Towards an Ecological Design of a 4-Dimensional Separation Assistance Interface

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Abstract—Currently the world’s airspace is being operated at the limits of both capacity and safety by different stakeholders. Various initiatives worldwide are investigating future air traffic management concepts. A shift towards trajectory-based environments is identified, where user needs and performance capabilities are leading to user preferred routing by using Airborne Separation Assistance Systems. Within the Control & Simulation Department two innovative interfaces have been developed based on the Ecological Interface Design paradigm, that prevent potential loss of separation in the horizontal and vertical plane respectively. This paper describes the foundations of these interfaces and describes the research heading towards an ecological design of a 4-dimensional (space and time) separation assistance interface.

I. INTRODUCTION

With their current tools and procedures, the different airspace users of the world’s airspace are operating at the limits of both capacity and safety. The airspace services and encompasses a myriad of stakeholders and the airspace is divided in fixed volumes and rigid route structures, both managed in a fragmented manner, resulting in the inability to fly the most efficient trajectories, as well as additional workload for air traffic control. Pilots have limited situational awareness of the traffic surrounding them, which can endanger safe operation. Besides this, it also restricts them from taking a more proactive role in the Air Traffic Management (ATM) process. Worldwide, different initiatives investigate future ATM concepts, like the European ‘SESAR ATM Target Concept’ [1] and the American ‘NGATS ATM - Airspace Project’ [2]. In future ATM concepts, airborne and ground based automated support tools play an increased role and represent a shift to a trajectory-based environment. This leads to user preferred routing, considering user needs and performance capabilities, without pre-defined routes.

New separation modes will be implemented over time, supported by controller and airborne tools to optimally utilize human capability in combination with automation. The modes will use trajectory control and airborne separation systems to minimize potential conflicts and controller’s interventions. The airspace will be designated in two categories ‘managed’ and ‘unmanaged’ airspace. Within the managed airspace, information on all traffic is shared and the Air Navigation Service Provider is the main separator, but the role of the separator may be delegated to the flight crew, with pre-defined agreed rules and criteria. Within unmanaged airspace, the main separator is the airspace user itself, a principle that is also called self-separation. To support the user in this self-separation role, various research projects work on the development of an Airborne Separation Assistance System (ASAS).

Traditional ASAS tools like the Predictive Airborne Separation Assistance System (P-ASAS), developed by the Dutch Aerospace Laboratory NLR [3], provide pilots with explicit resolution commands, complementing the Airborne Collision Avoidance Systems (ACAS) like the Traffic alert and Collision Avoidance System (TCAS) II. Within the Control & Simulation Department extensive research is being performed on Airborne Separation Assistance Systems, based on the Ecological Interface Design (EID) paradigm [4] to resolve a conflict without relying on resolutions provided by automation.

This paper will give an overview of the research that will lead to the development of a 4-Dimensional Separation Assistance Interface, where 4D refers to the combination of both space and time. Section II gives an overview of the principles of the EID paradigm. Section III will cover the development of a horizontal separation assistance system. An ASAS in the vertical plane, is covered in Section IV. Current developments towards the 4D ASAS are discussed in Section V and conclusions will be given in Section VI.

II. ECOLOGICAL INTERFACE DESIGN

The observation that large-scale accidents shared the fact that they were prompted by situations that were both unfamiliar to workers and that had not been anticipated by system designers, led to a change in paradigm to design interfaces for human-machine interaction [5]. Ultimately, it led to the Ecological Interface Design (EID) paradigm, which addresses the cognitive interaction between humans and complex socio technical systems. The ecological approach to interface design gives priority to the worker’s environment or ecology, concentrating on how the environment imposes constraints on the work domain, rather than on the end user or a specific
task. This approach is hypothesized to yield interfaces that better support worker adaptation, even, or especially, in situations that were not anticipated for by the system designers. Experiments showed that in several cases EID indeed resulted in better operator problem-solving performance as compared to traditional designs [6]. Within the Control & Simulation Department EID has also successfully been applied to energy management [7] and terrain awareness [8], for instance. Self-separation in unmanaged airspace is a task that leads to unique situations that could not have been anticipated for beforehand, so the EID paradigm seems a a valid and promising approach in the design of a 4D ASAS as well.

