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EID for a Terrain-Aware Synthetic Vision System

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EID FOR A TERRAIN-AWARE SYNTHETIC VISION SYSTEM

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Synthetic Vision Systems (SVS) are likely to become an integral part of the commercial flight deck in the future. The introduction of SVS is driven by the need to increase safety, most notably to reduce Controlled Flight Into Terrain (CFIT). Various avionics companies and research institutes have successfully developed SVS that have shown to increase the pilot's situational awareness regarding to attitude, position and clearance relative to the terrain. To further increase the pilot's terrain awareness, we believe that more meaningful information should be added to the synthetic view on the outside world. This can be accomplished by showing the pilot how the external constraints (terrain) relate to the internal aircraft constraints (e.g. climb performance). Based on that information, a pilot can see for himself what an obstacle actually means to him in terms of possibilities to fly over it, and if not, what his alternatives for action are. A guiding principle to develop a more meaningful interface is the paradigm of Ecological Interface Design (EID). This paper presents the preliminary results of an aviation work domain analysis conducted with respect to the manual control task of guiding aircraft through a terrain-challenged environment. This work will serve as the foundation for developing an ecological SVS interface with the objective to truly enhance the pilot's terrain awareness.

Introduction

The dominant factor in all aviation fatalities can be attributed to Controlled Flight Into Terrain (CFIT) accidents (Breen, 1997). Analysis conducted by the Flight Safety Foundation (FSF) showed that 90% of the CFIT accidents occurred in Instrument Meteorological Conditions (IMC) (FSF, 2002), which indicates that current aircraft safety and warning systems are inadequate in providing situational awareness (SA). In order to prevent these types of accidents, intuitive systems are needed that continuously inform the pilot about his/her spatial orientation in terms of terrain and flight path. Synthetic Vision Systems (SVS) are believed to provide these features, because the hypothesis is that when you show the picture, the pilot will get better awareness. However, recent research indicates that a SVS alone does not inform the flight crew accurately enough about their clearance relative to the terrain (Schiefele, Howland, Maris and Wipplinger, 2003). Therefore, a SVS is still backed by advanced terrain warning systems like the (Enhanced) Ground Proximity Warning System ((E)GPWS). These systems address this issue by providing warning messages and procedural tasks to be executed in order to avoid terrain collisions. They have proven to be of inestimable value in reducing the number of CFIT accidents (Figure 1). However, in combination with a SVS the warn-act strategy used by the (E)GPWS is not a very elegant solution. The warning messages and procedural tasks it supplies, force the flight crew to be reactive rather than proactive and this could decrease the SA. It would be better to have a SVS that graphically presents the meaning of the terrain towards conduction a safe flight. Hence, a better integration of the (E)GPWS functionality into the SVS is needed.

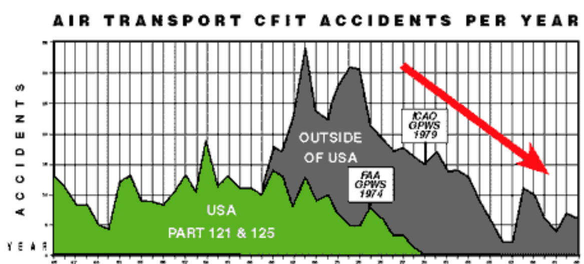

Figure 1 *The introduction of terrain warning systems such as the GPWS has reduced the number of CFIT accidents considerably.*

This paper investigates the possibility to use Ecological Interface Design (EID) to develop a SVS that adds more *meaning* to the computer-generated imagery of the outside world. This will be done by analyzing how the internal aircraft constraints, formed by its performance and maneuver limitations, relate to the external constraints formed by the terrain. Eventually, by visualizing the internal and external constraints on the SVS, the pilot will be much more aware of the margin within he can safely operate the aircraft.

The structure of this paper is as follows. First, the challenges that current SVS face are dealt with. Second, a definition for terrain-awareness is defined followed by the motivation for using the EID framework. Then, a test case in the vertical plane will be provided in order to analyze what is involved in flying over obstacles. Finally, the result of this analysis will be used to construct a preliminary AH of the manual control task when guiding an aircraft through a terrain-challenged environment.

