Design of an Ecological Vertical Separation Assistance Cockpit Display

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A tactical navigation support tool was designed to effectively deal with conflict situations in the vertical plane, while preserving travel freedom as much as possible. Based on Ecological Interface Design principles, the Vertical Separation Assistance Display is developed as an extension to the existing Vertical Situation Display. Functional information is presented via overlays that show pilots how their vertical maneuvering possibilities are constrained by ownship performance, and by limits imposed by surrounding traffic. A questionnaire-based evaluation shows that the ecological overlays considerably improved pilot traffic awareness in vertical conflict situations.

Airspace congestion and delays force airspace authorities and governments to explore more effective ways to manage air transportation. Novel Air Traffic Management concepts such as the Next-Generation Air Transportation System (FAA, 2008), and Single European Sky ATM Research (SESAR Consortium, 2007) initiatives, advocate the potential benefits of adopting a more flexible approach to ATM. In the future, during cruise flight aircraft may obtain more freedom to optimize their trajectories by allowing 'direct routing' and 'cruise climb'. In order to reduce the workload of the air traffic controller in this situation, the separation task is delegated to the flight deck. The problem of how to assist pilots in this task has attracted great interest in the research community, and several solutions have been proposed in the past decade (Merwin & Wickens, 1996; Johnson et al., 1997; Thomas & Johnson, 2001; Hoekstra, November 2001).

Many of these proposed airborne separation assistance tools provide pilots with *explicit*, ready-to-use automated solutions. This has proven to be effective as far as providing conflict resolution and reducing workload are concerned. However, the use of explicit solutions holds pilots back from exploring solutions other than those presented, and therefore may preclude full exploitation of airspace capacity. Also, the explicit advice often fails to show the 'cognition' behind the automation that deals with the separation problem, and requires cognitive effort from pilots to mentally integrate the different pieces of traffic-related information before they fully understand the conflict situation.

In this paper an alternative airborne self-separation assistance tool for the vertical plane is described. Adopting the principles of Ecological Interface Design (Vicente & Rasmussen, 1992), the Vertical Situation Display is extended with graphical overlays that present functional information regarding how the own aircraft vertical maneuvering possibilities are constrained by the ownship vertical flight performance limits, and by limits imposed by surrounding traffic. The resulting display, the Vertical Separation Assistance Display aims in particular at supporting pilots in maintaining a high level of traffic Situation Awareness (Endsley, 2000).

Ecological Approach

Ecological Interface Design (EID) is an interface design framework that addresses the cognitive interaction between users and complex socio-technical systems, and was originally applied to process control (Vicente & Rasmussen, 1992). Its approach to interface design gives priority to the worker's environment, concentrating on how it imposes constraints on the work. EID principles have been applied to support pilots in various tasks, including an interface for horizontal separation assistance support (Van Dam, Mulder, & Van Paassen, 2008). The Vertical Separation Assistance Display (VSAD) presented in this paper can be considered the 'vertical' complement of this earlier design.

Such an 'ecological' separation assistance tool would aim to visualize the separation problem in such a way that it reflects the cognition needed to cope with the conflict geometry in motion, while at the same time preserving maximum pilot maneuver freedom. EID is a design framework that provides useful tools to achieve these objectives. When adopting its design guidelines, two main questions need to be addressed (Vicente & Rasmussen, 1992). First, how can the content and structure of the work domain be described in a psychologically-relevant way? And second, in which form can this information be effectively communicated to the operator? In this paper, these questions are addressed through a Work-Domain Analysis, followed by an ecological interface design, which aims to visualize the constraints and means-end relationships in the environment in such a way, as to fully take advantage of the human capacity to directly perceive, and act upon cues from the environment.

Work Domain Analysis

The first step of ecological interface design consists of a workspace analysis, using Rasmussen's Abstraction Hierarchy (Rasmussen, 1986). Using the Abstraction Hierarchy (AH), the principal work domain functions and constraints can be identified. The boundaries of the work domain in this study are restricted to the task of self-separation in the vertical plane, during cruise flight. The pilot task consists of the on-board path (re-)planning of climb or descent maneuvers, with the main goal of separating themselves from other traffic in the vicinity.

Minimal separation can be defined using a Protected Zone (PZ), a virtual coin-shaped area, around each aircraft, which is to remain free of other aircraft. General dimensions for the PZ are: 5 NM horizontally, and 1000 ft vertically. A conflict occurs when two aircraft would enter each other's PZ at some instance in the near future, if neither aircraft changes its flight path. Many different ways of detecting a conflict and providing potential resolutions have been proposed; for a review see Kuchar & Yang (Kuchar & Yang, 2000).

