2009

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TOWARDS A FOUR-DIMENSIONAL SEPARATION ASSISTANCE COCKPIT DISPLAY

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An initial design of a tactical navigation support tool is proposed, designed to integrate horizontal and vertical separation assistance tools into one display. A novel representation of the separation problem, based on Ecological Interface Design, presents external conflict and performance constraints on an extended, wide-screen Primary Flight Display. Key issues in the current design are discussed, and an experiment is proposed to evaluate the display concept.

In the current airspace environment, congestion problems are expected in the near future, due to rapidly increasing amounts of traffic. Because of the rigid nature of the airspace, which is divided in fixed volumes and route structures, this growth will result in higher workload for air traffic controllers, and reduced efficiency of trajectories. New concepts for Air Traffic Management, such as SESAR, permit a flexible use of airspace, with airborne determination of user preferred trajectories (RTCA, 2002a; SESAR Consortium, 2007). This flexible use is expected to increase airspace capacity, and reduce air traffic controller workload. However, because the separation task is shifted from the air traffic controller to the pilot, it is expected that the pilot needs to be assisted in this task.

Traditional systems, such as Predictive Airborne Separation Assurance Systems (P-ASAS) (Hoekstra, 2001), have been developed to assist pilots in their task of self-separation. Generally such systems support the pilot by presenting a limited set of explicit, 'ready-to-use', avoidance maneuvers as a solution to a separation conflict. Such automated systems have proven to be effective in terms of conflict resolution and workload reduction, but they limit the pilot in exploring other solutions, and therefore, may prohibit full exploitation of the travel freedom offered by the airspace environment. Also, in a complex traffic environment, non-routine situations may arise, that may not have been foreseen in the automation design. In these exceptional cases, the pilot's ability to improvise is vital for successful conflict resolution. It is therefore of key importance that automation and instrumentation promote a high level of situation awareness.

At Delft University of Technology, extensive research is being performed on ecological interface design of Airborne Separation *Assistance* Systems: displays designed to visualize the affordances the airspace provides. These displays assist the pilot in their task of self-separation, without relying on resolutions provided by automation. Previously, several concept displays have been developed, for separation assistance in the horizontal plane, as well as the vertical plane (Heylen, van Dam, Mulder, & van Paassen, 2008; van Dam, Mulder, & van Paassen, 2008). Although these displays successfully support pilot decision-making in the task of self-separation, they still map the essentially four-dimensional problem (space and time) onto two displays. This article presents the initial iteration of design of a novel four-dimensional Separation Assistance Interface (referred to as 4D-SAI).

Ecological Approach

Ecological Interface Design (EID) is a design paradigm that originates from the domain of process control. It addresses the cognitive interaction between humans and complex socio-technical systems. Its approach to interface design gives priority to the workers environment (termed 'ecology'), focusing on how the environment poses constraints on the worker (Vicente & Rasmussen, 1992). Rather than taking the worker's cognitive capabilities as a starting point, EID tries to identify what elements in the environment shape the operator's behavior: The interface should reveal the possibilities and constraints afforded by the work domain. In other words, EID promises a more systematic approach to unambiguously define 'what is the situation' the pilot should be 'aware of' (Flach, Mulder, & van Paassen, 2004). By focusing on the affordances and constraints posed by the work domain, the worker can be supported in actions that go beyond the worker's anticipated tasks.

EID consists of two steps. The first step consists of determining the goal-relevant properties of the work domain (i.e., what to display), and the second step addresses the actual interface presentation (i.e., how to display). In the first step, a workspace analysis tries to identify functionalities, constraints, and means-end relationships withing the work domain. The main tools for this analysis are the Abstraction Hierarchy (AH), and the Skills, Rules, Knowledge taxonomy (SRK), both developed by Rasmussen (Rasmussen, 1983, 1985). Following the workspace analysis, EID 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, 1985). The abstraction hierarchy is a stratified hierarchical description of the workspace, defined by means-end relationships between the adjacent levels, see Figure 1. 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 (Rasmussen, 1985; Bisantz & Vicente, 1994). Along the horizontal axis, components and constraints are arranged from internal elements on the left, to external elements on the right.