Challenges of SVS

A SVS is basically a synthetic view of the surrounding world overlaid with essential aircraft status information (Figure 2). The main benefit of integrating all this information on a single interface is that pilots do not require diverting their visual attention away from external events and primary flight reference (Prinzel, Comstock, Glaab, Kramer and Arthur, 2004). Furthermore, it enables the flight crew to see the surrounding terrain even in low-visibility conditions. Therefore, SVS are believed to provide the adequate safety and SA enhancements needed to maneuver an aircraft through a terrain-challenged environment. By visualizing the terrain and obstacles ahead of the aircraft, the pilot can visually assess for himself whether or not an obstacle is a potential threat.

Figure 2 *SVS showing a perspective view on the surrounding terrain.*

Although a pilot can see the obstacles ahead of the aircraft, the SVS interface does not provide specific information what those obstacles actually mean to him. For example, the pilot sees on the SVS a mountain ridge at a certain distance ahead of the aircraft. What meaning has this mountain ridge to the pilot? Does it mean that the aircraft can fly over the ridge when it continues on the same course? If not, what kind of vertical maneuver will be required in order to fly over it safely? And at what moment in time should this maneuver be initiated? And if the aircraft will not be able fly over it due to its performance limitations, what kind of horizontal evasive maneuver will be required? Current SVS do not provide answers to these kinds of questions. They only show the pilots status and predictive information in terms of where they are and where they are going. Hence, the pilot himself is responsible for using his understanding of the aircraft's performance and its limitations in order to execute a feasible evasive maneuver. This task is further complicated by the relatively large Field Of View (FOV) adopted by many SVS, which makes it difficult to determine how close the aircraft is actually flying relative to the terrain and how fast the terrain is rising relative to the current altitude flown (Schiefele et al., 2003).

To give the pilot elementary meaning of the obstacles ahead of him, current SVS need to be equipped with Terrain Awareness Warning Systems (TAWS) or EGPWS. However, these warning systems were not designed to work specifically with a SVS interface. Therefore, the link between these systems and the SVS interface is not very elegant. Currently, when the EGPWS issues a caution, the caution is written as a message on the SVS interface (e.g. "Caution, Terrain" or "Terrain Ahead"). In case the EGPWS issues a warning, the warning message and what to do about it is also displayed on the SVS interface (e.g. "Terrain-Terrain, Pull Up-Pull Up"). It would be better to have a SVS that shows a graphical representation of the meaning of the terrain/obstacles ahead such that it will prevent the flight crew from ever coming in a hazardous situation where the EGPWS will be triggered. This requires the SVS to make the pilots aware of the aircraft's maneuver capabilities and limitations. Hence, the functionality of the EGPWS should be integrated into the SVS in order to increase the "terrain awareness" of the pilot.

Terrain Awareness

In general, keeping the SA of the flight crew at a high level is one of the most important jobs of the onboard aircraft systems. A definition for SA is '*the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future*' (Endsley and Garland, 2000). Applying this definition to the pilot's awareness of the environment, he must be able to perceive the obstacles ahead, determine what those obstacles mean to him and make decisions based on that information. Current terrain warning systems automate the process of comprehending the meaning of those obstacles and making decisions how to act accordingly. The computer-generated decisions are then presented to the pilot in the form of tasks to be executed. Although procedural tasks can reduce the pilot's mental workload, it can also reduce his awareness about the situation at hand. Hence, in order to increase the terrain awareness of the pilot, the onboard systems should actually *support* the pilot's process of comprehending and decision making instead of automating and hiding them. Real terrain awareness will only be obtained by not only showing the obstacles, like a SVS currently does, but also by continuously showing the aircraft's performance and maneuver limitations such that a pilot can see for himself whether a situation is a threat to safety or efficiency, and can also see what possibilities and alternatives there are to escape from this. However, it can be expected that an EGPWS will still be needed as a warning system. But by adding meaningful information about the terrain and the aircraft's performance to the SVS interface, it can be imagined that an EGPWS caution/warning will hardly ever be triggered, and when it is triggered, the pilot fully understands why. A guiding principle to develop such an interface is the paradigm of Ecological Interface Design (EID).

Reasons for Using the EID Framework

EID is a theoretical framework for designing human computer interfaces for complex socio-technical systems. The term 'ecological' reflects the need for incorporating environmental constraints of the application domain into the design of an interface. It is important to mention that the framework describes more or less a number of guidelines to analyze the cognitive work domain rather than giving a specific recipe to determine what the interface should look like.