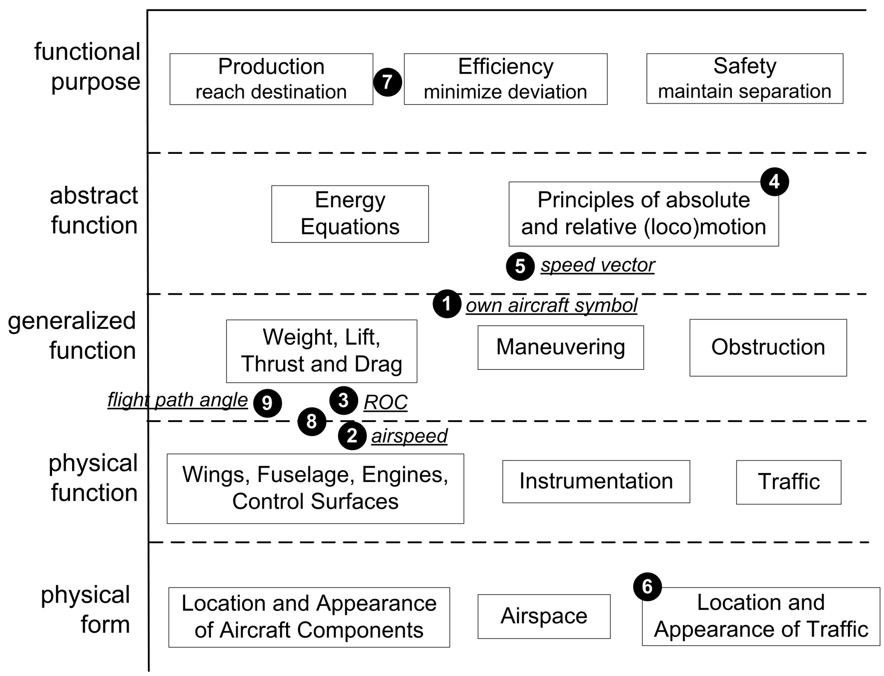


Figure 1: Abstraction Hierarchy for tactical navigation in the vertical plane.

Figure 1 shows the Abstraction Hierarchy that has been developed for the tactical navigation in the vertical plane. The abstraction hierarchy is a stratified hierarchical description of the workspace, defined by means-end relationships between the adjacent levels. Along the vertical axis, the five levels of the AH represent the constraints at decreasing levels of abstraction, starting at the top with the purpose(s) for which the system was designed, all the way down to the spatial topology and appearance of the components that make up the system on the bottom level. Along the horizontal axis, constraints are arranged from internal constraints on the left, to external constraints on the right.

At the functional purpose level, the purposes of the system are defined. As for most transportation systems, three main purposes can be identified at this level, production, efficiency and safety. Here, safety relates to staying within the performance envelope, maintaining separation. The efficiency purpose is to resolve and prevent conflict situations by minor deviations of the planned flight path. The production goal is to fly towards the destination of the programmed flight path. The abstract function level in this case contains the general physical laws that dictate locomotion. The general function level describes how the causal laws at the abstract function level are achieved, independent of the actual implementation of the system. Properties such as weight, lift, thrust and drag all impose internal constraints on aircraft behavior. Obstruction describes other traffic as external constraints. The physical function level describes the various components, and their capabilities and states, and at the physical form level the appearance and location of components, the airspace, and other aircraft are described.

Internal Aircraft Constraints

The internal constraints are defined by minimum and maximum speed and thrust. The minimum velocity is the stall speed. The maximum velocity is the never-exceed speed. Two particular figures of merit related to maximal thrust are the steepest (SC) and fastest climb (FC). SC flight establishes the maximum flight-path angle that an aircraft can achieve. FC occurs when the rate of climb is maximal. In gliding flight, aircraft fly on idle thrust. The minimum and maximum thrust settings yield non-linear contour lines for the flight-path at various airspeeds, Figure 2. These contours depend on aircraft type, configuration, and altitude. In this paper, a model of the Cessna Citation I is used, trimmed at 16,405 ft and 292 kts True Airspeed (TAS), in clean configuration.

