Ecological Approach to Pilot Traffic Awareness

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Summary

Future air traffic concepts foresee that in unmanaged airspace, to reduce workload of air traffic controllers and the resulting constraints on capacity, the separation task will be delegated to the flight deck. Technology-driven pilot self-separation support systems have been developed that present explicit automated solutions to deal with conflicts. These systems do not offer a transparent window on the reasoning of the automation, making it difficult for pilots to judge the validity of the proposed automated solution, or come up with safe 'good-enough' alternatives. This thesis engaged to solve the fundamental problem of determining 'what information', and 'what visual form' would best promote pilot situation awareness (SA), to safely and effectively deal with *traffic*. Several prototypes for an airborne trajectory planning tool were designed and evaluated.

A formative constraint-based design approach was adopted, Ecological Interface Design (EID), to create an 'ecological' airborne separation assistance system. The ecological approach gives priority to the worker's environment, or 'ecology', focusing on how the environment imposes constraints on the worker. EID is hypothesized to improve operator SA and overall system safety when compared to normative, task-oriented, user-centered design approaches, especially in situations that were unanticipated by designers.

EID starts with an analysis of the operator's work domain through a Work Domain Analysis (WDA). The WDA is an activity-independent analysis and aims at identifying and mapping-out the environment's goal-relevant constraints (and their relationships) that shape human, or automation, actions. EID was originally applied to process control and the application of WDA to the domain of vehicle control brought about changes in the constraints encountered at the five common levels of functional abstraction. The most significant challenge was found at the Abstract Function level, where the typical mass and energy flow based descriptions used in literature were substituted by descriptions of the physical laws of flight, absolute and relative locomotion and the geometrical properties of the separation problem.

EID then continues with designing the actual interface. From literature it is known that a ‘creative gap’ exists between the cognitive work domain analysis and the actual design of the interface. In this thesis it is shown that this gap can be closed by finding ‘meaningful physics’, that is, alternative descriptions of the constraints (in particular at the abstract function level), to create a more ‘practical’ match between user controls and the representation, and at the same time also a ‘functional’ match between system purpose and the representation. To become practical, it involved using lower-dimensional descriptions of aircraft motion that match current flight practices and cockpit interface design. To become meaningful, it involved mapping the internal constraints of flight, imposed by aircraft performance, within the context of external constraints to flight imposed by surrounding traffic.

It is found that conflict avoidance is not suitable to be visualized in an ‘absolute motion plane’, as the dynamic behavior of geometrical conflict properties is too dynamic and complex. When describing motion *relative* to the intruder aircraft, however, these conflict properties become much more ‘static’ and easier to understand. The concept of the ‘Forbidden Zone Beam’ (FBZ) was developed and to reinforce the coupling with current flight practice, this FBZ was translated to the absolute motion space, mapping the problem of separation back to the pilot’s natural (speed-vector) action-space. As a result, the FBZ almost perfectly illustrates how the conflict geometry imposes constraints on the own aircraft travel possibilities.

To further facilitate the integration with current-day interfaces, the ecological overlays were integrated with existing (horizontal and vertical) navigation displays. A best match with the ‘current ecology’ of flying was achieved by mapping the origin of the action space on the own aircraft position, resulting in a direct visual mapping between constraint zones (FBZs) and the location of the intruder aircraft (responsible for the FBZs). The resulting interface was called the (eXtended) Airborne Trajectory Planning (X)ATP.

Throughout working on this thesis it became clear that with each iteration of work domain analysis, interface design and experimental evaluation, the relations between different parts in the WDA functional abstraction hierarchy evolved more clearly. Not only did the ecological overlay make efficient conflict avoidance directly perceivable from the display, it also provided an extensive set of *meaningful* contextual information, potentially significantly enhancing conflict situation awareness. The richness of the display presentation is stunning and even at the very end of the project new useful properties were discovered.

One of the core challenges of the application of EID in many domains remains how to objectively compare traditional task-oriented displays with ecological displays. In this thesis, two collision avoidance displays, one the result of traditional engineering, predictive-ASAS (PASAS), and one the result of the ecological approach, XATP, were extensively compared. The PASAS' bands were chosen as the viable technology-driven design alternative to the ecological interface. From a evolutionary perspective, these 'no-go' bands in the heading and speed tapers where designed to prevent the creation of new conflicts when pilots agreed to implement automated ASAS solutions. These bands are in fact also a constraint-based visualization but map the – what is essentially a two-dimensional – speed-heading 'solution space' to two one-dimensional speed-only and heading-only solution spaces.

In a first experimental comparison between XATP and PASAS, the latter concept was implemented using the 'no go' bands only, to make a fair comparison in terms of equal levels of automation. With the absence of an automated resolution advisory in the traditional display, differences in pilot behavior between both systems were expected to be directly related to the differences between both constraint-based representations. However, no differences between both displays in terms of performance and workload were identified, leading to the conclusion that no direct relation exists between pilot traffic awareness on the one hand, and task performance and workload on the other.

This lead to a shift in evaluation methodology from a cognitive task-oriented approach of measuring workload and task performance to one of directly measuring conflict Situation Awareness. When the PASAS heading and speed bands were enhanced with the explicit automated resolution advisories by the use of taper markers, results showed that indeed the ecological display better supported pilots to deal with unforeseen situations and create a better mental model of the conflict situation. Overall, situation awareness was higher, which did not result, however, in better performance. As far as evaluating the designs in unanticipated events, the introduction of unlikely events such as a 'hostile maneuver' of an intruder aircraft, was not very successful. This will remain to be a challenge, as obtaining sufficient data for these events requires more repetitions, affecting their 'likeliness'.

The experimental results further show that, for more complex situations the one-dimensional bands provide less SA, require more cognitive effort to understand the situation than with XATP, leading a majority of the pilots to prefer the ecological display in those conditions. Some evidence is found for the hypothesis that reducing the dimension of the solution space (as with the PASAS bands) may have benefits in terms of lowering the cognitive load related to selecting and executing automated resolutions. It also disintegrates, however, the 'conflict situation' and may in fact require *more* cognitive effort from pilots to build a correct and complete mental

picture of the situation; the latter to the benefit of pilot SA, and air traffic safety.

Finally, in all experimental evaluations conducted in this thesis, it became clear that users of ecological interfaces need more elaborated instructions and much more user experience (training) before they start to understand the behavior and dynamics of work domain constraints represented on the interface. The time scale of many pilot experiments was too limited to notice this effect. Ecological interfaces are not meant for novices, and are unlikely to rapidly turn novices into experts. Rather, ecological interfaces are expert interfaces for experts, and should be treated as such.

This thesis showed that an ecological self-separation interface can be used by pilots to assure separation with other traffic without any help of automation. In several instances, however, it was noticed that presenting the basic FBZ could be insufficient. First, in multi-conflict situations, automation could play a role in computing the 'best way out' for all aircraft, and also indicate which aircraft should 'move first', in order to obtain the best global optimal solution. Secondly, the effects of instantaneous or planned intent information on the appearance of constraints have been modelled, and prototypes for visualizations were developed. Here it was found that including intent of traffic inevitably introduces more work domain constraints, in several dimensions, and may easily lead to a cluttered hard-to-use interface.

These findings bring us back to the fundamental question: What level of automation is needed to ensure effective human-machine interaction? Amongst the options to reduce overwhelming complexity could be automating the decision who of all pilots involved should act first, automating the decision to (dis)-engage the active mode of automation, introducing some type of explicit advisory, etcetera. Regardless the answer to this question the ecological overlays, presenting work domain constraints that are true for *both* pilots and automation, are still valid and can act as a 'window' on the rationale behind the automated solution (or suggestion), increasing the transparency of the automation considerably. This is also likely to result in increased pilot trust in the automation and also may lead to pilots accepting higher levels of automated solutions.

In this thesis, flight safety was measured in terms of the minimum distance between aircraft and loss of separations. Overall, the experiments showed that both ecological and traditional interfaces resulted in only a few, and minor, intrusions. The visualization of the ultimate boundaries for action sometimes lead pilots to 'push the envelope', an inevitable 'risk migration' effect common to all human-machine systems. It is recommended to study the existence and applicability of 'ecological' metrics for safety. Properly modeling the geometric properties of FBZs may lead to more ecological descriptions for conflict 'severity' or 'urgency' in particular, and flight safety as a whole.

From this thesis we conclude the following. First of all, this work has clearly shown that an ecological display, providing pilots a profound layer of information without *any* help of automation in terms of explicit advices, can be as safe and as effective as traditional displays that mainly present explicit automated advisories. Second, the design of ecological interfaces in domains where the abstract functions are less obvious, like the self-separation problem studied here, benefits from an incremental, evolutionary approach. Indeed, EID is not a recipe. Third, from the comparison with the more traditional design it became clear that although reducing the solution space dimension can have benefits in terms of reducing cognitive load, in the end it may lead to more cognitive load for operators to build a correct and complete mental model of the situation. Fourth, and related, although an appropriate ecologically-inspired interface can alleviate a pilot's dependency on an explicit compelling advisory, adding dimensionality to the pilot control actions (e.g., involving more and more constraints) may render the ecological display to become too complex to be used without some sort of automated advisories.