EID is 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 a fuel and engine systems interface (Dinadis and Vicente, 1999) and an interface for the approach-to-landing (Amelink, Van Paassen, Mulder and Flach, 2003).

The goal of EID is to design interfaces that reveal the affordances of the work domain in such a way that they support each level of cognitive control. The property that makes EID so interesting is that it allows the operator to freely choose whatever means are available to solve a problem, or to apply any control strategy that satisfies the system goals based on the operator's preference and expertise. Furthermore, it assists the operator in constructing a mental model of the system. In contrast to interfaces based on procedural tasks, which only tell the operator what to do by giving *directions*, an EID interface provides a more convenient "*map*" of the system/situation so the operator can decide form himself what to do, how to do it and what his alternatives are. A well designed EID interface could even support the operator in coping with unanticipated events, which makes the interface more robust than interfaces or systems based on pre-programmed algorithms. Hence, this makes the EID framework a suitable candidate for designing a SVS interface or SVS overlays that will truly increase the pilot's terrain awareness.

EID for Supporting Terrain Awareness

System boundary

In order to successfully conduct a work domain analysis, a precise definition of the system's boundary is needed first. For this preliminary work the focus will be limited to the manual control task in the vertical plane of guiding an aircraft through a terrain-challenged environment. Therefore, the primary goal or "functional purpose" of the system (the aircraft) in the environment will be to safely operate it without colliding with terrain, or simply 'terrain avoidance'. In order to further analyze the work domain, the constraints that influence the system goals must be identified. These will primarily consist of external (terrain) and internal (aircraft) constraints. Most of the internal aircraft constraints have already been identified (Amelink et al, 2003). A brief summary of those results will be provided in the following text.

The Role of Energy in Flying

Pilots unconsciously act on the energy state of the aircraft in order to control it effectively. By experience, a pilot knows that he has enough room for safe maneuvering when he flies high and fast. From there, a pilot can safely exchange altitude to gain speed or the other way around (Langewiesche, 1944). They will especially avoid flying low and slow as this means that e.g. they do not have enough freedom to pull-up and gain altitude at the cost of speed in order to avoid obstacles or terrain. In essence, this mental model of maneuvering awareness is directly related to the awareness of the energy state of the aircraft. Hence, pilots like to have lots of total energy such that they have enough opportunity, as dictated by the law of conservation of energy, to exchange kinetic energy (speed) and potential energy (altitude) for maneuvering. This means that in the vertical plane the pilot essentially plays the role of energy manager of the aircraft.

Aircraft Manual Control Task

The aircraft manual control task with respect to energy has already been investigated. To manage the energy state of the aircraft, the pilot will generally apply two control strategies. In the first strategy, the throttle is used to control the vertical flight path (altitude) and the elevator to control speed. In the second strategy, the elevator is use to control the vertical flight path and the throttle to control speed. In terms of energy, the pilot actually controls with the throttle the total energy rate. The elevator is used to distribute the total energy between potential and kinetic energy. An abstract view of the manual control task (in the vertical plane) can be depicted as "the reservoir analogy" (Figure 3).

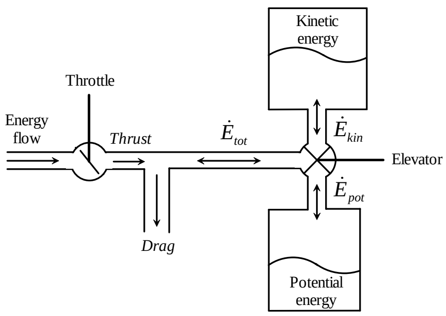

Figure 3 *The reservoir analogy, in which the throttle regulates the total energy flow and the elevator distributes the total energy flow between kinetic and potential energy (Amelink et al, 2003).*

Now that the aircraft manual control task is described in terms of energy, it remains to describe how this can help the pilot to maneuver over an obstacle. Clearly, the above analysis describes more or less the physics behind piloting itself, but it does not provide any information on how a pilot uses this to construct his mental model of the aircraft's maneuver capabilities to avoid terrain/obstacles. Therefore, in order to enhance the pilot's terrain awareness, he should continuously be confronted with the aircraft's performance and maneuver limitations based on its energy state.

