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An Ecological Approach to Pilot Terrain Awareness

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Supporting pilot situation awareness is considered essential in safeguarding safety. There is much disagreement, however, regarding a formal definition of situation awareness. On the one hand, the most commonly cited definition, from a cognitive perspective, describes it in terms of human information processing stages involving the three levels of perception, comprehension and projection. On the other hand, an ecological approach exists that focuses on defining the 'situation' instead of the 'awareness', using Rasmussen's abstraction hierarchy. This paper investigates the usefulness of the ecological approach in defining pilot terrain awareness. An abstraction hierarchy is defined that captures the characteristics of situations involving terrain awareness. It is used to explore the informational content in existing terrain awareness enhancing avionics. Suggestions will be made on how to enhance them to better support pilot terrain awareness from an ecological perspective.

Introduction

Situation Awareness (SA) is considered to be an important factor for the safe operation of aircraft (Sarter and Woods, 1991). Intuitively, pilot SA is generally described as "seeing the big picture" and is thought to correlate with pilot performance. If operational problems occur due to pilot error, a pilot has failed to see the big picture. Generally, this phenomenon is labeled as pilot error due to a low SA. For example, the primary cause for Controlled Flight Into Terrain (CFIT) accidents is commonly attributed to a low pilot SA (Khatwa and Roelen, 1999). The problem, however, with using SA as an explanatory tool for pilot error is that it can lead to circular reasoning (Flach, 1995). Furthermore, what aspects exactly define a 'low' and a 'high' SA? Apparently, SA may be more complex than simply described as seeing the big picture.

Many attempts have been done by researchers to capture the concept of SA into a formal psychological construct to both develop an operational definition (e.g., to be useful for display design and training procedures) and an experimental paradigm for researching it (Uhlarik and Comerford, 2002). As a result, many different approaches to SA exist. In general, they can be divided into a cognitive and ecological approach.

The most well-known cognitive approach to SA is the one suggested by Endsley (2003), which uses the information-processing model. She defines and explains SA by means of human cognitive processes involving three levels: perception, comprehension and projection. Opposed to this cognitive approach, an ecological approach exists that starts by focusing on defining the 'situation' instead of the 'awareness' (Flach, Mulder and Van Paassen, 2004) and proposes Rasmussen's Abstraction Hierarchy (AH) (Vicente and Rasmussen, 1992) as a useful tool to describe situations.

This paper investigates the usefulness of using the ecological approach in aviation to develop aviation interface design criteria. To limit the focus, pilot terrain awareness is taken as a case study. An AH is proposed that may capture the characteristics of situations involving terrain awareness. Thereby, it will also be indicated what information might be missing from existing terrain awareness enhancing avionics and suggestions will be made on how to enhance them using the Cognitive Systems Engineering (CSE) approach.

The structure of this paper is as follows. First, existing terrain awareness enhancing avionics are briefly described. Second, the properties of the cognitive approach to terrain awareness are briefly discussed, followed by the ecological approach. Then an ecological approach to pilot terrain awareness is elaborated by means of a work domain analysis. The result of this analysis is used to explore existing terrain awareness systems.

Technological Approach to Terrain Awareness

With today's technologies for computing and sensing, the designers of aviation human-machine interfaces (HMI) can almost freely create the worker interface. That is, there are virtually no constraints on the type and quantity of information or on the display format. Two examples of technology-centered systems that were developed to support terrain awareness are the Enhanced Ground Proximity Warning System (EGPWS) and the Synthetic Vision System (SVS). The goal of the EGPWS is to prevent CFIT accidents by enabling pilots to recognize hazardous terrain on a terrain awareness display (Figure 1) and confronts them with (aural and visual) advisories and commands to avoid a collision. The SVS provides a three-dimensional synthetic view of the surrounding world overlaid with essential flight status information (Figure 2).