The recommendations of this thesis are that, first, although some evidence was found for the hypothesis that ecological interfaces better support pilots in dealing with rare and unanticipated situations, this remains an important avenue for future research. Second, the horizontal and vertical designs should be better integrated, to show the full dimensionality of the three-dimensional separation problem. The ecological displays should also be able to facilitate 4D trajectory management, as it all boils down to relative motion of vehicles in space and time. Third, it would be very interesting to experimentally evaluate ecological interfaces in scenarios where multiple pilots use the interface simultaneously in the same space, as this will likely bring up occasions where the unexpected behavior of one of the pilots involved will yield the unexpected and 'random' events that are so difficult to define beforehand. Fourth, the findings in this thesis call for an investigation of the possible use of ecological interface designs as training tools, to promote long-term learning effects on the physics that govern the work domain, showing the ecological overlays as decision aids while learning the dimensions of the task and also understanding the underlying rationale of automation. This approach may also foster a successful introduction of 'hybrid' system designs in the future.

As a final statement, the ecological overlays developed here could be the 'missing link' to design a Joint Cognitive System (JCS). That is, the ecological overlays may be used to close the gap in the awareness of situations shared between automation and pilot, enabling pilots to better judge the fidelity of the proposed solution and, in case the automation fails, to come up with good-enough alternative resolutions. That is, traditional task-oriented displays and the ecological displays do not exclude each other's use in one system. On the contrary, whereas task-oriented support may lower cognitive workload in simple standard situations through the

availability of easy-to-use, automated instructions, the ecological decision support overlays show the 'total situation' to help the operator to become an expert and able to deal with unanticipated events. Key in this JCS design effort is to use automation as a tool to lower cognitive effort and improve decision making in such a way that it does not destroy the benefits of ecological properties of the design.

Contents

1

Introduction

In this chapter we introduce the subject of traffic awareness, elaborate on the problem statement, discuss the research approach, the main challenges and assumptions. Apart from the Introduction and Conclusions chapters, the thesis is comprised of papers published in peer-reviewed academic journals and conferences.

1-1 Delegation of the aircraft separation task

Aviation is one of the world's safest means of public transportation. Despite the increase in air traffic volume, flight safety has significantly improved over the past decades. Technological innovations, such as more reliable engines, the development of Electronic Flight Instrument System (EFIS) and advanced automation such as the Flight Management System (FMS), but also non-technological advances such as the Aviation System Reporting System (ASRS) and Crew Resource Management (CRM) techniques, have been the major drivers for aviation safety.

Airspace congestion and delays, however, force airspace authorities and governments to explore more effective ways to manage air transportation. Novel Air Traffic Management (ATM) programs such as the Next-Generation Air Transportation System (NextGen) in the United States and Single European Sky ATM Research (SESAR) [1] in Europe, advocate the potential benefits of adopting a more flexible approach to ATM [2–6], and stress the importance of four-dimensional (4D) trajectory planning to enable safe and efficient air travel. Both programs aim to radically innovate the ways in which air transport will be conducted in the decades to come, aiming for higher capacity, efficiency and safety levels.

In the future, airspace users will obtain more freedom to adapt their trajectories to their own needs through the use of user-preferred trajectories that allow direct routing and cruise climb. Inevitably, these concepts will lead to more complex traffic situations and would increase workload on air traffic controllers who secure safe separation between aircraft. A possible way to reduce their workload would be to **delegate the separation task to the flight deck**. This may also lead, however, to higher workload for pilots who will become responsible for separation. The problem of how to assist pilots in performing this, for them new and additional, task of self-separation has attracted great interest in the research community, and several solutions have been proposed in the past decades.

First, Cockpit Displays of Traffic Information (CDTI) were designed, including advanced route analysis tools that helped pilots in conflict detection and resolution [7–14]. Second, Airborne Separation Assurance Systems (ASAS)[†], like Predictive ASAS (PASAS), have been developed and tested in combination with CDTI [15–17]. Both solutions deal with conflict situations and form a strategic complement to currently-deployed Airborne Collision Avoidance Systems (ACAS) like the Traffic alert and Collision Avoidance System, TCAS II [18]. These solutions illustrate, what we refer to as, *technology-driven* flight deck philosophies.

[†] In recent years, the air traffic research community increasingly used the term Airborne Separation 'Assistance' System. Both definitions refer to the same system, however, the word assistance reflects a still on-going discussion on how to distribute separation task responsibilities between on-board automation, pilots and Air Traffic Control.

1-1-1 Automated solutions

Many of the proposed airborne separation assistance tools provide pilots with *explicit* automated solutions, in the same way as for ACAS systems. That is, typically these tools tell the pilot how to resolve a conflict, by presenting a *ready-to-use* avoidance maneuver. Support systems that apply explicit, automated solutions have proven to be effective as far as providing conflict resolution and reducing workload are concerned. A few observations can be made, however, with respect to the use and presentation of CDTI and ASAS displays [19].

First, as explicit automated solutions only become visible at the time of conflict detection, these *sudden* alerts may come as a surprise to the flight crew. In case a given conflict situation is urgent and needs immediate and correct action, this might induce high stress levels exactly when human problem solving and reasoning capabilities are most needed [20].

Second, they do not allow pilots to explore actions other than those presented, and therefore do not allow pilots to explore alternatives for action that may be safer and more efficient than the one(s) presented. Generalizing, they do not support pilots to fully exploit the travel freedom and airspace capacity offered by future airspace environments.

Third, they do not show the *cognition* behind the automation that deals with the separation problem, and pilots are not actively involved in the decision-making process [21–24]. That is, the solution commands do not show underlying data or rationale of the separation problem nor the rationale of how the automation deals with it. This requires additional cognitive effort from pilots to reflect on the separation problem and validity of the issued solutions.

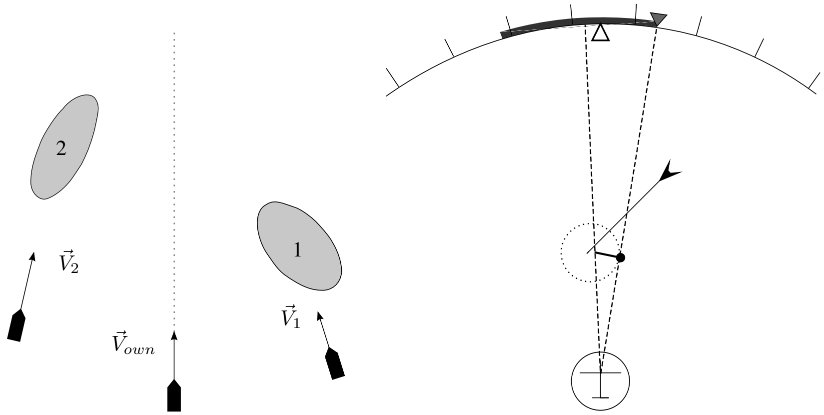
Fourth, in a complex traffic environment, non-routine situations may arise, beyond the scope of the automation and not anticipated for in the automation design. In these exceptional cases, the pilot's ability to improvise outperforms automated solutions. To support pilots in these unforseen situations, automation and instrumentation need to promote a high level of situation awareness (SA).

These considerations call for an alternative approach to designing a system (automation and interface) that assists pilots in maintaining separation.

1-1-2 Constraint-based visualizations

Several traffic displays in air and vessel transport domain have included visualizations of the conflict problem that show *no-go* constraint areas inside the navigation space, Figure 1.1(a) [25, 26], or *no-go maneuver bands* inside the speed and heading tapers on the flight instruments, Figure 1.1(b) [16, 17].

The presentation of constraint-based graphical descriptions of the conflict problem is a promising initiative to help human operators to prevent the creation of *new*



(a) PAD [25] (b) PASAS [16]

FIGURE 1-1: Examples of existing traffic displays that support for self-separation: Predicted Aera of Danger (PAD, left), and Predictive ASAS (right).

conflicts. However, their current visual formats and behavior are far from perfect, sometimes even confusing, in terms of helping pilots to understand the conflict, and judge the validity of the 'conflict-free' solutions proposed by automation.

Several issues can be noticed such as the behavior of these zones as a result of aircraft maneuvers, the linking of aircraft to respective constraint areas, the role of the behavior and intent of intruders (e.g., coordination), the urgency of each individual conflict, the time available to act before separation is lost, and aircraft control mode changes.

It might be argued that some of these information gaps can be 'fixed' by the intelligent use of additional signs or symbols in the display design. What would be preferred, however, would be to have a transparent *window* on the underlying physics that govern the conflict problem, and the rationale of the automation that provides a solution. This calls for a more profound analysis.

1-1-3 Problem definition

With respect to the design challenges of airborne self-separation, the existing representations of the conflict problem on the navigation interface do not seem to be completely satisfying. It is still unclear what conflict information pilots exactly require and in what form it is best presented. This thesis engaged to solve this fundamental problem, formulated as follows:

Problem definition

What information and what visual form would promote pilot traffic awareness needed to safely and effectively deal with traffic conflict situations?

In comparison with current CDTI and ASAS displays, novel solutions should promote pilot problem-solving and reasoning, the exploration of maneuver alternatives, understanding of the cognition behind the automation, and support for non-routine situations. In this thesis an **ecological approach** is adopted, the rationale and origins of which will be briefly discussed in the next section.

1-2 Ecological interface design

Many introductions to EID are available in the literature [27–29], for an excellent overview of the methodology the reader is referred to Vicente's book *Cognitive Work Analysis* [30]. The PhD thesis of my co-worker Borst [31] contains an elaborate introduction on the application of EID in the aerospace domain, focusing on *terrain* situation awareness. For the sake of brevity, only a brief synopsis will be provided here, emphasizing the *traffic* application of this thesis.