The Role of Energy in Terrain Avoidance

With respect to terrain collision the position of the aircraft relative to the terrain is an important factor. Besides the position, also the aircraft's performance will play an important role. In the vertical plane it can be imagined that the energy state of an aircraft determines its climbing capabilities. Whether an aircraft is capable of safely passing an obstacle depends on the total amount of energy it possesses. If it is sufficient, enough kinetic energy can be exchanged by potential energy to be able to pass over the obstacle. This exchange is only limited by the minimum kinetic energy of the aircraft, referring to its minimum speed (stall). However, no aircraft is capable of exchanging its energy instantaneously. The exchange is bounded by the performance limitations of the aircraft and this also determines at what moment in time the pilot should initiate the evasive maneuver (Figure 4).

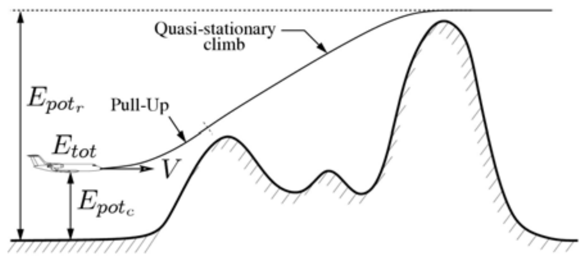

Figure 4 *How fast an aircraft is able to exchange its kinetic energy into the potential energy level that is required ($E_{pot,r}$) to safely pass over the terrain is limited by the pull-up maneuver and climb performance.*

Analysis showed that in the vertical plane three types of dynamic maneuver boundaries are important: the pull-up/pull-down maneuver, the optimal quasi-stationary climbing flight and the optimal gliding flight in case of total engine failure.

Performance Limitations

Pull-up/Pull-down Maneuver. As mentioned before, an aircraft will never be able to exchange energy instantaneously. When there is an excess (deficiency) of kinetic energy, a pull-up (pull-down) maneuver is used to initiate the exchange of energy. The pull-up or pull-down maneuver can be approximated by a circular maneuver (in the vertical plane). Analysis showed that when the vertical load factor of the aircraft will be limited to a certain value, the radius of the circle will increase with increasing speed. Hence, in high speed conditions, the pull-up maneuver will be important in avoiding terrain collision.

Optimal Climbing Flight. In general, there are three types of optimal climbing flights (Ruijgrok, 1996):

1. **The fastest climb** or least time to climb,
2. **The steepest climb** or minimum range during climb,
3. **The most economical climb,** where the smallest amount of fuel is consumed.

Here, the second type of climb is of highest concern since the functional purpose of the system is to increase safety and avoid terrain collisions at all costs. The steepest optimal climb will generally be executed by setting the thrust to climb-power and holding the indicated airspeed corresponding to this type of climb. This results in a maximum climb angle.

Optimal Gliding Flight. In general, there are two types of optimal gliding flights (Ruijgrok, 1996):

1. The gliding flight with the **longest duration** or flight at the minimum rate of descent,
2. The gliding flight resulting in the **maximum range** or flight at the minimum angle of descent.

Here, the second type of optimal gliding flight is of highest concern since it will not be interesting to know how long an aircraft is able to stay in the air. The optimal gliding flight will generally be executed by holding the indicated airspeed corresponding to this type of descent (typically, at which the drag is minimal).

The two optimal flights and the pull-up/pull-down will serve as the system's upper (climb) and lower (descent) performance boundaries (Figure 5). These boundaries can be used to detect a possible threat to safety and what the pilot can do to circumvent this threat and what his limitations are. For example, if a mountain rises steeper than the steepest climb angle reachable by the aircraft, the pilot is in trouble and should perform an evasive maneuver in the horizontal plane.