Several independent research studies have shown that although such systems have proven to yield significant improvements in terms of safety (Breen, 1997), the lack of communication between those systems still requires the flight crew to mentally integrate information from different sources. This can still put pilots in a hazardous situation. On the one hand, an SVS shows the terrain topology, but lacks properties to communicate the ‘meaning’ that could support pilot understanding and extrapolation (Borst, Suijkerbuijk, Mulder and Van Paassen, 2006). On the other hand, a terrain warning system attaches and communicates relevant significance to the environment, but automates this process. In other words, the cognition is in the system and hidden from the pilot.

To investigate the effectiveness of the above systems in providing terrain awareness, they could be analyzed by using a cognitive approach and/or an ecological approach to terrain awareness.

Figure 1. Terrain awareness display of the Enhanced Ground Proximity Warning System.

Cognitive Approach to Terrain Awareness

The cognitive approach to SA is based on the classical human information processing stages that are believed to occur ‘inside the human head’. According to Endsley (2003) SA “*is the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*” (p. 13).

Figure 2. Synthetic Vision System (SVS).

These levels form the characteristics of user-centered system design to increase SA. As opposed to technology-centered design, the principles and processes of user-centered design are to organize technology 1) around the user’s goals, tasks, and abilities, 2) around the way users process information and make decisions, and 3) such that the user is kept in control and aware of the state of the system (Endsley, Bolté and Jones, 2003).

Putting Endsley’s definition of SA into the terrain awareness perspective, a pilot first has to perceive the terrain elements in the current situation. Based on that information, a pilot is said to comprehend the situation if the perceived terrain is recognized to form a threat to safety, or not. If the pilot is able to predict the time at which a possible collision will occur and is able to determine at what moment in time an escape maneuver must be initiated, the pilot is said to have projected the future status of the current situation. Recalling the technology-centered terrain systems, it can be said that the functionality of the EGPWS maps onto the comprehension and projection levels, whereas the SVS maps onto the perception level. User-centered design can be used to fill the missing levels in each of the two systems.

Ecological Approach to Terrain Awareness

Ecological psychology studies human-environment interrelations and assumes that human behavior is constrained by the environment they work in. Hence, ecological psychologists criticize the cognitive approach to situation awareness because of the primary focus on ‘awareness’ (Flach et al, 2004). Instead, they claim that a clear approach to obtain ‘awareness’ is accomplished by first starting to measure and define the stimuli and events of interest, that is, the ‘situation’. Then, it is assumed that the flexible and adaptive nature of humans will allow them to adapt to the situation. The strongest claim is that this approach can be helpful in coping with unexpected tasks not foreseen by system designers who start from a user-centered approach (Burns and Hajdukiewicz, 2004).

The ecological approach to SA defines a situation as "*a nested set of constraints that have the potential to shape performance*." (Flach et al, 2004). High and low SA is then reflected by the ability of the operator to chunk the constraints into a structured whole to make sense of situations. A useful tool to describe the constraints is Rasmussen's Abstraction Hierarchy (AH). This tool can be seen as a model/representation to structure purposes and constraints of the situation at different levels of abstraction (Figure 3). The relation between the levels is described as a 'why-what-how' or 'means-ends' relation (Vicente et al, 1992). Observing the work domain at a certain level defines the 'what' level. The level above defines the 'ends' that are realized by the 'means' defined on the level below.

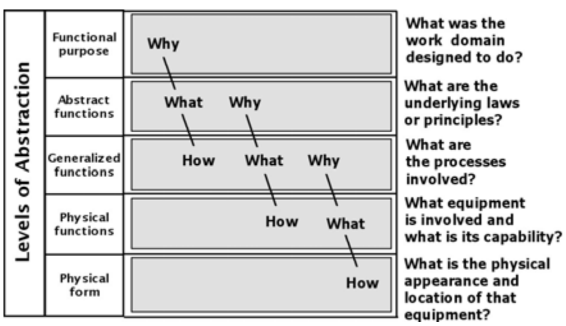

Figure 3. Abstraction hierarchy (Burns et al, 2004).

A theoretical framework for designing human computer interfaces for complex socio-technical systems that uses the ecological approach is called Ecological Interface Design (EID). EID was originally developed by Rasmussen and Vicente (1992) to increase the safety in process control work domains like nuclear power plants. The EID framework has been applied successfully in the aviation domain for the design of an interface for the approach-to-landing (Amelink, Van Paassen, Mulder and Flach, 2005) and a performance-based Vertical Situation Display (Borst et al, 2006).