Ecological Interface Design (EID) is an interface design framework that addresses the cognitive interaction between users and complex socio-technical systems. It was originally applied to process control [27, 30]; a more encompassing term for the approach is Cognitive Systems Engineering (CSE). The ecological approach to interface design gives priority to the worker's environment, or 'ecology', focusing on how the environment imposes 'constraints' on the worker. It intends to express (in most cases: visualize) these constraints in a meaningful, functional way, taking advantage of the human capacity to directly perceive and act upon what the environment 'affords' [32].

EID consists of two main steps. The first step relates to the *content* and *structure* of the work domain, the second step addresses the interface *form* [19]. In the first step, a Work Domain Analysis (WDA) aims to identify the functions, constraints, and means-end relationships within the worker's environment, as these 'shape' the possibilities of goal-directed human or automation actions within that environment [30, 33]. The work domain analysis is performed using Rasmussen's Abstraction Hierarchy (AH) [34], which encapsulates all constraints of the work domain *independent* of its state [35]. The AH is a stratified hierarchical description of the workspace, defined by means-end relationships between adjacent levels [27].

In the second step, EID aims to make these workspace constraints and means-end relationships easily visible on the display. A visual form is created that intends to support the cognitive processing of humans at all three levels of Rasmussen's Skills, Rules and Knowledge (SRK) taxonomy, where EID aims to not force the operator to act on a higher level of cognitive control than demanded by the task [36].

Basically, the ultimate goal of EID is to transform a *cognitive* task into a *perceptual* task by providing humans with the meaningful information of the work domain in such a way that they can directly perceive and act upon accordingly. This transformation can also be described as, and is often referred to as: "*making visible the invisible*" [31, 37]. In the context of this thesis, the work in our lab emphasizes the analysis and identification of 'meaningful physics', that is, meaningful descriptions of the physics governing the aviation work domain, perhaps even developing these meaningful physics ourselves [19, 31, 38].

Along the line of thinking of the ecological psychologist James Gibson's [32], EID advocates a visualization of all constraints relevant for goal-directed behavior in such a way that the operator can take effective action and understand more about how these actions will fulfill the objectives. Applying these principles to aircraft self-separation, Gibson's direct coupling between perception (what is the traffic situation?) and action (what can I do about it?) is achieved by mapping the affordances for the own aircraft locomotion on the interface. The motion of aircraft in the vicinity of the own aircraft may have an effect (that is, limit) the own aircraft locomotion possibilities. These affordances should be an integral part of the separation display, and should be somehow connected to the means of the individual pilot.

The EID approach is considered a **formative** approach to interface design, an approach that emphasizes the analysis and visualization of **constraint-based** descriptions of the environment, which are independent of its state [31]. The work supported in that environment should therefore be independent from anticipations on events, tasks and system states which users may face [30].

The ecological approach is hypothesized to yield interfaces that better support worker adaptation, also in situations that were not anticipated by the interface designers [30]. A survey showed that in many cases EID indeed resulted in better operator problem-solving performance as compared to traditional designs [29]. Previous work in our laboratory often confirmed this finding, in various applications that aimed at supporting pilot situation awareness and decision-making in tasks ranging from energy management to terrain awareness [31, 39–43].

1-3 Research goal and challenges

1-3-1 Thesis goal

To answer the research question formulated above, the main goals of this thesis can be formulated as follows:

Thesis goal

Determine the *meaningful* information in the work domain of air traffic conflict avoidance. Design and evaluate interface mappings that enhance pilot traffic situation awareness and decision making as compared to state-of-the-art CDTI and ASAS displays.

The *ecological approach* to situation awareness and interface design is adopted. Conventional EID tools as proposed by Vicente and Rasmussen are used, such as the Abstraction Hierarchy and the Skills, Rules, Knowledge taxonomy, to perform the work domain analysis and design the interfaces.

Given that previous studies on EID showed its advantage in supporting operators in unforeseen situations, the main hypothesis is the following:

EID hypothesis

Ecological interface designs improve pilot situation awareness as compared to current CDTI and ASAS interfaces, to the benefit of safety in situations that were unforeseen in the system design phase.

To date, not many 'truly ecological' interfaces exist for the control and supervision of aircraft. A first published EID design in aerospace, by Dinadis and Vicente, concerns the supervision of the aircraft's engine status [39], an application that still very much resembles that of 'typical' processs control. Later, Amelink evaluated aircraft energy management aspects, [40], the processes of exchanging potential and kinetic energy by means of a 'reservoir analogy', and in this respect resembling DURESS, Vicente's application for which EID was validated the first time [30], but extending it to aircraft vertical motion control.

Borst [31] was the first to publish a PhD thesis that was completely dedicated to the application of EID on supporting pilots in one of their primary control tasks, separation with terrain, involving also the 'basic' controls and navigation systems of aircraft. In this thesis, originating in the same time-frame as the latter, the geometric and kinematic constraints between aircraft moving in the same airspace will be analyzed in detail, the first results of which were published in [44] and [19].

1-3-2 Research challenges

Four major challenges need to be addressed when applying the ecological approach to the problem of pilot traffic situation awareness.

Research challenges

1. Gain insight into the laws of physics that govern the work domain of tactical self-separation and express them in a format meaningful to pilots.

2. Gain insight into interface mappings by addressing the *creative gap* between work domain analysis and interface design.

3. Gain insight into *how* and *to what extent* automation should be involved in tactical self-separation, such that a high level of pilot situation awareness is maintained.

4. Gain insight into how conflict avoidance displays could be objectively evaluated and compared, such that the EID benefits or pitfalls become apparent.

These challenges are fundamental for *any* application of the ecological approach to design interfaces. Borst faced very similar challenges in his attempts to apply the ecological approach to support pilot terrain awareness, see Ref. [31]. This thesis will address the issues encountered when aiming to support pilots in separating their own aircraft from other aircraft. In contrast to terrain constraints, which are static, other traffic involves *dynamic* constraints in the aircraft motion. Another important difference is that whereas separation with terrain involves especially the aircraft vertical motion, the problem of separation with other traffic also, and primarily, involves the aircraft lateral motion capabilities.

The **first challenge** is to conduct a WDA for a vehicle motion problem. Three important differences exist between the traditional EID work domain of process control, and the flight deck. First, a flight deck is an *open* system. In a more *closed* system, such as a washing machine as a very simple example of a process control plant, the processes involved (electricity, water supply) as well as the physical location of the plant (fixed, in a safe place), are very much contained, and all external constraints are well known and measurable or quantifiable. Many of the system malfunctions can be thought of beforehand, and countermeasures taken and accounted for in the automation design. In contrast, an aircraft is much more subject to complex and also unpredictable behavior of external constraints that are beyond the control of the flight deck crew. External constraints imposed by weather and other traffic can result in *poorly-defined* dynamics of the work domain [45, 46]. Second, traffic has also an *intentional nature* making the modeling of its behavior in the WDA and the implications for interface design a concrete challenge in this research. And third, the *time scale* of the work domain is very different, as aircraft motion involves faster dynamics than controlling, e.g., a power plant, resulting in completely different interface features and control inputs [31]. As stated above, an important aspect of this thesis is that it needs to capture the dynamic constraints of other traffic in the WDA, which may lead to completely different visualizations than what is available on the flight deck today.

The **second challenge** is the actual interface design process. An extensive list of literature can be found on the WDA and the AH, but the *design* of the interface is mostly left to the designer's imagination, leaving a *creative gap* between the domain domain analysis and the actual interface [19, 29, 31, 33]. Experience from our earlier research indicates that setting up the AH and creating the interface often involves many iterations, where the results of the WDA and the interface design affect each other, feeding each other in ways that are often unexpected [31, 42]. In becoming more and more of an expert, the display designer can more and more clearly state what elements and constraints of the work domain really matter, and which ones do not. Here the consequences of the dynamic and intentional constraints of other traffic will need to be captured and visualized in a compelling way, such that the pilots can directly perceive their aircraft motion capabilities.

The **third challenge** is that the ecological design, like any interface design or automation 'help', for that matter, should not add complexity to the operator's task [29, 33, 43, 47]. Clearly, complex work domains may require (and lead to) complex and visually cluttered interfaces that often overwhelm novice users and even domain experts. It is here where often (part-task) automation is included to help the users to cope with complexity, leaving the challenge becomes to determine *how* and *to what extent* automation should be introduced. In the context of this thesis, the pitfall for the designer would be to simplify the conflict situation in an attempt to make the task easier, but which may make the interpretation of the complete situation a cognitively more demanding process.

The **fourth challenge** is that although ecological interfaces are expected to yield benefits to pilot SA and decision making, very few experimental comparisons exist of EID designs against viable design alternatives. Task- and cognitive-oriented evaluation methods may fail to capture the benefits gained from the ecological display, as these are hypothesized to appear in particular for rare, unforeseen events which are difficult to test experimentally. The challenge in this research is therefore to develop an evaluation method (and metrics) that allows for an objective comparison of conflict avoidance displays, targeted at revealing EID benefits such as improved conflict awareness and support for unforseen situations.

1-4 Thesis scope and assumptions

1-4-1 Scope: work domain boundaries

Clearly, the scope of the thesis cannot capture all elements of the flight deck. Constraints imposed by terrain and weather are not considered here, for which the reader is referred to Refs. [31, 41, 48] and [49], respectively.

