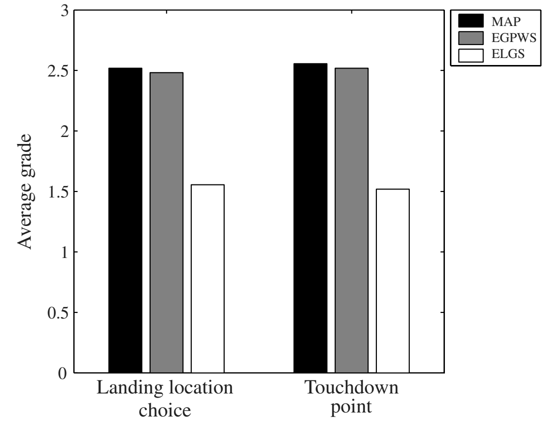


Fig. 10 The average grades of the landing location choice and touchdown point for each display mode.

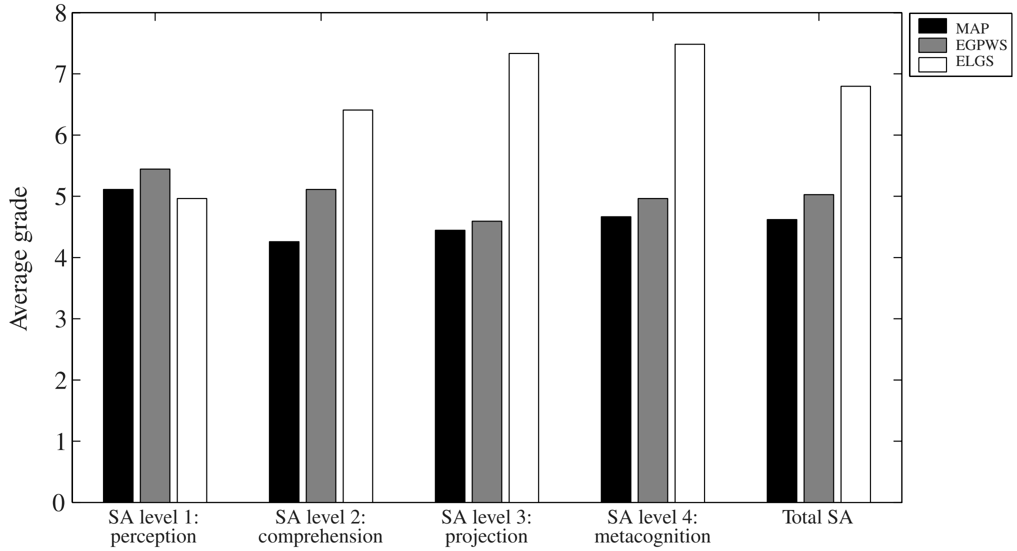


Fig. 11 The average grades of the SA levels for each display mode.

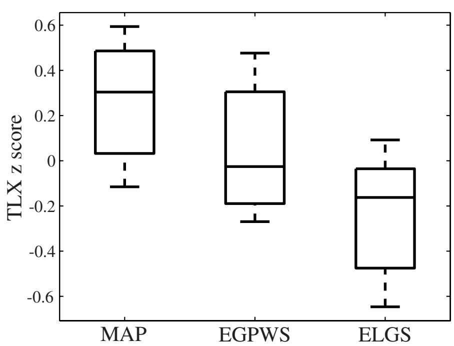


Fig. 12 Boxplot of the TLX workload z scores.

5. Correlation Analysis

A Spearman correlation test was done on the dependent measures due to the nonnormal distributed nature of the data [47]. The test showed that SA level 1 (perception) was uncorrelated to the remaining SA levels, landing location choice, touchdown point, and workload. SA level 2 had a significant positive correlation ($r = 0.378$, $p \leq 0.01$) to the metacognition level, as well as SA level 3 ($r = 0.492$, $p \leq 0.01$), indicating that pilots felt more confident about their given answers when their comprehension and projection abilities increased. The total SA showed a significant negative correlation to the landing location choice ($r = -0.50$, $p \leq 0.01$), the touchdown point ($r = -0.484$, $p \leq 0.01$), and the pilot workload ($r = -0.433$, $p \leq 0.01$). This shows that when the pilot SA increases, pilots were able to make better decisions, improve their touchdown point (lower grades), and decrease their workload.

6. Post-Run Questionnaire

The questions in the final questionnaire on the colors and symbology of the ELGS display were answered positively by the majority of the pilots. They almost all agreed on the usefulness of the features provided by the display. Some pilots, however, complained about clutter and found it sometimes difficult to interpret the meaning of the different color codings.

Table 6 Number of intrusions and crashes excluding the final approach phase

	Intrusion below			
	500 ft	300 ft	100 ft	Crashes
MAP	11	8	0	0
EGPWS	16	13	1	2
ELGS	11	19	4	0

B. Discussion

The goal of the design of the ELGS, using EID, was to improve pilot terrain awareness in the situation of a total engine failure. The experiment results show that pilots made significantly better decisions and were more aware of the situation when flying with the ELGS. Although the ELGS did not significantly improve SA at the perception and comprehension levels, the ecological approach created an interface enhancement that increased the support of the higher levels of situation awareness, i.e., projection and metacognition. The ELGS interface therefore achieved its goal, that is, to support pilot reasoning. This resulted in better pilot judgment regarding the landing location choice based on the provided information about the aircraft capabilities in relation to the terrain.

Using the current measures for safety, the ELGS did not improve safety. On the contrary, it appeared that the ELGS was less safe than MAP and EGPWS in terms of ground proximity intrusions. This conclusion was also found in the research into the performance-based vertical situation display [17]. Showing the aircraft performance boundaries in relation to the terrain apparently promotes pilots to operate at those boundaries. This behavior, however, can also be positively interpreted. That is, by showing the boundaries, pilots are better supported when they are operating at those boundaries. After all, none of the pilots crashed when flying with the ELGS although they were flying closer to the terrain than in MAP and EGPWS. Furthermore, pilots also significantly improved their touchdown point when using the ELGS, which is a logical result of flying closer to the terrain. Whether operations are less safe when flying with the ELGS, therefore, remains a subject of choosing the right metrics for safety.

Another remaining issue is the ELGS evaluation. Attention was limited to the case of a total engine failure, a situation for which the ELGS was specifically designed whereas the other interfaces (MAP and EGPWS) were not. Hence, it may not be fair to compare the ELGS with the conventional interfaces, although these are currently the only available interfaces that aim to increase pilot terrain awareness. This raises the question of whether the increase in pilot terrain awareness and improved pilot decision making can be attributed to the ecological interface or to the chosen situation. Therefore, future research should compare ecological interfaces to viable design alternatives, that is, interfaces which are not designed by using the ecological approach, to clearly show the benefits of the EID framework when considering specific situations. Ultimately, the lessons learned from this and previous research [17] will be used to develop an ecological, perspective SVS interface to benefit pilot terrain awareness.

VI. Conclusions

To support pilot terrain awareness, a new display was developed that informed pilots about the functional meaning of the terrain (the external constraint), in relation to the aircraft performance limitations (the internal constraints). The experimental evaluation of the ELGS, based on an ecological approach to interface design, showed that the advantages primarily lie in supporting SA at higher levels of human cognition, improving the capability of pilots to project their future status and reflect on it appropriately. The experiment results also showed that pilots operated more closely to the limits of performance, thereby negatively affecting the metrics for safety. Whether operations with the new display are less safe, therefore, remains a subject of choosing the right metrics for safety.

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