The first step in designing ecological interfaces is to identify the purposes of the work domain. This is different from cognitive task analysis and physical task analysis, commonly found in user-centered design, in that it searches for information on how the environment works, regardless of the user's tasks. This can help to teach the user more about the work domain they operate in. By structuring this in an AH and by making the structure accessible to users, they are provided with a map of the situation such that they can decide for themselves what to do, how to do it and what alternatives for action there might be. Hence, conducting a work domain analysis can be a useful approach to provide the content and structure of an interface that aims at improving pilot terrain awareness.

Ecological Approach Benefits

The cognitive approach seems to be problematic for two reasons. First, it uses psychological constructs that are themselves not well understood and the processes to obtain SA appears to be relatively static and finite (Ulharik et al, 2002), whereas the principles and laws of physics describing the environment are usually better understood than psychological processes. Second, user-centered design can lead to task oriented systems that are only capable of coping with particular (and familiar) cases (Burns et al, 2004), whereas the ecological approach can help users to cope with tasks not foreseen by system designers.

An example ecological approach is the use of a total energy display in the approach-to-landing for aircraft (Amelink et al, 2005). Pilots think about their states and maneuvering capabilities in terms of speed and altitude. A work domain analysis has shown that these variables are combined in the energy state of the aircraft. Hence, making the pilots aware of the aircraft energy state allows them to chunk spatio-temporal constraints at a missing intermediate level of abstraction and therefore helps pilots to reason on their task in finding correct throttle and elevator settings.

The benefits of the ecological approach do not mean that the cognitive approach should be avoided. On the contrary, it is advised to use it complementary to ecological designs. Especially, Endsley's assessment techniques for SA can be useful for evaluating ecological interfaces (Burns et al, 2004).

Abstraction Hierarchy for Terrain Awareness

A work domain analysis for terrain awareness has been conducted in earlier work (Borst et al, 2006). 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 maneuvering performance. The result of the analysis is summarized in the AH, shown in Figure 4, and briefly described below.

Functional purpose

The purpose of the aircraft and its crew in the environment is to provide air transportation in a productive, efficient and safe way. In terms of terrain awareness, the safety purpose means to avoid terrain collisions.

Abstract function

In the present context, the energy laws that govern the aircraft's motion in the vertical and lateral plane, aircraft locomotion and the separation (spatial constraint) between the aircraft and the terrain are necessary to satisfy the system's purpose. Energy management can be seen as a representation for locomotion in terms of speed and altitude (Amelink et al., 2005). Energy management in flight can be defined as controlling the aircraft's total energy rate and the distribution between kinetic energy and potential energy. Awareness of the aircraft energy state and energy rate constraints helps to be aware of the current maneuvering capabilities to avoid terrain collision. In terms of terrain awareness, the most important constraint is the minimal potential energy of the aircraft to remain clear from the terrain.

Generalized function

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 into potential energy and visa versa. Aircraft maneuvering constraints are the optimal climb, optimal glide and the pull-up/push-over.

The first two maneuvers require a maximum lift-over-drag ratio. 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. Obstructions come back in the abstract function level in terms of spatial constraints.

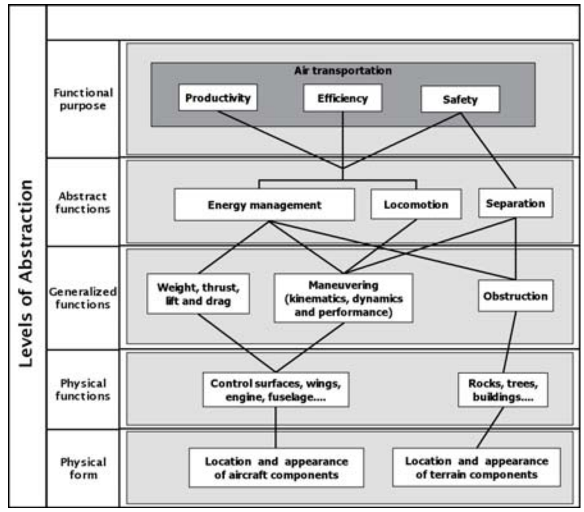

Figure 4. AH with 'means-ends' links for terrain awareness**.**

Physical function

At this 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 level above.