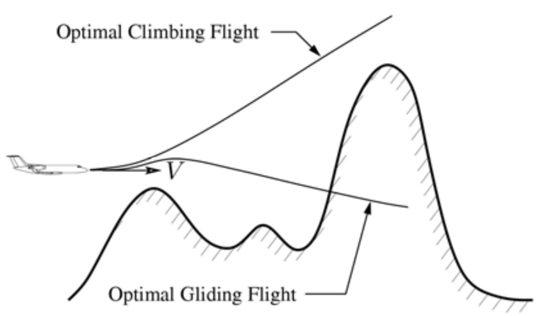

Figure 5 *The performance limitations can be used to detect a possible threat to safety. Here, the aircraft can still fly over the mountain ridge when initiating the optimal climb. However, in case of total engine failure an evasive maneuver in the horizontal plane will be required.*

A Preliminary Abstraction Hierarchy for Aircraft Terrain-Avoidance

In EID, the abstraction-decomposition space will serve as a representation of the work domain. The space consists of two dimensions, with along the top the *decomposition* (or *part-whole*) hierarchy and along the side the *abstraction* (or *means-ends*) hierarchy. In the decomposition space, each level represents a different granularity of the same work domain. Moving from left to right is equivalent to "zooming-in" because each successive level provides a more detailed 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. In general, higher levels in the AH represent the work domain in terms of its functional properties, whereas lower levels represent it in terms of its physical form.

The AH in this preliminary work will describe the work domain of aircraft terrain-avoidance in the vertical plane. The names of the levels are left the same as in Amelink's work. The content of the AH, for the analysis described in this paper, will be briefly discussed below and is summarized in Figure 6.

Functional Purpose

In general, the purpose of the system, i.e. the aircraft, in the environment is to fly to some destination and let it conduct a safe flight. Hence, the main goal is to reach the destination without colliding into terrain.

Abstract Function

This level describes the energy relations that govern the aircraft's movement in the vertical plane along with the energy of the terrain. In order to satisfy the goals of the level above, the potential energy constraint of the terrain and the aircraft's energy state are important.

Generalized Function

This level describes the aircraft maneuver functions and terrain shape function. The lift, weight, drag and thrust determine the constraints on the aircraft maneuver capabilities (pull-up/pull-down, optimal climb and optimal glide). The terrain's altitude profile determines the environmental constraint that the aircraft has to consider in order to satisfy the goals of the level above.

Physical Function

This level describes the physical implementation of the aircraft and terrain itself. They are the means that serve the ends of the level above. It includes the wings, control surfaces, power plant (engine) and the terrain's profile.

Physical Form

This level contains the geometry of the aircraft and the terrain's shape.

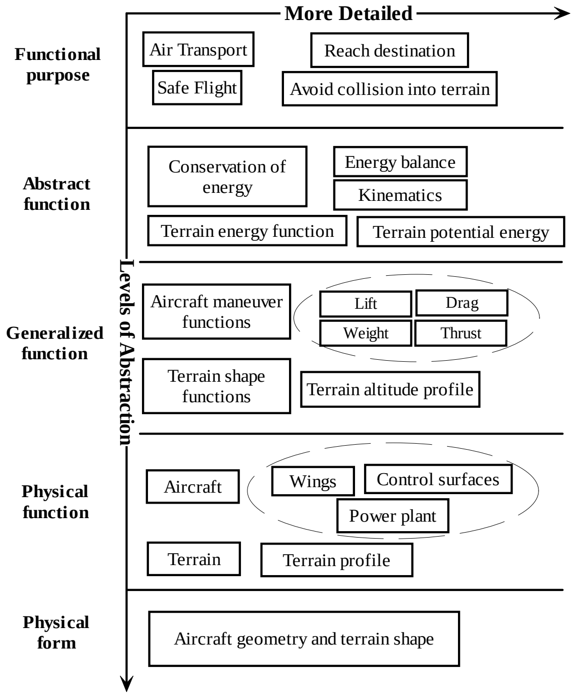

Figure 6 *A preliminary Abstraction Hierarchy (AH) for the aircraft manual control task in the vertical plane with respect to avoiding terrain collision.*

Conclusions

This paper can be considered to be work in progress. The preliminary AH has structured the problem of terrain collision avoidance in the vertical plane with respect to the external constraints (terrain) and internal aircraft constraints. The ultimate goal is to develop an ecological SVS interface that will assist the pilot in building a mental model of the aircraft maneuver capabilities in order to conduct a safe flight without colliding into terrain. The above analysis and AH reveals the dynamic aircraft maneuver limitations that has to become part of the interface. It is expected that the ecological SVS interface can be applied in a larger range of application domains than the EGPWS, because the analytical foundation of the interface's content contains more of the work domain.

The next step will be to evaluate a low-altitude terrain following task with a display concept based on the above analysis. Its purpose will be to determine to what extend the pilot is capable of avoiding terrain collisions with and without support by the interface.

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