Towards a 4-Dimensional Separation Assistance Cockpit Display

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In today’s airspace, rapidly increasing amounts of traffic are pushing the limits of capacity and safety. In an effort to optimize available airspace, various initiatives have been undertaken to investigate future air traffic management concepts. In these efforts, a shift towards trajectory-based environments can be identified, where user needs and performance capabilities are leading to user preferred routing, using Airborne Separation Assistance Systems. This paper describes the initial research towards an ecological design of a four-dimensional Separation Assistance interface. A novel representation of the separation problem is proposed, where conflicts are mapped on an extended PFD. Key issues in the current design are discussed, and an experiment is proposed to evaluate the display concept.

Introduction

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 Free Flight, permit a flexible use of airspace, with airborne determination of user preferred trajectories (RTCA, 2002). 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, by presenting a limited set of explicit, ‘ready-to-use’, avoidance maneuvers as a solution to a separation conflict. These 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.

At Delft University of Technology, extensive research is being performed on 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 (see Figure 1) (Heylen, van Dam, Mulder and van Paassen, 2008; van Dam, Mulder and van Paassen, 2008).

![Figure 1: Separation Assistance displays.](image)

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). The following two sections will respectively introduce the ecological approach that was applied in the design of the display, and illustrate the work domain analysis that preceded the actual design. The third section presents the initial design of the 4D-SAI. The article concludes with a discussion on the key issues in the current display concept.

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 and Rasmussen, 1992; Burns and Hajdukiewicz, 2004). 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 and van Paassen, 2004).

EID consists of two steps. The first step consists of determining the goal-relevant properties of the work domain (ie. what to display), and the second step addresses the actual interface presentation (ie. 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, both developed by Rasmussen (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, Figure 2. 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, which in this case is flying safely, productively, comfortably and efficiently through unmanaged airspace. For the separation problem, safely relates to the separation minima. In general, productively is defined as the fact that the distance to the destination should be continuously decreasing. The abstract function level in this case contains the general physical laws that dictate locomotion. The general function level describes how the causal laws of 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.

Interface Design

The essential problem in congested airspace is a possible (future) loss of separation of the ownship, with one or more ‘intruder’ aircraft. This problem is illustrated in Figure 3, showing the situation from above and from behind the ownship. For both the horizontal as well as the vertical situation, ecological displays have been developed in the past (Heylen et al., 2008; van Dam et al., 2008). The current challenge is to integrate these two projections into a true four-dimensional (space and time) separation assistance interface.
of the work domain analysis into an interface design is done through Functional Modeling. Functional Modeling 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 in such a way, that the pilot’s perception of these cues directly triggers desired goal relevant steering actions. In the first design of the four-dimensional separation assistance display, an approach similar to that in the earlier display designs was followed. That is, the visualization of the constraints imposed by intruder aircraft is based on relative speed. There is an important difference, however, with the previous designs: While the X-ATP and VSAD display visualizations were based on the ownship velocity relative to the intruder, the present design considers the opposite. As such, in the following illustrations, ownship is standing still, and intruder aircraft move relative to ownship with velocity \( V_{\text{rel}} = V_{\text{int}} - V_{\text{own}} \).

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 in the resolving of 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 8). When drawing lines between the borders of the ownship protected zone (\( PZ_{\text{own}} \)) and the intruder aircraft, a three-dimensional shape is obtained, similar to the “Forbidden Beam Zone”-concepts developed in the previous designs.

Then, a second sphere is drawn, with origin at the intruder aircraft and with radius equal to the relative speed of the intruder, \( V_{\text{rel, int}} \). The intersection of the three-dimensional Forbidden Beam Zone and this sphere is called the “Danger Area Protected Zone” (DAPZ for short). The DAPZ represents all velocities with equal magnitude of the intruder relative to ownship that correspond with possible future loss of separation. The DAPZ is illustrated in Figure 8 with the thick black line. Figure 5 illustrates that both the FBZ as well as the DAPZ can now be projected on the imaginary projection sphere introduced above.

The projection of the FBZ and DAPZ onto the spherical projection surface results (with proper scaling) in a shape that will be referred to as “the puck”, shown in Figure 6. The word “puck” is chosen as the PZ is shaped like a flat disc (Figure 3), similar to a puck used in (ice-) hockey. Note that the curvature of the puck is caused by its circular shape, 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 puck will be a rectangular box. Also note that in principle all intruder aircraft can be visualized with their own puck. Within the puck, see Figure

![Figure 4: The Danger Area Protected Zone.](image)

![Figure 5: Close-up of the projection geometry for the DAPZ and the FBZ.](image)

![Figure 6: Construction of the 'Puck'.](image)
6, 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.

Figure 7 shows some examples of what the puck may look like, for three different situations. In Figure 7(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. In this case, we can also see that the intruder aircraft moves upwards and to the left, relative to ownship. In Figure 7(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 loss of separation will occur, if no further action is taken. Note that when both the ownship as well as the intruder aircraft are equipped with the same interface, their representations would be very similar. In Figure 7(c) a situation is shown where the relative velocity vector is still inside the DAPZ, and a loss of separation will occur when nothing is done. Also, the intruder aircraft will move to the right and ascends relative to ownship. 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 problems. As the four-dimensional separation assurance interface (4DSAI) to be developed 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 (Borst, Suijkerbuijk, Mulder and van Paassen, 2006), was adopted. In this concept, the current flight-path vector (FPV) of the ownship plays a crucial role. Essentially, the DAPZ represents an area where the relative velocity vector can not be positioned. Then, in order to present the pilot of ownship any useful information about what he can do about a particular situation, the DAPZ has to be transformed to an area that says something about the constraints for his own velocity vector.
Figure 10: The initial interface design of the 4DSAI showing the example situation

The components of the 4DSAI, i.e., the puck, the DAPZ and the FAZ, have now been introduced. Figure 10 illustrates the first design prototype of the separation assurance interface. It is based on a conventional primary flight display (PFD), but with a wide-angle heading range (± 180 degrees). The line-of-sight is along the ownship longitudinal body axis, similar to conventional PFDs. Clearly, to visualize the separation assistance information regarding all intruder aircraft located within time-vicinity (e.g., 5 minutes separation in time), several different options are available. One could, for instance, present the aircraft in front of the ownship (± 90 degrees) on the PFD, and then have a “rear-view mirror” to present all intruder aircraft behind the ownship (from -180 to -90 and from 180 to 90). Although the current implementation uses a complete “omni camera”-like heading presentation, other presentations will be considered as well in future experiments and designs.

Returning to Figure 10, 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 ⑤/⑥, etcetera. On the horizon the compass headings are shown ⑦. 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 ① shows the current direction of flight. The energy angle is shown as well ②, i.e., the flight-path the pilot can select to realize a steady climb or descent. The white curved line ③ 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 ④, the steepest climb (or descent) is shown as a green line with blue stripe ⑤.

Conflicts are shown using the puck ⑥; 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 ⑦. 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 ⑧.

The yellow dot with the cross ⑨ gives an indication of the velocity vector of the intruder. Deciding to resolve the conflict by moving the ownship flight-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.
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 Rasmussen’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 addressed in an upcoming experiment, evaluating the first concept in a flight-simulator.

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References