EID consists of two main steps. The first step relates to the ‘content’ and ‘structure’ of the work domain, the second addresses the interface ‘form’. First, a workspace analysis tries to identify functionalities, constraints, and means-end relationships within the worker’s environment, as these shape the possibilities of goal-directed worker actions within that environment. The identification is done using Rasmussen’s Abstraction Hierarchy (AH) [9]. Earlier attempts to design ecological interfaces have shown that a useful distinction can be made between ‘internal’ and ‘external’ constraints [10] [11]. The internal constraints originate from the own vehicle performance characteristics and limit the capabilities of the pilot-aircraft system itself. The external or environmental constraints originate for instance from the terrain, weather, and the surrounding traffic, and further limit the opportunities for the own aircraft (loco-)motion. The second step aims to make these workspace constraints and means-end relationships easily visible on the display. It intends to express them in a meaningful, functional way, taking advantage of the human capacity to directly perceive and act upon what the environment affords [12]. In the present context, automation is used for the benefit of pilot situation awareness, in line with objectives mentioned in the previous Section.

III. AIRBORNE TRAJECTORY PLANNING

Airborne Trajectory Planning (ATP) [11] refers to on-board (re-)planning to achieve a safe, conflict-free and efficient trajectory to the destination within a future air traffic management environment, and relates to a number of pilot-aircraft activities. It is also used as a label for the separation assistance display in the horizontal plane. Figure 1 shows a plan view of a conflict situation, also with the definitions of a Protected Zone (PZ) and the Closest Point of Approach (CPA). The PZ is a puck-shaped space which visualizes the separation standards. A conflict is defined as a predicted loss of separation between two aircraft. Note that the conflict is shown but the solution is not. Changing to \( \vec{V}_{\text{own}} \) does not resolve the conflict. The EID paradigm is used to design an interface that allows desired pilot actions to emerge from the visualization of the workspace affordances in terms of a suitable description of (loco-)motion of aircraft. Aircraft behavior is modeled by combined speed and heading change maneuvers, after which a novel interface, the State Vector Envelope (SVE) is presented. In line with the EID paradigm, the SVE aims to support all levels of cognitive control, while not forcing the operator to control at a higher level than necessary, saving cognitive resources [6]. It is intended to provide the pilot with both low-level information, allowing direct action, and high-level information, allowing conflict understanding and situation awareness [11].

A. The Forbidden Beam Zone

Aircraft (loco-)motion can better be related to spatial separation constraints in a relative velocity plane. The calculations associated with ATP are better performed in the relative speed plane, as shown in 2. By subtracting the speed vector of the intruder, \( \vec{V}_{\text{int}} \), from the own speed vector, \( \vec{V}_{\text{own}} \), the relative speed vector, \( \vec{V}_{\text{rel}} \), is calculated. If the extension of this relative speed crosses the PZ of the intruder, as is the case here, then at some future point in time an intrusion will happen if no evasive maneuvers are performed. Within this relative plane a beam-shaped area can be defined, outlined outlined in Figure 2, by two lines originating from the own position and tangent to, respectively, the left and right side of the PZ of the intruder. This zone is referred to as the Forbidden Beam Zone (FBZ). If the relative speed is inside the FBZ a conflict situation will occur in time. Because pilots can not intuitively alter the relative speed, the FBZ is translated by the speed vector of the other aircraft, thereby bringing it into the absolute plane. The pilots can now change the own speed vector, \( \vec{V}_{\text{own}} \), and aim to keep that out of the FBZ, thereby indirectly controlling the
relative speed vector. The direction of the origin of the FBZ from the own position gives information about the heading of the intruder, and the distance to the origin of the FBZ is an indication of its speed. Spatial separation can be realized by a vector state change of the own speed vector, the intruder speed vector, or a combination of both. The pilots can now change the own speed vector, $V_{\text{own}}$, and aim to keep that out of the FBZ, thereby indirectly controlling the relative speed vector. The direction of the origin of the FBZ from the own position gives information about the heading of the intruder, and the distance to the origin of the FBZ is an indication of its speed. Spatial separation can be realized by a vector state change of the own speed vector, the intruder speed vector, or a combination of both.

B. The State Vector Envelope

Not every point in the speed-heading space represents a feasible maneuver to resolve a conflict. In reality, the possibilities are bound by constraints and/or affordances. Limitations to aircraft performance such as maximum and minimum values for aircraft velocity can be applied. Due to productivity, the heading change is limited to 90 degrees left and right in order to show travel opportunities that will decrease the distance between the aircraft and the destination. The SVE is a combination of the FBZ and the internal constraints, aircraft performance, and external constraints, productivity constraints.