At the functional purpose level, the goals of the system are defined, which in the case of flight in general, are flying safely, productively, comfortably and efficiently through unmanaged airspace. Aside from issues such as staying within the flight envelope, safety in aircraft locomotion is assured by maintaining sufficient separation from potentially hazardous objects, such as other aircraft and terrain. In case of the ASAS self-separation application (FAA-Eurocontrol, 2001), this means adhering to the defined separation minima between aircraft. Although more complex in reality, in this paper it is assumed that work is productive, when the distance to the destination is continuously decreasing. For flight in general, comfort poses constraints such as upper limits on maneuver accelerations. The realization of efficiency is much more complicated however, as it depends not only on fuel efficiency, but also on time and position constraints with respect to a flight schedule.

The abstract function level describes the underlying causal relationships that govern the realization of the purpose of the system. In the case of air travel, this level contains the general physical laws that dictate absolute and relative locomotion, and separation (van Paassen, Amelink, Borst, van Dam, & Mulder, 2007).

The general function level describes how the functions at the abstract function level are achieved, independent of the actual implementation of the system. Properties such as weight, lift, thrust and drag, and the maneuvering performance of the aircraft all impose internal constraints on aircraft behavior. External obstructions further constrain aircraft motion, and dictate the (lack of) separation. On the bottom of the abstraction hierarchy, the physical form and functions are described by modeling the internal layout of aircraft components, and external airspace properties such as other traffic, weather, and terrain. The physical function level describes the various components, and their capabilities, and at the physical form level the appearance and location of components, the airspace, and other aircraft are described.

In this paper, the workspace content and boundaries are limited to trajectory planning functions in direct relation with conflict resolution and prevention during cruise flight and in situations with multiple aircraft. Functions related to aircraft control and stability, like staying within the flight envelope and accounting for passenger comfort, are kept out of the analysis. The time interval in which this workspace is analyzed is determined by the applicability of conflict management and is more or less situated between 60 seconds and around 15 minutes. Below 60 seconds, collision avoidance systems like the TCAS II must take over in order to prevent collision (RTCA, 2002b). A 15 minute upper threshold is chosen because the vast majority of conflict resolution and recovery maneuvers take place in less than 15 minutes.

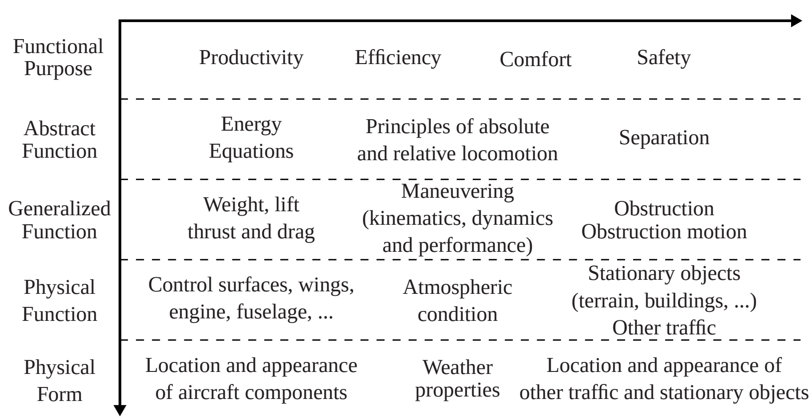


Figure 1: Abstraction Hierarchy for the Separation Assistance Display.

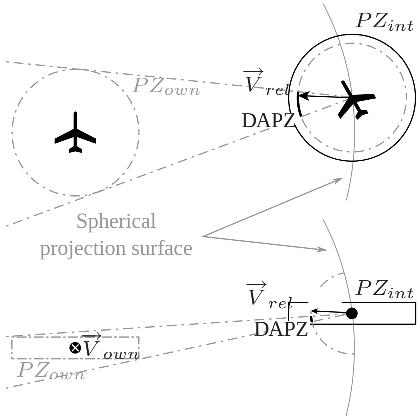


Figure 2: The Danger Area Protected Zone.