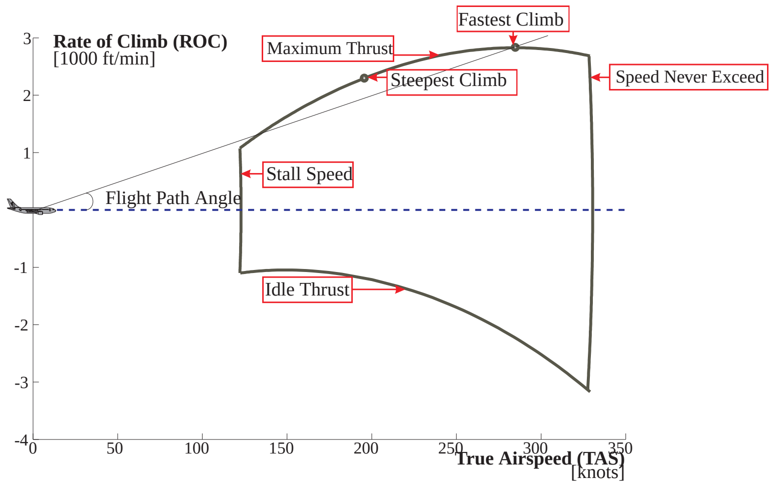
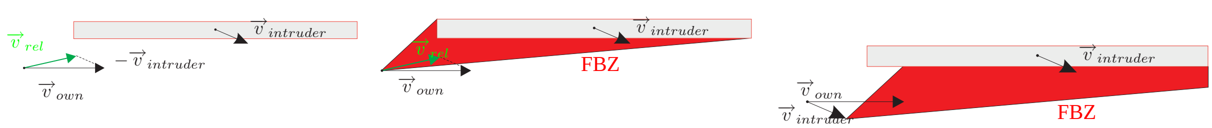


Figure 2: Performance envelope of the Cessna Citation I, in TAS/ROC state space.

External Traffic Constraints

The position and motion of ‘traffic’ in the vicinity of the own aircraft determine the external constraints on the maneuvering of the own aircraft. A conflict will occur if the speed vector relative to the intruder points in the direction of the intruder aircraft protected zone, Figure 3. This can also be visualized by drawing a beam-shaped area, originating from the ownship position and tangent to the outer sides of the rectangular shape of the protected zone, from hereon called the ‘Forbidden Beam Zone’ (FBZ). If the tip of the relative velocity vector lies within or moves into this FBZ, separation will eventually be lost. In order to be able to combine the internal and external constraints, the external constraints are translated to the aerodynamic reference frame. In this frame, the conflict geometry is presented from the perspective of the own speed vector, by translating the FBZ over the intruder’s speed vector, see Figure 3(c). Then, the pilot should simply move the own aircraft speed vector out of the FBZ to resolve the conflict. If multiple conflicts occur simultaneously, the FBZ’s are superimposed after being translated and presented in the absolute velocity plane. This allows pilots to choose a ‘global’ solution that avoids all FBZ’s at once. The combination of the performance overlay and the conflict geometry overlay is called the State Vector Envelope (SVE) (Van Dam et al., 2008).



(a) Relative velocity (b) FBZ in the Relative Plane (c) FBZ in the Absolute Plane

Figure 3: Definition of the Forbidden Beam Zone (FBZ), in the relative and absolute velocity planes.

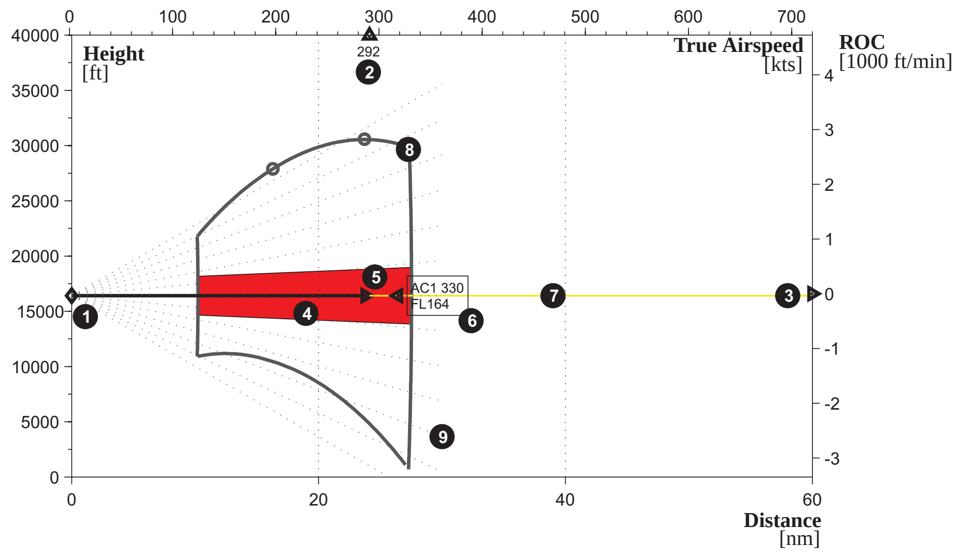


Figure 4: The Vertical Separation Assistance Display (VSAD).