The FBZ has several characteristics. When multiple conflicts occur simultaneously, several FBZs can be shown superimposed onto each other. The position of the origin of the FBZ represents the intruder speed vector, a location where $V_{\text{own}}$ should not be maneuvered, as the aircraft will end up flying parallel to the intruder, which is a very inproductive maneuver. The direction of the opening of the beam reveals the intruder relative position. A large angle between the legs of the FBZ indicates that the distance between the own and intruder aircraft is small. In case of a conflict, the geometry of the FBZ from the perspective of one aircraft is complementary to the perspective of the other aircraft. Each pilot can move to the FBZ leg that is situated closest, yielding simultaneous, cooperative maneuvers. The changing relative aircraft positions cause the FBZ to expand. Both ownship and intruder maneuvers result in translation and/or rotation of the FBZ. The use of speed-heading space (motion) and plan view (airspace) for presenting constraints, enhances the natural ecology that pilots have and use when moving through airspace.

IV. VERTICAL SEPARATION ASSISTANCE DISPLAY

The construction of a FBZ can also be performed in the vertical plane and resulted in the development of a Vertical Separation Assistance Display [13], which is shown in Figure 4. The maneuver boundary capabilities for aircraft performance can be visually presented by plotting the performance envelope in a polar graph within a true airspeed/rate-of-climb state space. The internal aircraft performance constraints are given by minimum and maximum speed, as well as by minimum and maximum thrust. In line with the horizontal separation assistance interface, the combination of the performance overlay and the conflict geometry overlay is also called the State Vector Envelope. In this SVE, the resolution maneuvers can also be performed by moving $V_{\text{own}}$ out of the FBZ, however a horizontal maneuver is required, possibly in addition speed change(s), but a climb or descent.

Adding the layers with internal and external constraints to an existing Vertical Situation Display (VSD) results in the VSAD, which can be seen in Figure 5. In this display, circled number 1 is the own aircraft symbol, circled number 2 is the speed indicator, circled number 3 is the ROC indicator, circled number 4 is the conflict geometry overlay, circled number 5 is the own speed vector, circled number 6 shows the intruder aircraft with a label containing the aircraft identification, its true airspeed and flight level, circled number 7 shows the own aircraft programmed flight path, circled number 8 is the performance envelope overlay, transformed to the 5 minute time interval, and circled number 9 shows potential flight path angle settings in one-degree intervals. 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 ROC, speed and altitude give the pilot an additional reference to this prediction.

The conflict geometry also allows pilots to derive the speed and ROC, or equivalently, flight-path angle, of the intruder aircraft, as the tip of the FBZ is translated over the intruder speed. In the vertical plane, this can only be seen when the aircraft fly at a parallel speed. If the intruder aircraft is flying with an opposite speed, the FBZ tip is located to the left of the own aircraft, and its airspeed and flight level can only be derived from the intruder aircraft label, circled number 6.

Note that, as far as separation assistance is concerned, it would be preferable to also show part of the airspace ‘behind’ the own aircraft on the VSAD, as this presentation would include all intruder aircraft that could possibly impose constraints on the own aircraft motion in absolute space. The yellow line, circled number 7 in 5, in the VSAD represents the flight path as programmed in the Flight Management System. Besides serving the performance purpose, the speed vector also relates to the navigation purpose as it is a predictor of where the aircraft will be located in 5 minutes time. If the tip of the speed vector is located on the edge of the FBZ, circled number 4, the own aircraft will just avoid the conflict, and so the efficiency of the escape maneuver will be high. Note that to prevent inefficient resolution maneuvers, the tip of the FBZ should be avoided as then the conflict will never be resolved since the own aircraft will fly parallel with the conflicting intruder.

The FBZ of the VSAD shows similar characteristics as the FBZ in ATP, explained in Section III-A, for instance with superimposition of FBZs of multiple conflicts and FBZ dynamics.

V. CURRENT RESEARCH

The mentioned research in the area of Airborne Separation Assistance Systems based on the Ecological Interface Design paradigm has been very promising and several designs for both the horizontal and vertical situation have been validated. It turned out that the systems support human cognitive control in reaction to available information. Both the horizontal and vertical Airborne Separation Assistance Systems considerably improved pilot (conflict) situation awareness while not increasing the workload or decreasing the task performance. With the validation of previous research, some interesting evaluations have risen. A better connection between the intruder aircraft and its SVE needs to be found. Besides that, an indication between real conflicts and potential conflicts would be very welcome as well as an integration of ACAS and ASAS, using similar symbology for clarification purposes for time and risk. Being able to include traffic behind the own aircraft that could impose constraints on the own (loco-)motion turned out to be an important recommendation for a future system as well.