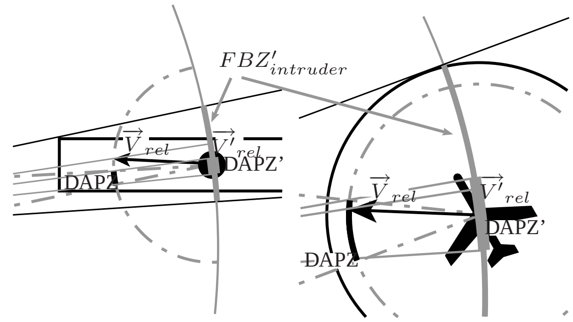


Figure 3: Close-up of the projection geometry for the DAPZ and the FBZ.

Functional Modeling of Aircraft Behavior and Separation

Based on the ecological interface design concept (Vicente & Rasmussen, 1992), the translation of the work domain analysis into an interface design is done through Functional Modeling, which tries to formulate the behavior of a system relevant to achieving its ends. For trajectory planning this implies that the goal relevant affordances must be visualized such, that the pilot's perception of these cues directly triggers desired goal-relevant steering actions.

The visualization of the external constraints in the first concept is based on relative speed, similar to the earlier display designs. There is an important difference, however: While the X-ATP and VSAD display visualizations were based on the ownship velocity relative to the intruder, the present design considers the opposite.

An often heard comment from pilots, in the evaluation of the previous display designs, was that while it featured as a valid and equal option in both displays, velocity changes are rarely used when resolving a conflict. Based on this feedback, the present design uses a cutting plane based on constant velocity to project the 3D situation onto a 2D display. The presentation of conflicts to the pilot is realized by a projection of the separation problem on the surface of an imaginary sphere, with its radius equal to the distance from ownship to intruder (Figure 2). When drawing lines between the borders of the ownship protected zone (PZ_{own}) and the intruder aircraft, a three-dimensional shape is obtained, similar to the Forbidden Beam Zone-concepts developed in the previous designs.

A second sphere is drawn, with origin at the intruder aircraft and with radius equal to the intruder relative speed. The intersection of the three-dimensional FBZ and this sphere is called the "Danger Area Protected Zone" (DAPZ). It represents all velocities with equal magnitude of the intruder relative to ownship that correspond with possible future loss of separation. Both the FBZ as well as the DAPZ can be projected on the imaginary projection sphere introduced above (Figure 3), resulting in a shape that will be referred to as "the puck" (Figure 4). The word "puck" is chosen as the PZ resembles a flat disc, similar to a puck used in icehockey. The curvature of the projection is caused by the circular shape of the puck, and changes as a function of the vertical position of the intruder, relative to the ownship. When the intruder is at the same altitude as the ownship the projection will be rectangular.

Within the puck, the relative speed of the intruder is shown. Clearly, when the tip of this relative velocity vector is located outside the DAPZ, separation is guaranteed. To better indicate the position of the tip of the relative velocity vector, four lines are drawn from the boundaries of the puck towards the velocity vector tip, see Figure 4.

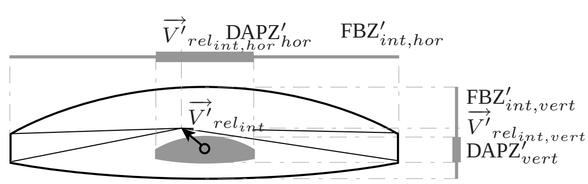
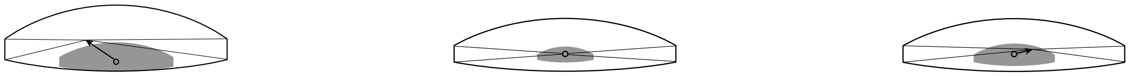


Figure 4: Construction of the 'Puck'.



(a) A grown puck (b) Collision course (c) The puck in a conflict

Figure 5: Some examples of the 'Puck'.