Here, the states and settings of the wings, control surfaces (elevator, ailerons, rudder, flaps and speed brakes), fuselage and engine serve the ends of lift, drag, thrust, weight and maneuvering. The rocks, trees, buildings, protrusions and undulations define the obstruction function of the terrain.

Physical form

This level contains the appearance, condition and location of each component that form the aircraft's geometry and specific shape of the terrain's profile.

CSE Analysis of Existing Terrain Avoidance Systems

In general, analyzing existing displays and how to enhance them (using a CSE/EID approach) is important in a domain such as aviation, where one cannot simply replace all current displays without taking previous training of pilots into account. Therefore, a detailed description of the relations and constraints in the AH and the way some of these are mapped onto the EGPWS and SVS is provided below.

EGPWS

The functionality of the EGPWS maps onto the AH as indicated in Figure 5. Considering the terrain awareness display (TAD) of the EGPWS, the two lowest levels in the AH are supported by means of a digital terrain database (DTED), which depicts external terrain constraints such as terrain data, obstacle data and airport locations on a plan view. On the abstract function level, the TAD shows the (vertical and horizontal) separation between the aircraft and terrain elements in distance and time by means of color-coding (Figure 1). Threatening obstacles on a collision course between 30 and 60 seconds ahead are depicted in bright yellow combined with an aural warning “Caution Terrain”, whereas threatening obstacles on a collision course less than 30 seconds ahead are depicted in bright red combined with an aural command “Terrain Terrain Pull-up”.

The remainder of the EGPWS operates on the generalized function level by means of look-ahead algorithms that make use of the internal aircraft constraints. The algorithms predict the future trajectory of the aircraft and compare that with terrain elements found along the predicted trajectory. If obstructions are found, the system determines when to initiate a pull-up and climb to clear the obstruction. To detect obstacles, the algorithm looks down, based on the current flight path angle and nearest runway, look ahead based on the ground speed, look aside based on turn maneuvers with 30 degrees bank angle, and look up by about 6 degrees (Honeywell, 2007).

The most important shortcoming of the EGPWS from a CSE perspective in providing terrain awareness is that the mapping of the internal aircraft constraints onto the external terrain constraints is automated by the system. The processes that lead to the result presented on the TAD are hidden from the pilot. Practice has shown that the system does not always do a good job at mapping the constraints and making the connections to the higher levels. The frequent false alarms associated with EGPWS confuse pilots about the situation at hand. As a result, pilots often ignore the warnings issued by the system (Pritchett, 2001). Furthermore, the internal aircraft energy management constraints are not supported by the EGPWS. These could help pilots to determine if enough energy can be generated within the time frame to clear an obstacle.

A way to improve terrain awareness in the EGPWS is by making the internal operation of the system on the generalized function level more transparent (Lenaerts, Borst, Mulder and Van Paassen, 2007). This can help pilots to understand why the system is giving an alarm and whether they should ignore it. Furthermore, showing the aircraft energy state constraints projected onto the terrain can help to determine if a pull-up and climb maneuver is possible to clear an obstacle (Sjer, Borst, Mulder and Van Paassen, 2007). If not, the pilot knows that a horizontal maneuver is required to avoid a collision.

SVS

The functionality of the SVS maps onto the AH as indicated in Figure 6. An SVS supports the two lowest levels in the AH by means of a three-dimensional visualization of the external terrain constraints such as terrain data, obstacle data and runway locations (Figure 2). The data source is the same as used in the EGPWS.

On the generalized function level, obstructions can be visually detected by means of the flight path vector and terrain elements. On the abstract function level, the horizontal and vertical separation between the aircraft and surrounding elements can be estimated from the perspective view.