Research has been performed with adding turn dynamics and aircraft intent information [14], eXtended ATP (XATP) and intent eXtended ATP (iXATP). The next important step is to combine the previous research in a 4-dimensional Airborne Separation Assistance System, based on the EID paradigm. Note that this does not need to be a 3-dimensional visualization, but rather a visualization that uses innovative viewpoints and projection planes to represent the conflict(s) and solution possibilities.

A. Forbidden Beam Zone Projection

The construction of a FBZ has been discussed in Section III-A. Figure 6 shows the FBZ as used in the search for a 4-dimensional ASAS. First the FBZ for the intruder is calculated, indicated with $FBZ_{intruder}$. In the same way, the FBZ of the onship can also be drawn from the perspective of the intruder, indicated with $FBZ_{own}$. As opposed to previous calculations, now the own aircraft is pinpointed and its flight vector is located on the edge of the FBZ, circled number 4, the own aircraft will just avoid the conflict, and so the efficiency of the escape maneuver will be high. Note that to prevent inefficient resolution maneuvers, the tip of the FBZ should be avoided as then the conflict will never be resolved since the own aircraft will fly parallel with the conflicting intruder.
with the boundary of the Protected Zone of the intruder, can be projected onto plane \( e \) as well. If this point is within area \( f' \) a conflict will appear, as \( V_{rel} \) is within the own FBZ.

Looking from the own position to the vertical plane through plane \( e \), the puck becomes visible. Figure 7 gives examples of a possible visualization of a conflict for different points in time. Puck 1 refers to the situation as plotted in Figure 6, puck 3 to a situation some minutes later, and puck 2 to a situation in between. To indicate how the pucks are constructed, the projection \( e - e' \), as constructed in Figure 6, is added for every puck, which is not part of the final visualization. The width of the puck is determined by \( f' \) and the width of the projected FBZ is determined by \( FBZ' \). At the center of the puck a small circle is used to visualize the position of the intruder. From this circle \( V_{rel} \) is drawn. Connecting lines from the corners of the puck to the end of \( V_{rel} \) are added for visual support. Choosing plane \( e \) to go through the position of the intruder causes the width of the puck to increase when the intruder closes in, indicating the urgency of the conflict. The projected FBZ increases as well, giving an indication of the time to maneuver. If the tip of \( V_{rel} \) is situated outside the gray area, \( V_{rel} \) is maneuvered outside the FBZ, either in the lateral direction or vertically, and the conflict is solved. In Figure 7, the projected FBZ area is gray.

B. Research Challenges & Discussion

As this research is currently being performed, several questions need to be addressed in the near future. Is a projection of a 4-dimensional conflict representation onto a plane preferable, with its implicated perspective distortion, or is a planar view using previously developed displays on both the VSD and the ND the best solution? What display in the cockpit can be used for the new visualisation, or is an additional display necessary? How can multiple conflicts be visualized? What is the influence of the changes in the own state? What technique will be used to solve conflicts and is this done in either the vertical or horizontal way or is a 4-dimensional combination preferable? Will all possible conflicts be displayed on the displays, or can surrounding traffic be visualized with a similar scanning technique as used for the weather radar?

The research will not only lead to a new design, but will also be validated by means of an experiment with several pilots in the loop. Will the newly developed system also increase situation awareness at the same level of task performance? If the situation awareness is increased, does the pilot use the available information to plan his resolution maneuver and solve the conflict effectively? What will the pilot acceptance be? What could be improvements and additions in order to be a valid system to be integrated in future air traffic management concepts? Are combinations possible with terrain and weather visualisations? All examples of very elementary and complex questions that will need to be addressed in the near future.

VI. CONCLUSION

Various examples of research performed within the department of Control & Simulation on both horizontal and vertical visualisations. All examples of very elementary and complex questions that will need to be addressed in the near future.

Airborne Separation Assistance systems have been discussed. Results and recommendation from this work have lead to research about a 4-dimensional ASAS, which is currently being performed. A first step towards this system has been made, of which a visualization has been shown. In the near future, the preliminary analysis and design needs to be further developed and elementary questions need to be addressed, with the final objective to experimentally validate this research.

REFERENCES