Figure 5 shows what the puck may look like, for three different situations. In Figure 5(a) the DAPZ has grown, indicating that the probability of a loss of separation has become larger. Note that the puck would have grown too in size on what is essentially a three-dimensional perspective projection. From the location of the tip of the velocity vector we can see, however, that no loss of separation will actually occur in this situation, as it is located outside of the DAPZ. We can also see that the intruder aircraft moves upward and to the left, relative to ownship. In Figure 5(b) the relative velocity vector is such that it points directly at ownship, and therefore is located in the center of the DAPZ. This means that in this situation a collision will occur, if no further action is taken. In Figure 5(c) a situation is shown where the relative velocity vector is still inside the DAPZ, indicating a future loss of separation.

The puck shows the relative speed of the intruder, i.e., its relative movement, the urgency of the potential conflict, and the area in which the relative speed vector should not be positioned. It does not show, however, and this is crucial, what the pilot of ownship can *do* to keep the relative velocity outside of the DAPZ. In the current concept, this is one of the main challenges. As the current design is likely to contain perspective elements (using the projection sphere centered around ownship), the "visual angle" design principle, also successfully applied in ecological synthetic vision overlays, was adopted (Borst, Suijkerbuijk, Mulder, & van Paassen, 2006).

Figure 6 shows the problem in 3D perspective. The situation is similar to the previous horizontal/vertical projections, except that now the FBZ is not a two-dimensional wedge, but rather its three-dimensional counterpart. Similar to the transformations applied in the design of the X-ATP display, the constraints on ownship travel can be visualized by a translation of the 3D FBZ with the intruder velocity, resulting in Figure 7. The intersection of a sphere with radius equal to the ownship velocity with the 3D FBZ yields the so-called "Flight-path vector Avoidance Zone" (FAZ). This shape shows the constraints imposed by intruder motion on the ownship flight-path vector, for the current speed of ownship. Future design iterations will investigate how to visualize the effects of changes in ownship velocity. The next step is then to project the FAZ on the perspective projection sphere that is also used for presenting the puck. This is shown in Figure 7. Note that the current derivation of the DAPZ and FAZ assumes instant state changes. It can be shown that this is a safe assumption when a predicted conflict is still in the far future. However, maneuver dynamics will start to play a larger role when conflicts become more imminent: in the case of tactical maneuvers (within 10 minutes of a predicted conflict), unmodeled dynamics will cause significant errors, particularly speed maneuvers (Paielli, 2003; van Dam, Mulder, & van Paassen, 2007). To compensate for such inaccuracies, future iterations of the 4D-SAI will use maneuver dynamics in the presentation of airspace affordances.

Interface design

For the first design prototype of the separation assurance interface, the visual components introduced in the previous section will be presented on a wide-angle Primary Flight Display (PFD), with a heading range of $\pm 180°$, see Figure 8. Clearly, to visualize the separation assistance information regarding all intruder aircraft located within time-vicinity (e.g., 5 minutes), several different options are available. Although the current implementation uses a "omni camera"-like heading presentation on the PFD, alternatives will be considered as well in future designs.

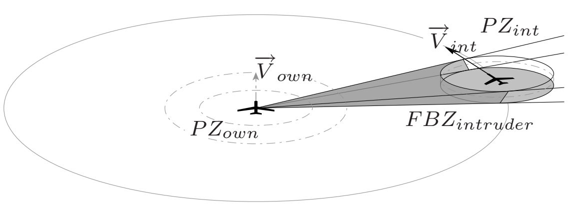


Figure 6: Forbidden beam zone of the intruder.

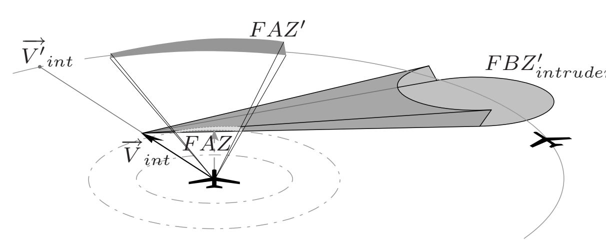


Figure 7: Flight-path vector Avoidance Zone (FAZ)