This dissertation discusses the application of the EID design principles to promote traffic awareness and support airborne self-separation. Thus, only other traffic in the tactical time horizon is considered, i.e., it considers the tactical maneuvering of the aircraft with the purpose to avoid loss of separation with other aircraft.[§]

The type of automation in this thesis applies to traffic awareness systems where traffic information to support tactical self-separation is *added* to the conventional Navigation Display (ND) and pilots always have the final authority in terms of decisions and control. Throughout this work the domain of *tactical self-separation* may also be referred to by generally used terms as *conflict avoidance* or *separation assistance*. In our group it was originally addressed as *Airborne Trajectory Planning* (ATP): it reflects a more integrated view on 4D trajectory planning in relation with several external constraints, and became the label for the horizontal design.

The EID design principles are used firstly to determine which constraints determine pilot decision making and how they relate with each other (domain analysis), and secondly to find viable representation formats for *hidden* constraints, that is, constraints which are currently not yet explicitly shown in the cockpit (interface design). Three different designs are discussed: 1) the horizontal plane; 2) the vertical plane, and 3) the horizontal plane re-design, which includes the use of intent information from Autopilot (AP) and Flight Management System (FMS).

1-4-2 Research assumptions

Now that the system boundary is defined, the main research assumptions can be stated.

First of all, it is assumed that pilots are operating in cruise flight conditions in an uncontrolled airspace that is not constrained by standard conflict management procedures or Air Traffic Control (ATC) requirements. They have complete authority to decide about and perform aircraft maneuvers based on the interpretation of the navigation information overlays. It allows to explore less-obvious designs shaped by the physical rather than current intentional work domain constraints. Maneuver

[§]Note the difference between aircraft self-separation ASAS systems with collision avoidance systems such as TCAS. ASAS systems are primarily designed to assist pilots in preventing a loss of separation whereas collision avoidance systems explicitly provide (command, actually) escape maneuvers to avoid aircraft collision once separation has been lost.

strategies to resolve conflict situations may be designed as part of the EID design process.

Second, in the design of the ecological overlays it is assumed that no current technological boundaries limit the design. Similar to the ecological terrain awareness display design of Borst [31], we assume that all input variables needed by the interface are available by some means of either onboard measurements, inter-aircraft communication, and computing systems. The accuracy, availability and integrity of aircraft navigation and traffic information is not considered an issue.

Third, only the conventional Navigation Display (ND), for the horizontal design, and the Vertical Situation Display (VSD), for the vertical design, will be considered for the ecological overlays. The Primary Flight Display (PFD) will be unaltered, as it is considered here to be better suited for shorter-term aircraft control problems.

Fourth, the design overlays are aimed at supporting single pilot actions entailing a *global* solution to a given (multi-)conflict situation. This means that preferably one maneuver action is used to resolve or prevent conflicts with all nearby traffic. After this action, additional actions are allowed in response to changes in the conflict situation, or, as a final path recovery maneuver.

Fifth, automation is primarily used to *calculate and visualize* constraint-based conflict information, and does *not* show explicit automated solutions. Figure 1-2 illustrates the three most common aircraft control states [50]: (1) the direct manual control of the vehicle by a pilot, (2) the 'target state control' mode where pilots put set-points (e.g., altitude, speed, heading) into their autopilot systems, and (3) the fully automated mode where pilots program the aircraft trajectory, through their Control Display Unit (CDU), which is then used by the FMS to put the autopilot to work. In this thesis, the pilots are assumed to be working in the second mode, 'Target State Control', setting target states for the auto-pilot using their Mode Control Panel (MCP).

Finally, the scenarios that are designed to evaluate the ecological designs can be considered to be rare events, to investigate the pilot response in these off-normal situations. The design evaluations are single-pilot experiments, where pilots make decisions to deal with intruder aircraft flying near the own aircraft. The motions of these intruder aircraft are pre-programmed and do not depend on the particular decisions of pilots participating in the experiment. This is done to eliminate any emerging scenarios and to better 'control' the experimental 'situations'.

1-5 Chapters in the thesis

Except for the first and last chapters, the thesis consists of (adaptions of) journal publications and peer-reviewed conference proceedings; their content has been

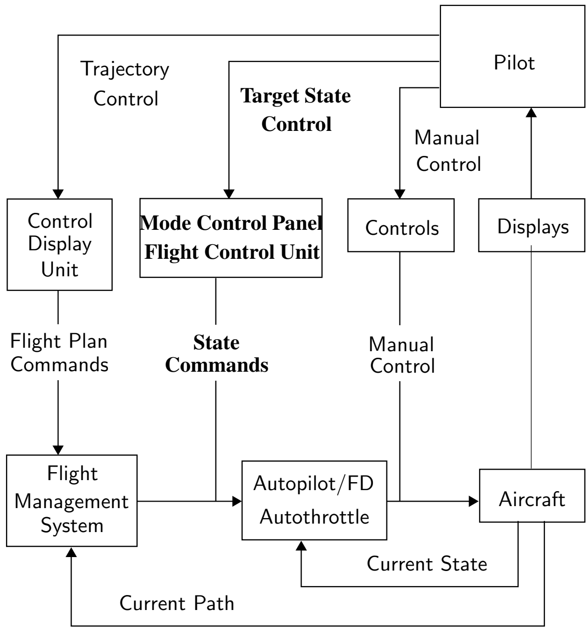


FIGURE 1-2: The three aircraft control states: (1) Manual Control; (2) Target State Control, and (3) Trajectory Control [50].

mostly preserved and chapters can be read independently.

All chapters have been ordered in a logical way to differentiate between the dimension (horizontal or vertical) and the available traffic information (state-based or including also intent). The chapter titles may differ from the original papers, for the sake of consistency of the thesis. With exception of the chapter on the vertical design, the order can also be interpreted chronologically with respect to the conducted research. In some cases, similar elements might be found in the introductory sections of the papers. Each chapter is introduced on the first page with a short description, that aims to explains how the chapter fits into the thesis storyline. In the following these descriptions are included as a summary of the following 5 chapters, and the conclusions chapter.

Chapter 2: An ecological approach to airborne self-separation This chapter describes the application of EID to the problem of airborne self-separation. It summarizes some findings from earlier research. Several concepts and tools related to the ecological approach are specifically addressed in the context of trajectory planning and dealing with conflict situations. In the horizontal plane, two design iterations with their respective locomotion models and representation formats are discussed (heading, speed-heading function). As a result, a state-based Airborne Trajectory Planner (ATP) design uses actual position and velocity information of the surrounding traffic to calculate and present tactical maneuver constraints in a speed-heading vector space overlay. A first experimental evaluation tests the validity of the design concept for several conflict geometries. The ideas expressed in this chapter and the resulting interface overlay serve as a starting point for further design iterations and extensions presented in the following chapters.

Chapter 3: Comparison with a viable design alternative In this chapter a second design iteration is presented, the eXtended ATP (XATP) display that accounts for turn dynamics when presenting the forbidden beam one (FBZ) areas. Whereas in the previous chapter an exploratory evaluation was done to check the validity of the design, this chapter discusses an extended theoretical and experimental comparison between the XATP design and a viable design alternative: PASAS. The comparison was restricted to the representation of 'no-go' maneuver constraints, in other words, the FBZ areas are compared with PASAS speed and heading bands. A theoretical analysis using the EID framework is given, and the results of an experiment measuring safety, performance and workload are discussed. Relations between display type, conflict geometry, and pilot decision making will be identified. Although the theoretical comparison indicates that XATP is better suited to promote pilot traffic situation awarenes, the ultimate self-separation performance metrics were found to be similar with both displays.

Chapter 4: Evaluating pilot conflict situation awareness In the previous chapter, the expected differences from the analytical comparison are not reflected in the results of the pilot experiment. These findings acknowledge that measuring pilot subjective workload and performance may be less suitable when evaluating the ecological features of an EID against alternative designs. In this chapter, a second comparative evaluation applies a more situation-oriented approach by developing objective, explicit measures and measurement techniques for traffic SA. In addition to the former comparison, the automated ASAS resolution advisory is added to the PASAS bands, i.e., the complete PASAS design is used. A new experiment using the most promising SA measures and techniques is set up and discussed.

Chapter 5: Vertical design The ecological approach to visualize separation is applied to the vertical plane. Using the Vertical Situation Display as a basis, novel ecological overlays are added, yielding the Vertical Situation Awareness Display (VSAD) which can be considered to be the vertical counterpart of the horizontal (X)ATP design. In addition to the existing work domain content for the horizontal plane, the vertical plane analysis also includes energy conservation laws. This chapter discusses the design in the vertical plane with its particular design issues, including an off-line pilot experiment that focuses on traffic situation awareness.

Chapter 6: Use of intruder intent information In the previous chapters the 'state-based' XATP and VSAD interfaces all used trajectory and conflict prediction based on *current* speed and heading of the own aircraft and the surrounding traffic. This assumption limits the applicability of the system as it does not use autopilot information such as the current speed or heading settings, neither FMS flight plan information. In this chapter, information on autopilot settings is used to enhance the presentation of ongoing intruder maneuvers, while the FMS Trajectory Change Points (TCP) are communicated over ADS-B to provide a better tactical image of the traffic situation according to each flight plan. We will analyse how *intent* information could enhance the state-based design and proposes an intent-based XATP design, and related maneuver strategies capable of supporting pilots in different aircraft control modes.

Chapter 7: Conclusions and recommendations In this chapter the main results of the thesis will be discussed at the hand of the four research challenges stated in the Introduction. Final conclusions of the thesis are stated, followed by recommendations for future work.