Interface design

The VSAD has been implemented using an existing VSD standard (Prevot & Palmer, 2000), adding layers of functional information identified in the previous section. Since the VSD describes vertical space in terms of distance and height, a transformation of the vertical speed towards height and the horizontal speed towards distance was needed. For this purpose, a horizontal and vertical speed overlay was added on the VSD. The scaling of the speed overlay was based on a prediction time of five minutes, a prediction interval that is frequently used for the detection of conflict situations (Hoekstra, November 2001; Kuchar & Yang, 2000).

Figure 4 shows the VSAD. It integrates the performance envelope of Figure 2 and the conflict geometry visualization of Figure 3(c) in a conventional VSD. Here, ❶ is the own aircraft symbol, ❷ is the speed indicator, ❸ is the ROC indicator, ❹ is the conflict geometry overlay, ❺ is the own speed vector, ❻ shows the intruder aircraft with a label containing callsign, true airspeed and flight level, ❼ shows the own aircraft programmed flight path, ❽ is the performance envelope overlay, transformed to the 5 minute time interval, and ❾ shows potential flight path angle settings in one-degree intervals. These numbers also correspond with the numbers in the abstraction hierarchy, Figure 1. The use of the prediction time means that the performance envelope of the aircraft represents any location the aircraft can reach within that time frame. The speed vector represents a trajectory predictor within the VSAD, based on the current state. Three markers for the Rate of Climb (ROC), airspeed and altitude give the pilot an additional reference to this prediction.

Evaluation

To check whether the Vertical Separation Assistance Display is set to meet its main goal of supporting pilot traffic SA, an evaluation was conducted, with twelve professional airline pilots, with extensive experience with glass cockpits. Pilots were shown movies of 20 to 30 seconds, illustrating dynamically a certain conflict situation in the vertical plane. Using a set of questionnaires before and after the experiment, pilot situation awareness was measured in a systematic fashion. Two display configurations were compared: the Vertical Situation Display (VSD), and the Vertical Separation Assistance Display (VSAD). Ten scenarios were designed that were considered to best represent six ‘typical’ conflict situations. These consisted of opposite maneuvers, parallel maneuvers, overtake maneuvers, situations with multiple intruders, and situations where no conflict is present. For each scenario, between 1 to 5 intruder aircraft were simulated. The overtake scenarios, or in fact, any scenario where traffic was not visible on the VSD, were considered ultimate test-cases for one of the benefits of the VSAD, although here a comparison with the VSD is not possible. It was hypothesized that the traffic SA scores depend neither on the number of intruder aircraft, nor on the conflict situation. Also, the VSAD was hypothesized to significantly improve pilot traffic SA.

Results and Discussion

Regarding their flight strategy, 7 of the 12 pilots indicated that, primarily based on their day-to-day experience, they preferred to resolve a conflict by changing velocity, not altitude. This is contrary to pilots' preferred strategies in the horizontal plane, collected in previous work on the horizontal separation assistance display (Van Dam et al., 2008), where pilots indicated that they preferred heading changes over speed changes. Pilots further commented that during cruise flight it is often impossible to climb higher or fly any faster. Note that this would indeed be shown by the VSAD, through the performance envelope overlay, but none of the scenarios involved cruise flight near maximum altitude.

Rather surprisingly, the answers from the pre- and post-questionnaires indicate that pilots were more appreciative of the performance envelope overlay in the VSAD *before* the dynamic questionnaire. In the post-questionnaire, 4 out of 12 pilots judged the overlay to be 'too theoretical', whereas another 2 pilots found that not all boundaries were necessary. Tentatively, this reflects their preferred flying strategy to resolve conflicts through changing speed only, a strategy for which the aircraft climbing capability, presented through the minimum and maximum thrust contours, would be irrelevant.