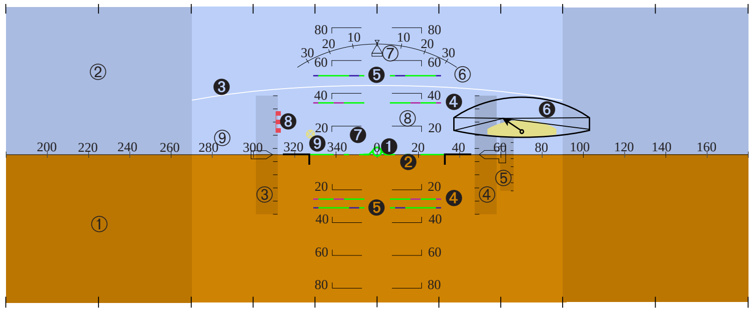


Figure 8: The initial interface design of the 4DSAI showing the example situation

Returning to Figure 8, the numbers indicate the various features of the 4DSAI prototype. Traditional pieces of information are shown using the transparent circles, examples are earth ①, and sky ②, speed ③, altitude ④, bank and slip ⑥/⑦, etcetera. On the horizon the compass headings are shown ⑨. On the speed tape the minimum and maximum velocities can be shown. The altitude and ROC tapes can present similar constraints to the ownship motion. The 4DSAI-related components are shown in the black circles. First, the flight-path vector ❶ shows the current direction of flight. The energy angle is shown as well ❷, i.e., the flight-path the pilot can select to realize a steady climb or descent. The white curved line ❸ shows the maximum flight path angle that can be achieved in a combing turn (max. g-level of 1.4, i.e., maximum bank 45 degrees). The fastest climb (or descent) is shown as the green line with purple stripe ❹, the steepest climb (or descent) is shown as a green line with blue stripe ❺.

Conflicts are shown using the puck ❻; conflicts are only shown when they are predicted to occur within 5 minutes. The small circle in the center of the puck represents the location where the intruder is located. The arrow and its four lines indicate the direction and (projected!) magnitude of the relative velocity of the intruder. When the lines are present the intruder is moving towards ownship, when they are absent the intruder is moving away from ownship. The size of the puck depends on the distance to the ownship (smaller is further away). The DAPZ is the shaded area in the puck and represents the area where the tip of the relative velocity vector should not be located.

The area where the ownship flight-path vector should not be positioned, the FAZ, is shown as well ❼. Note that the FAZ only holds for the current speed. The shading of the FAZ depends on the conflict urgency, from yellow to red. Because the conflict(s) may also be resolved by ownship speed changes, the speeds that are to be avoided are shown as well, on the speed tape ❽. The yellow dot with the cross ❾ gives an indication of the velocity vector of the intruder. Deciding to resolve the conflict by moving the ownship fligh-path vector to this dot will result in a very inefficient resolution, as the ownship will then fly more or less parallel to the intruder (van Dam et al., 2008).

Conclusions

The design of a separation assistance display described in this paper was motivated by the fact that the earlier designs map an essentially four-dimensional problem onto two displays. Using Vicente's Ecological Interface Design paradigm, a first attempt was made with the design of a four-dimensional Separation Assistance Interface. The initial design, presented in this paper, uses a spherical projection of the separation conflict based on a constant velocity. The resulting elements, a flight-path avoidance zone, and a projection of the intruder aircraft Protected Zone, are presented to the pilot on a modified, wide-screen Primary Flight Display. The most important issues in the current design are the method of presenting situations where the conflicting intruder comes from behind the ownship, and the fact that the inside-out presentation of a PFD causes a varying field of view. This means that the separation assistance elements on the display are non-stationary, possibly making interpretation of an impending conflict more difficult. These issues will be adressed in an upcoming evaluation experiment.

Acknowledgements

This work has been co-financed by the European Organisation for the Safety of Air Navigation (EUROCONTROL) under its research grant scheme of the innovative studies programme. Additional funding for this project is provided by the National Aerospace Laboratory (NLR), The Netherlands. The content of the work does not necessarily reflect the official position of EUROCONTROL nor NLR on the matter.

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