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2

Horizontal design

This chapter describes the application of EID to the problem of airborne self-separation. It summarizes some findings from earlier research. Several concepts and tools related to the ecological approach are specifically addressed in the context of trajectory planning and dealing with conflict situations. In the horizontal plane, two design iterations with their respective locomotion models and representation formats are discussed (heading, speed-heading function). As a result, a state-based Airborne Trajectory Planner (ATP) design uses actual position and velocity information of the surrounding traffic to calculate and present tactical maneuver constraints in a speed-heading vector space overlay. A first experimental evaluation tests the validity of the design concept for several conflict geometries. The ideas expressed in this chapter and the resulting interface overlay serve as a starting point for further design iterations and extensions presented in the following chapters.

Paper title Ecological Interface Design of a Tactical Airborne Separation Assistance Tool

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ABSTRACT

In a free flight airspace environment, pilots have more freedom to choose user-preferred trajectories. An on-board pilot support system is needed that exploits travel freedom while maintaining spatial separation with other traffic. Ecological Interface Design is used to design an interface tool that assists pilots with the tactical planning of efficient conflict-free trajectories towards their destination. Desired pilot actions emerge from the visualization of workspace affordances in terms of a suitable description of aircraft (loco)motion. Traditional models and descriptions for aircraft motion can not be applied efficiently for this purpose. Through functional modeling, more suitable locomotion models for trajectory planning are analyzed. As a result, a novel interface, the State Vector Envelope, is presented that is intended to provide the pilot with both low-level information, allowing direct action, and high-level information, allowing conflict understanding and situation awareness.

Nomenclature

$ADS-B$	Automatic Dependent Surveillance - Broadcast
$ASAS$	Airborne Separation Assurance System
AH	Abstraction Hierarchy
ATP	Airborne Trajectory Planning
CPA	Closest Point of Approach
EID	Ecological Interface Design
FBZ	Forbidden Beam Zone
ND	Navigation Display
$P-ASAS$	Predictive ASAS
SVE	State Vector Envelope
$X-ATP$	eXtended Airborne Trajectory Planning

2-1 Introduction

IN the traditional airspace environment, capacity problems are expected in the near future due to growing air traffic. New concepts for Air Traffic Management, such as Free Flight, permit a more flexible use of airspace with airborne determination of user-preferred trajectories that allow direct routing and cruise climb [1]. This will increase airspace capacity and reduce congestion problems, but at the same time it leads to more complex traffic flows, increasing workload of air traffic controllers.

A possible way to reduce workload would be to delegate the separation task to the pilot. In order to assist pilots in self-separation, Airborne Separation Assurance Systems (ASAS) [2], like Predictive ASAS (P-ASAS) [3], have been developed.

ASAS systems form a strategic complement to currently deployed Airborne Collision Avoidance Systems (ACAS) like the Traffic alert and Collision Avoidance System, TCAS II [4]. In the same way as ACAS systems do, traditional ASAS systems present a ready-to-use avoidance maneuver as a solution.

Generally, these automated systems present a limited set of explicit solutions to the pilot, and have proven to be effective as far as providing conflict* resolution and reducing workload are concerned. A few observations can be made, however, with respect to automated airborne self-separation support. First, when a conflict situation exists, explicit automated solutions hold pilots back from exploring solutions other than the one(s) presented, and therefore, may preclude the full exploitation of travel freedom and airspace capacity offered by future airspace environments. Second, in a complex traffic environment, non-routine situations may arise, often beyond the scope of the automation and not anticipated for in the automation design. In these exceptional cases, the pilot's ability to improvise outperforms automated solutions. To support pilots in these unforseen situations, automation and instrumentation need to promote a high level of situation awareness.

These considerations call for an alternative approach to designing a system that assists pilots in maintaining separation. In the present work, the term "separation assistance" rather than 'separation assurance' is used to label systems that help the pilot maneuver tactically in order to manage conflict situations, without giving an explicit resolution. Our objective is to show how Ecological Interface Design (EID) [5] can be used to design such a decision-support tool. The design of this tool is based on an analysis of aircraft motion in the context of exploring travel possibilities. With the help of functional modeling techniques [6], aircraft behavior can be modeled in such a way that a presentation of the 'travel function' allows pilots to directly perceive which control actions lead to desired aircraft behavior, in a goal-directed fashion.

The paper is structured as follows. After some introductory definitions, first the cognitive work associated with planning a conflict-free trajectory is analyzed. Then, two aircraft locomotion models and the visualizations and afforded planning strategies associated with them, are discussed. The most promising interface, the State Vector Envelope, is described, focusing on how it supports pilot cognitive control. Finally, the results of a preliminary pilot evaluation are described.

*The term 'conflict' means a predicted loss of separation between two aircraft in the near future. It will be defined more accurately below.

2-2 Ecological Interface Design

Ecological Interface Design (EID) is a design paradigm that addresses the cognitive interaction between humans and complex sociotechnical systems. It was originally applied to process control [5]. Its approach to interface design gives priority to the workers environment ('ecology'), focusing on how the environment imposes constraints on the worker. EID supports worker adaptation and has proven better problem-solving performance when compared to other approaches [7].

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) [8]. Second, EID 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 [9]. System functionalities and mechanisms that are often 'hidden' from operators in traditional automated systems are made more transparent. In the present context, automation is used for the benefit of pilot situation awareness.

2-3 Workspace Analysis

The analysis is made for the tactical navigation work, which will be referred to as Airborne Trajectory Planning† (ATP). The work involves on-board (re-)planning to achieve a safe, conflict-free and efficient trajectory to the destination within a future, Free-Flight like, airspace environment. A number of pilot-aircraft activities relate to this work, such as resolving and preventing conflicts, arriving on-time at a destination, etc. The Abstraction Hierarchy serves as a tool to set out a guide map of how different processes on different levels of functional abstraction relate with each other [5].

2-3-1 Abstraction Hierarchy

Figure 2-1 shows an abstraction hierarchy for airborne trajectory planning showing only the most important functions. Relations between functions are not explicitly shown. The AH is a stratified hierarchical description of the workspace, defined

†Note that the term 'trajectory planning' might suggest on-board *strategic* Flight Management System trajectory planning, which it is not. The terms 'ATP' or simply 'planning' or 'planning work' used throughout this paper strictly address on-board *tactical* trajectory planning work.

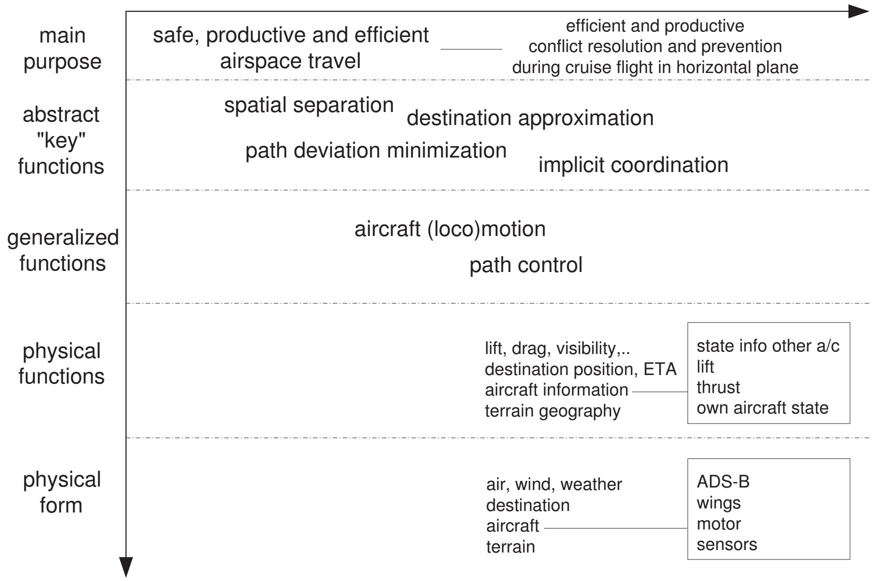


FIGURE 2-1: Abstraction Hierarchy for airborne trajectory planning workspace.

by means-end relationships between adjacent levels [5]. In the vertical direction, a functional "means-end" decomposition of the workspace is presented. In the horizontal direction, connection lines indicate a whole-part decomposition. It reveals constraints of, and relationships between, aircraft and airspace components, path control, locomotion physics, planning key functions and the achievement of travel goals in terms of safety, production and efficiency.

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 [4]. A 15 minute upper threshold is chosen because the vast majority of conflict resolution and recovery maneuvers take less than 15 minutes. In order to reduce problem complexity, only motion in the horizontal plane is considered in this study. Extensions to the vertical plane as well as combined vertical/horizontal representations are currently being developed [10].

The hierarchy was developed using a top-down approach. At the highest abstraction level, i.e., the functional purpose, the ATP systems' main goals are identified as safe, productive and efficient travel through airspace. In the context of conflict management, this means the efficient and productive prevention/resolution of conflict situations during cruise flight in the horizontal plane. At the abstract function level, the key functions describe how these goals can be achieved: while approaching the destination and limiting path deviation, spatial separation must be maintained at all times. Implicit coordination between different aircraft is beneficial for the realization of the key functions. On the general function level, the processes of aircraft locomotion and pilot control are described. Path control is done using the autopilot. Pilot control inputs relate to aircraft motion through aircraft kinematics and dynamics. On the bottom of the AH, the physical form and functions are described using the airspace model, including the ownship and intruder aircraft. While these levels are relevant for the physical implementation of the system, they are not directly relevant to the work described here and will not be considered further.