Linking of the conflict geometry to the conflicting aircraft was initially thought to be easy if the number of intruder aircraft stays limited. After the dynamic questionnaire, however, 8 out of 12 pilots found it hard to detect which conflict geometry belongs to which intruder aircraft. It can be concluded that, generally, pilots found it easy to attach information presented by the VSAD with data from the PFD. Some pilots (3) found it unnecessary to have any additional links between both displays, 6 other pilots appreciated the speed vector presentation in the VSAD though.

Regarding pilots' overall opinion about their traffic awareness with the VSAD, mixed responses were obtained. Whereas 7 pilots were more or less satisfied, 5 pilots were sceptical about the VSAD; one pilot found it 'too complicated', 4 pilots commented that, in actual flight, they expect to simply lack the time to check all information provided. Note that, in contrast to the decline in pilot appreciation of the VSAD overlays during the experiment, pilots became more supportive about the VSAD as a tool to improve their traffic awareness.

Some pilots commented on the symbology used to show whether intruder aircraft were climbing or descending. They suggested to adopt more TCAS-like symbology, like the use of an 'arrow up' when the intruder aircraft is climbing more than 500ft/min, to be positioned near the intruder label. Similar to TCAS, pilots also recommended to show the difference in height rather than the intruder aircraft flight level in the label. To become better aware of the time-to-conflict, pilots proposed the use of a color scheme: 'yellow', when conflict was more than 3.5 minutes away; 'orange', conflict 2 minutes away; 'red', conflict 1 minute away and prepare for traffic advisory. Subjective pilot SA ratings also indicated that pilots found themselves less aware of the time-before-conflict, and that they had difficulty in understanding what intruder belonged to what FBZ on the VSAD conflict geometry overlay.

Despite the overall lack of appreciation, pilot SA and meta-cognition scores were significantly larger with the VSAD. The averaged SA and meta-cognition scores indicate that pilot SA is higher with the VSAD as compared to the VSD, at all levels of SA and meta-cognition. These effects were all highly-significant ($p < 0.001$), except for the meta-cognition scores at the 'perception' level, where the difference between VSD and VSAD was small and not significant. SA and meta-cognition scores are lowest at the comprehension level, for both displays, but especially for the VSD. The benefits of the VSAD appear in particular at the levels of comprehension and projection, as was hypothesized. The fact that the meta-cognition scores are rather low with the VSD at these levels indicate that pilots often gave the wrong answer to SA queries that regarded a potential conflict's risk level, the time before initiating an escape maneuver, and also the understanding of how many aircraft would cause a potential conflict. Although the scores with the VSAD are higher, on average they do not reach the level of 'fairly sure'. This illustrates that, although the pilots' answers to the SA queries were generally correct with the VSAD, pilots were still unsure about their understanding of the situation. Tentatively, working with the VSAD for a longer time might increase these scores considerably, as the pilots would gain more experience and confidence in using the novel ecological overlays.

What also became clear is that whereas the SA and meta-cognition scores remain more or less the same for the VSAD, they decrease significantly with the VSD when the number of intruder aircraft increases. This causes a significant effect of 'intruder' (total SA: p=0.018; total meta-cognition: p=0.021), and a significant two-way interaction 'display $\times$ intruder' for the SA scores (p=0.006). The interaction was not significant for the meta-cognition scores. This result supports our hypothesis that with the VSAD, pilot SA does not depend on the number of intruder aircraft. In fact, remarkably, the scores with the VSAD are highest for the situations with the largest number of intruders, a non-significant effect, however.

Conclusions and Recommendations

Pilot Situation Awareness scores improve significantly with the ecological overlays presented on the Vertical Separation Assistance Display. These overlays give pilots a better sense of what maneuvers are possible to assure separation from surrounding traffic. Traffic awareness increases in particular at the higher levels of comprehension and projection. Awareness scores did not drop when the number of intruder aircraft increased, nor were they affected by changing conflict situations. The relatively low meta-cognition scores reflect the fact that although pilots were generally correct in answering the situation awareness queries in the questionnaires, they were still rather unsure about their answers. Extensive training with the novel display concepts are expected to increase pilot confidence and appreciation considerably. The evaluation further showed that in particular the conflict geometry overlay needs improvement, as pilots had difficulties in relating its components to the various intruders. Also, part of the display 'space' should be used to show 'what is behind' the own aircraft. Future research should also investigate the influence of maneuvering dynamics on the prediction times. It is recommended to conduct an extensive flight simulator evaluation, where pilots are more actively involved in maintaining safe separation.

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