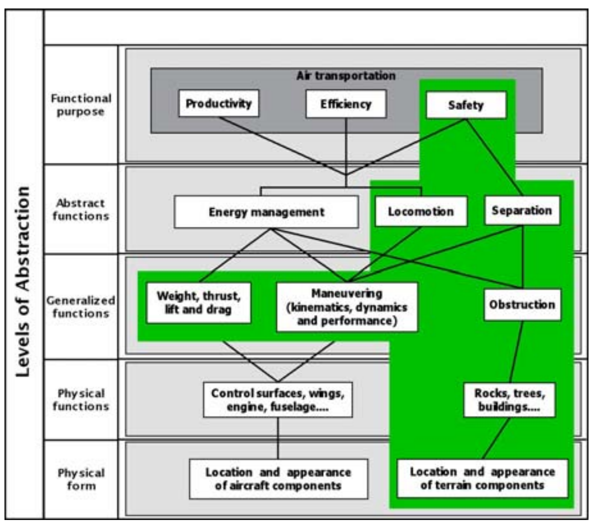

Figure 5. EGPWS functionality mapped onto the terrain awareness AH.

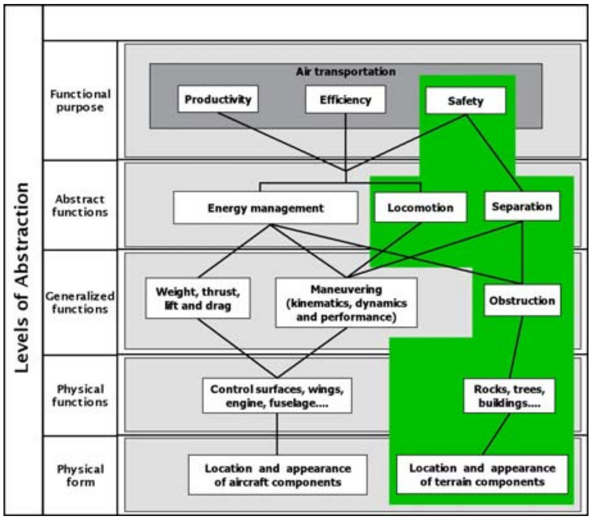

Figure 6: SVS functionality mapped onto the terrain awareness AH.

The most important shortcoming of the SVS from a CSE perspective in providing terrain awareness is that it only provides perceptual data and does not communicate its functional meaning. Pilots have to mentally map the internal aircraft maneuvering and energy constraints onto the external terrain constraints based on their knowledge of the aircraft's performance. Additionally, research has shown that a perspective view is biased. A relatively large field of view needs to be presented on a small display, which results in a distorted picture of the real environment. As a consequence, the terrain appears to be flattened and it is difficult to estimate distances to obstacles (Wickens, 2002). Hence, these perceptual biases may cause the flight crew to put the aircraft in an unsafe situation. Therefore, a SVS is still backed by an EGPWS to provide elementary meaning of the environment.

A way to improve terrain awareness in a SVS is to visualize and map the internal maneuvering and energy constraints onto the terrain. Additionally, the spatial separation constraints have to be compensated for the perceptual biases of the perspective view, for example, by means of communicating 'distance-to-collision' and 'time-to-collision' variables.

Conclusions

This paper discussed an ecological approach to pilot terrain awareness. The resulting abstraction hierarchy captured the characteristics of terrain awareness and was used to explore the informational content in both the EGPWS and SVS. From this analysis it became clear that, in order to provide adequate terrain awareness, the EGPWS has to communicate its constraints on the generalized function level. This can help pilots to determine why the system is giving an alarm and how to act. The SVS has to communicate the aircraft maneuvering constraints on the generalized function level to add a functional meaning to the terrain. Additionally, it should compensate for the perceptual biases of the perspective view by means of visually supporting separation estimations in distance (and time). Furthermore, both systems lack to visualize aircraft energy constraints on the abstract function level that are regarded as the fundamental principle in flying an aircraft. Supporting this can help pilots to reason on their current and possible escape maneuvers.

Future work will encompass the design and evaluation of 'ecological' interface overlays to enhance pilot terrain awareness in a SVS.

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