2-3-2 Workspace Key Functions

In this subsection the requirements for goal achievement are analyzed and the relations with lower levels (locomotion, control, aircraft state, etc.) are identified.

Spatial separation [safety goal]. Spatial separation addresses separation from terrain and objects in space. Regarding separation from other aircraft, a separation standard is defined through a Protected Zone (PZ) centered around the aircraft [1] [1]. Intrusion of this space is referred to as a 'loss of separation', destroying the safety goal. In the horizontal plane, the PZ is a circle with a radius of 5 NM, Figure 2-2. A conflict situation is defined as a future loss of separation within a given look-ahead horizon of 5 minutes. Based on the ownship speed vector $\vec{V}_{own}$, and the intruder speed vector $\vec{V}_{int}$, a conflict detection algorithm can predict where the separation between both aircraft is minimal, the Closest Point of Approach (CPA). In the situation illustrated in Figure 2-2, the CPA lies inside the PZ, and separation will be lost within 5 minutes if no action is taken. Aircraft positions and PZ at the moment of CPA are also drawn in grey; these predictions are based on a new ownship speed vector, $\vec{V}_{new}$. Clearly, separation can still be lost, even if the ownship turns away from the original PZ.

Destination approximation [production goal]. Production addresses certain "performance" to be produced by traveling. In general, this comes down to transporting persons or goods comfortably from A to B and deliver them on-time. For trajectory planning, spatio-temporal deviation constraints, also known as time slots

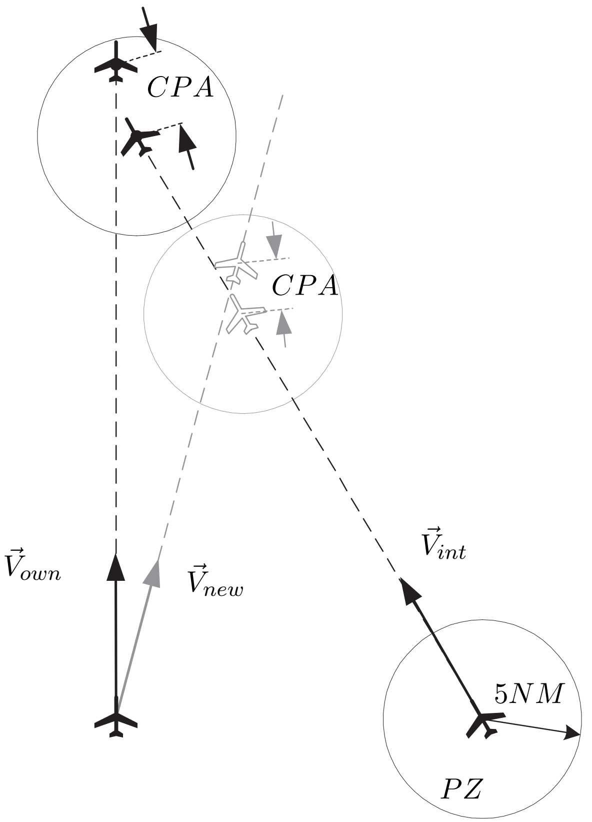


FIGURE 2-2: Plan view of a conflict. The CPA is calculated for the current ownship speed vector (black) and a new owncraft speed vector (grey) after a turn.

or time 'gates', exist with respect to the destination, next waypoint or other point. For this study, a simple requirement will be used, stating that the distance between aircraft and destination should decrease at all times. Thus, the pilot would nominally head straight towards the destination.

Path deviation minimization [efficiency goal]. Efficient travel addresses economic, fuel-efficient flight. Regarding conflict situations, the maximum spatial deviation from the path, δ_{max}, is defined as the distance between the ownship's reference position and its actual position at CPA instance, see Figure 2-3. The reference position is based on the prediction using the original ownship's speed vector $\vec{V}_{own}$. The actual position is based on the resolution vector $\vec{V}_{res}$. After the CPA instance, the pilot will start a recovery maneuver to direct the aircraft back towards the original

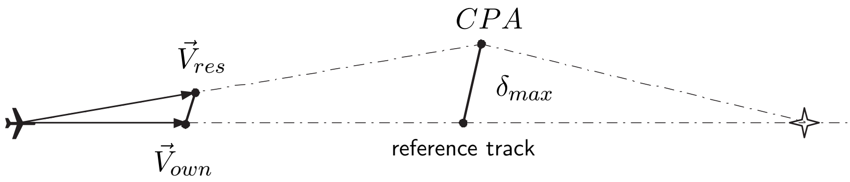


FIGURE 2-3: Maximum path deviation δ_{max} at instance of CPA.

trajectory. The deviation due to conflict resolution is determined by two physical phenomena: the state change magnitude $|\Delta\vec{V}|$ and the duration of the resolution, the resolution time t_{res}. The most efficient resolution minimizes the product of both factors:

$$\delta_{max} = (|\Delta\vec{V}| * t_{res}). \tag{2-1}$$

The state change magnitude $|\Delta\vec{V}|$ is obtained by subtraction of the original ownship's velocity vector $\vec{V}_{own}$ from the new ownship's resolution velocity vector $\vec{V}_{res}$:

$$\Delta\vec{V} = \vec{V}_{res} - \vec{V}_{own}. \tag{2-2}$$

The deviation measure δ_{max} is useful to compare different resolution maneuvers when considering their efficiency.

Implicit coordination. Aircraft involved in the same conflict can have a mutual benefit from their maneuver actions if they are done in a coordinated fashion. E.g., for two aircraft on a head-on collision course, coordination is fully exploited if both make a starboard turn maneuver. This way, the required resolution time or maneuver magnitude can be halved if compared to the case where only one aircraft maneuvers. As a result, the realization of other key functions becomes easier. Since no intent information is explicitly exchanged, a support tool should preferably "implicitly" assure coordination by the way it presents the conflict situation.

Goal priority. Situations may occur in which not all goals can be met. In these cases, goal priority comes into play [11]. Safety is the highest priority, followed by production, then efficiency. For example, conflict situations may require trajectory deviations away from the destination.

2-4 Functional Modeling of aircraft behavior

The workspace analysis provides an overview of the content and structure of the planning workspace, but does not yet provide us with any clues on how to create a meaningful display given that it doesn't answer the following questions:

By which aircraft (loco)motion can separation best be realized and how must it be visualized? How can we reveal the relation between a conflict resolution and path deviation, implicit coordination and aircraft locomotion?

Thus, a step that facilitates the acquisition of workspace constraints in a way that abets visual presentation is necessary. A good interface design requires a clear presentation of the workspace constraints and support for goal-directed behavior to enhance quick (re)action upon behavior of the environment [12].

In the present context, the 'system' dynamics are complex, as they depend on the behavior of multiple aircraft moving relative to each other. Traditional formulations of aircraft dynamics express aircraft (loco)motion through formulations given in the form of non-linear state-space equations, e.g.:

$$\underline{\mathrm{x}} = \big(p, q, r, \phi, \theta, \psi, u, v, w, x, y, z\big)^T \,,\ \dot{\underline{\mathrm{x}}} = f(\underline{\mathrm{x}}, \underline{\mathrm{u}}, t). \tag{2-3}$$

Although two (or more) of these equations (one for the ownship, one (or more) for any other nearby aircraft) describe the aircraft behavior adequately, a description of aircraft locomotion in this format is not useful for interface design as it fails to answer the two design requirements stated above.

First, the state-space formulation has too many degrees of freedom to be of practical use for goal-directed control. The input to the controlled system, the aircraft, is a function of time, $\underline{\mathrm{u}}(t)$, and in principle any input can be given, (resulting in a high-dimensional "possible behavior" of the aircraft). Evaluating all possible inputs is impractical, and trying to display these options and their consequences even more so. A low-dimensional description of aircraft behavior that uses inputs that match flight practice should be used. If not, the pilot will be unable to perform the described aircraft behavior.

Second, the state-space formulation is not related to any goal-oriented behavior of the pilot. That is, for pilots the main concern is not: "Which path will the aircraft follow if I do this?", but rather: "Will it reach the destination without crashing into something?". Engineering descriptions for aircraft motion and motion paths, like the state-space description, do not directly relate to the goal-directed constraints in the planning workspace. Consequently, they are of little use in designing presentations that help pilots choose a trajectory.

In order to obtain goal-directed descriptions for aircraft behavior, or (loco)motion, one needs to describe the "function of" locomotion. Here the word function is defined as ‘useful behavior’ [13], i.e., behavior that is relevant to achieving one’s ends. Functional modeling [6] describes the goal-relevant behavior of a system. By determining what types of possible behavior are functional to goal achievement, the possible alternatives for goal achievement are obtained.

Considering that we are matching the capabilities for action of a pilot-aircraft system, and their consequences as determined by its airspace environment (including other aircraft in the vicinity), parallels can be drawn with ecological psychology [9]. In this context, the affordances of the surrounding airspace describe the options available to aircraft and pilot, of which some are functional (avoiding other aircraft). A visualization of affordances of travel was already exemplified in the illustrations in Gibson’s classic 1938 paper [14].

In the original EID framework applied to process control, the interface built for the power plant formed a new ecology/environment for the operator. For travel, however, pilots already use an existing ecology, in the form of the outside view and cockpit instruments, and therefore natural ecological perception of affordances already exists. A pilot can for example predict a future collision by perceiving the angle between the ownship heading and the line extending to the intruder. If this angle remains constant in time, both travelers will eventually collide if no action is taken. A new interface tool should not substitute, but enhance this natural perception, by making visible those airspace affordances that are “hidden” from the naked eye [15]. In Figure 2-2, one is not able to see by which maneuver the situation will or will not be resolved, even when the CPA and PZ are presented.

Different airspace elements yield different travel affordances. With respect to the ownship, intruder aircraft afford “collision” or “avoidance”. With respect to the actual position of the aircraft, the destination or planned position affords “approximation” or “deviation”. With respect to the aircraft traveling, air affords locomotion. With respect to the wings, air affords pressure difference. Note how airspace affordances relate to workspace constraints on different functional levels as well as decomposition levels of the AH (Figure 2-1). The planning affordances that directly relate to more functional levels of abstraction are summarized in Table 2-1. The next sections will investigate how the airspace environment should be presented, so that planning affordances can be perceived and fluently transformed into functional aircraft behavior, supporting the natural coupling between perception and action.

2-5 Heading Travel Function (HTF)

The description of locomotion used to present the affordances must match pilot flight practice and limit the number of degrees of freedom. The present research took the approach to select a reasonable locomotion model and analyze if it was

TABLE 2-1: Planning goals, key functions, affordances of airspace elements, and maneuver strategies for Heading Travel Function (HTF) and Speed-Heading Travel Function (SHTF). The strategy for implicit coordination only holds for conflict resolution.

planning goal	**key function** **affordance [airspace element]**	**HTF strategy** **SHTF strategy**
safety	spatial separation avoidance [other aircraft]	stay/get outside band stay/get outside FBZ
production	destination approximation approach [destination]	keep destination in front keep destination in front
efficiency	deviation minimization approach [original trajectory]	choose nearest band edge limit state change avoid FBZ origin
safety/efficiency	implicit coordination coordination [other aircraft]	choose nearest band edge go to nearest FBZ leg

possible to present planning affordances. For cruise flight limited to the horizontal plane, the pilot controls the aircraft through heading and/or speed settings.

The first generation of locomotion models aimed at presenting planning affordances in terms of travel opportunities governed by manipulating only the aircraft heading [16]. The first model was based on constant speed and instantaneous heading changes. A second model, the Heading Travel Function (HTF), included realistic turn dynamics. When considering these maneuver possibilities in a traditional plan view presentation where the ownship and other aircraft are shown, conflicts cannot easily be perceived. Knowing the velocities and trajectories of the involved aircraft conflicts can be detected, however, in a fast-time simulation, which is essentially the basis for current conflict detection and avoidance systems.

If the PZ is shown at the moment of CPA, as in Figure 2-2, one can see whether separation is lost for the current trajectory prediction based on vector $\vec{V}_{own}$. The CPA, however, is a characteristic of four-dimensional space, it only remains constant when the aircraft locomotion states are not changed. If a turn maneuver to starboard is made, the predictions for the new vector, $\vec{V}_{new}$, show that the CPA has moved and the conflict is not resolved at all. Thus, presenting the CPA does not enable pilots to "see" which maneuvers would resolve the conflict. Thus, in plan view orthogonal space, maneuvers can not be directly linked to separation. It is unclear which paths will eventually stay out of or enter the intruder aircraft PZ.

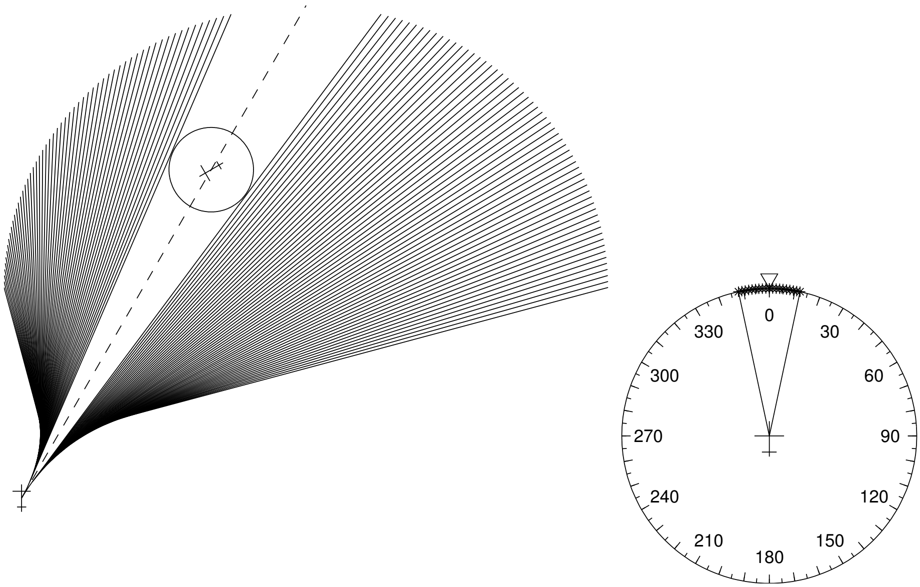


FIGURE 2-4: Heading Travel Function in intruder-centered reference frame (left); the heading band shows turns that will lose separation (right).

Conflicts can, however, easily be seen in a relative velocity field. In an intruder-centered reference frame, the motion of the ownship is expressed relative to the intruder and the intruder's PZ is pinpointed in space. In this field, aircraft maneuvers can be linked to spatial separation. Subtracting the speed of the intruder yields a representation that shows travel of the ownship in a relative space, i.e., the space and travel relative to the intruder aircraft. On the left hand side of Figure 2-4, the HTF expresses which of the possible ownship paths will stay out of the intruder aircraft PZ. Note that the effects of turn maneuver dynamics are included, as can be noticed by the bended shape of each ownship path, together forming the set of relative motion paths that will realize separation.

2-5-1 Heading bands presentation

Safety. Travel in "relative space" is not a practical way to present travel options to the pilot. It is preferred to directly present which turn maneuvers resolve the conflict(s) and which do not. This way so-called heading bands can be created[‡].

[‡]It is important to emphasize the distinction between a "travel function", such as the HTF, and an "interface concept", such as the heading bands. A travel function is a formulation of aircraft motion

That is, the interval of turns that will lead to loss of separation is presented on the heading scale through colored heading bands, see the right hand side of Figure 2-4.

Since the turn geometry is included in the functional locomotion model, as soon as a turn to a conflict-free heading is initiated, the heading band edges remain stable, i.e., they maintain the same heading values. Note that our first locomotion model, based on instantaneous heading changes, did not take the turn dynamics into account and therefore failed to accurately predict the turn maneuver needed to get out of the heading band. From the heading bands presentation, a simple turn strategy can be used to resolve a conflict, i.e., "turn out of the heading band", see Table 2-1.

Production. The production goal, accomplished by the strategy to "head towards the destination", is easily realized by limiting possible heading changes for conflict resolution to 90 degrees. Generally speaking, for trajectory planning pilots can always turn "towards" the destination: making a turn so that the destination lies in the extension of the current heading.

2-5-2 Hypothesis for efficiency and implicit coordination

In order to set up a "turn" travel strategy that assures cooperation between two aircraft, the following planning rule was defined: "a conflict must be resolved by taking a turn towards the closest heading band edge". Because of the symmetrical conflict geometry, this will generally result in cooperative maneuvers. Both aircraft can simultaneously initiate these maneuvers, based on the position of their heading marker inside the heading band. Furthermore, an efficiency hypothesis can be explored: a conflict resolution maneuver towards the nearest band edge results in the smallest lateral deviation δ_{max}. A complete overview of the HTF planning strategies with respect to the key functions is presented in Table 2-1.

Research showed that the angular proximity of the heading band edge is not proportional to maximum lateral deviation [17]. The perception of both heading band edges and, then, the strategy of steering towards the closest edge, does not necessarily result in the smallest δ_{max} of the two possible turn resolutions. Some trajectories to resolve a potential conflict bring the aircraft on a parallel course. If the speed vectors of both aircraft are approximately equal, resolution time t_{res} becomes very high. As a consequence, a very large path deviation is obtained. Although steering towards the nearest heading band edge results in the smallest state change $\Delta\vec{V}$, the bands provide no measure of the duration of a conflict resolution. In some situations, a small $\Delta\vec{V}$ is accompanied by an extremely large t_{res}, causing the product of both terms, the path deviation δ_{max}, to become very large as well.

presenting a set of travel options to the pilot, whereas an interface concept is a presentation format that visualizes workspace constraints/affordances in terms of these travel options.

Another aspect of the HTF travel strategy is that it does not consider aircraft speed changes. In previous research on P-ASAS, the heading bands' width and position showed to be very dependent on speed [3]. When speed changes, heading bands move, split up, shrink or expand, changing the range of conflict-free headings. The unsteady heading band behavior based on the current speed caused P-ASAS to be extended with a multiple heading band presentation, based on a set of different speeds around the current speed [3].

Clearly, the presentations based on the HTF only present separation in an invariable way as long as the pilot avoids changing speed. However, satisfying other goals might require these speed changes to, for instance, compensate for time deviation along track. In that case, the bands lose their current width and position and it becomes useless and even misleading to show separation by heading bands. It is also doubtful whether implicit cooperation between aircraft can be perceived when multiple conflicts occur simultaneously. In that case, multiple heading bands belonging to different aircraft will appear and overlap each other on the heading scale.

An alternative for visualizing separation on a traditional plan view display is the presentation of "forbidden areas" where current trajectory prediction (conflict zone) and potential trajectories (no-go zone) will lose separation [18]. However, since these are also based on heading changes, they have the same deficiencies as the heading bands. That is, although adequate for pure heading changes (at constant speed), the shape is dependent on speed and sometimes fails to visualize more efficient conflict resolutions. Similarly, speed bands based on locomotion models that use constant heading have the same drawbacks as the heading bands: they are sensitive to heading changes and they fail to present efficient conflict resolutions. Presentations that use both speed and heading bands simultaneously do not improve much either as changing the state within one band changes the appearance of the other band. Clearly, a fundamentally different approach is needed.

2-6 Speed-heading travel function (SHTF)

The interaction between speed and heading must be fully understood. Hence, in the third locomotion model, the Speed-Heading Travel Function (SHTF) model, the aircraft behavior was modeled by combined speed *and* heading change maneuvers [17]. At this stage the aircraft dynamics were neglected, however, due to the increased complexity of expressing combined heading and speed changes. The main challenge lies in finding an invariable visualization for efficient conflict resolution in such a way that it supports a travel strategy that yields implicit coordination between two or more aircraft.

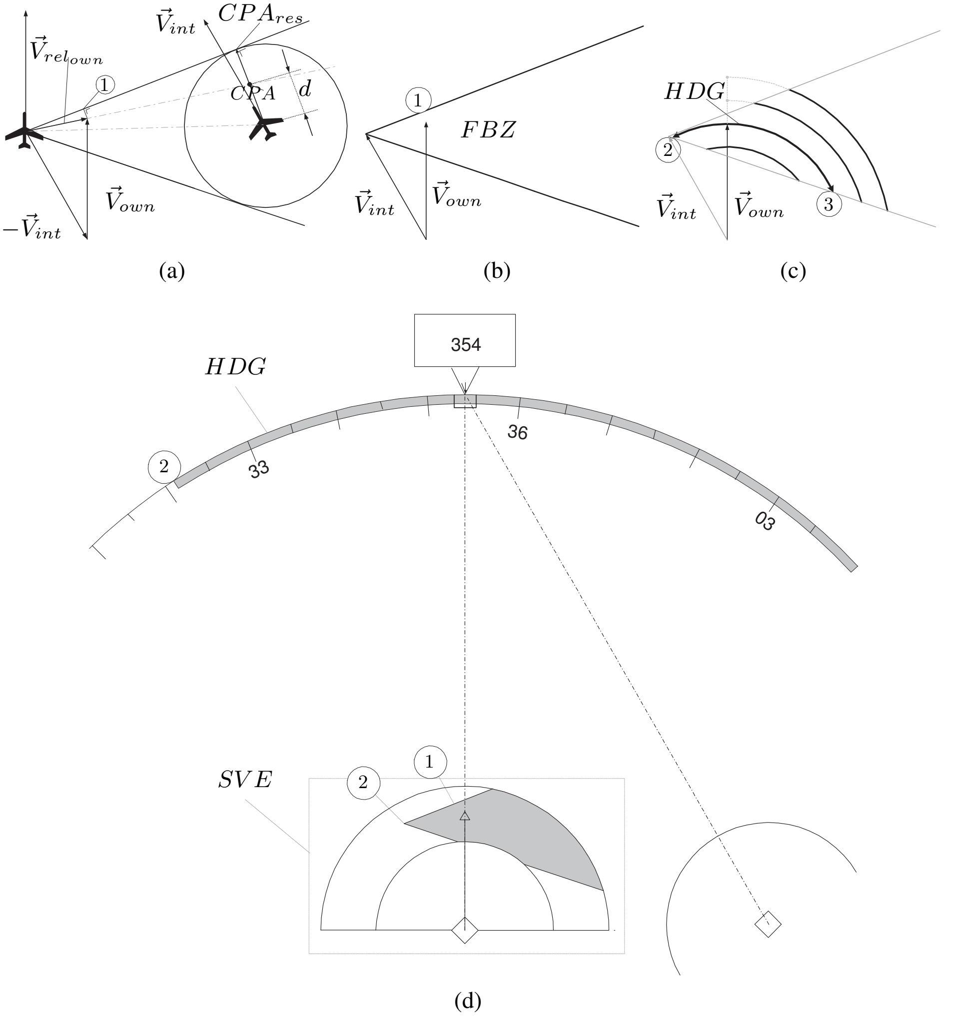


FIGURE 2-5: Presentation of a conflict situation: numbers 1 to 3 present possible conflict resolution maneuvers based on FBZ (1) and Heading Band HDG (2, 3). CPA_{res} is the resolution position of the CPA. (a) Relative motion of ownship with respect to intruder in an intruder-fixed reference frame. (b) Forbidden Beam Zone (FBZ) in an ownship-centered speed-heading space. (c) Heading Band (HDG) for different speeds in an ownship-centered speed-heading space. (d) State Vector Envelope (SVE) and Heading Band on a navigation display.

2-6-1 Forbidden Beam Zone and State Vector Envelope

Safety. As mentioned in the previous section, (loco)motion can be better related to spatial separation constraints in a relative velocity plane. Within this plane, a beam-shaped area can be defined, outlined in Figure 2.5(a), 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). In this example, the relative velocity vector $\vec{V}_{rel_{own}}$ is inside this area, and therefore the aircraft will eventually enter the PZ and separation will be lost. The minimum separation distance at CPA instance is indicated by d.

Separation can be realized by actions that cause the relative velocity vector to lie outside the FBZ. The nearest "exit" point on the FBZ is indicated by circled number 1 in Figure 2.5(a). If $\vec{V}_{rel_{own}}$ is moved to this position, the resulting resolution position of the CPA is then indicated by CPA_{res}. This particular resolution is identical to the resolution given by the 'voltage potential' method used in P-ASAS [3]. Since the relative vector is constructed by the own speed vector $\vec{V}_{own}$ and the intruder vector $\vec{V}_{int}$, spatial separation can be realized by a vector state change of the own speed vector, the intruder speed vector, or a combination of both.

In an ownship-centered speed-heading vector space, illustrated in Figure 2.5(b), the FBZ remains visible with respect to the own speed vector which is centered and placed upwards. The geometrical relations from Figure 2.5(a) remain identical, but the space is now pinpointed around the origin of the ownship speed vector $\vec{V}_{own}$. In the same space, one can draw an arc of constant speed inside the FBZ, revealing one (or more) heading bands. In Figure 2.5(c), the band is shown for the current speed (including arrow heads) and three other speeds (one band for slower speed, two bands for higher speeds). It shows why the position and shape of the heading bands in the HTF are sensitive to speed changes, and how this relates to the shape of the FBZ. Similarly, speed bands are sensitive to heading changes and they also fit inside the FBZ. This explains how the state bands based on a single variable (like heading in case of the heading band), behave when other control variables (in this case speed) are manipulated. In [3], this behavior was reported in the P-ASAS state bands designed for preventing the triggering of new conflicts during conflict resolution.

Efficiency. On the FBZ in Figure 2.5(b), the resolution maneuver that gives the smallest state change $|\Delta\vec{V}|$ is marked with the circled number 1. This maneuver is identical to the resolution proposed in the previous paragraph. The resolution time t_{res} equals the distance between both aircraft, $\Delta\vec{X}$, divided by the relative approaching velocity of the resolution speed vector $|\vec{V}_{res_{rel}}|$:

$$t_{res} = |\Delta\vec{X}|/\vec{V}_{res_{rel}}. \tag{2-4}$$

Since $\Delta\vec{X}$ is constant at the instance of choosing a resolution, t_{res} is inversely proportional to $|\vec{V}_{res_{rel}}|$. $|\vec{V}_{res_{rel}}|$ is the difference between the resolution vector

$\vec{V}_{res}$ and the vector pointing to the origin of the FBZ, $F\vec{B}Z_{origin}$:

$$t_{res} = c/|\vec{V}_{res} - F\vec{B}Z_{origin}|, \tag{2-5}$$

where c is a constant. $F\vec{B}Z_{origin}$ is equal in magnitude and direction to the intruder speed vector $\vec{V}_{int}$. As a consequence, t_{res} can be perceived by the distance between the resolution velocity vector $\vec{V}_{res}$ and the intruder vector $\vec{V}_{int}$:

$$t_{res} = c/|\vec{V}_{res} - \vec{V}_{int}|, \tag{2-6}$$

where c is a constant. If the resolution vector $\vec{V}_{res}$ lies far away from the intruder vector $\vec{V}_{int}$, the resolution time t_{res} will be small. When $\vec{V}_{res}$ has nearly the same heading and speed as $\vec{V}_{int}$, then the resolution time will go to infinity as nearly "parallel" trajectories are flown.

The description for the maximal deviation δ_{max} in Equation 2-1, can now be replaced by:

$$\delta_{max} = c * (|\vec{V}_{res} - \vec{V}_{ref}|/|\vec{V}_{res} - \vec{V}_{int}|), \tag{2-7}$$

where c is a constant. δ_{max} is proportional to the quotient of resolution state change magnitude $|\vec{V}_{res} - \vec{V}_{ref}|$ and the distance between resolution state and FBZ origin $|\vec{V}_{res} - \vec{V}_{int}|$. Since an efficient conflict resolution comes down to minimizing the maximal deviation, an efficient conflict-free travel strategy will require a small state change away from the FBZ origin.

If one now considers the heading band for the current speed in Figure 2.5(c), two resolution maneuvers are possible: a port turn to the point indicated by circled number 2, or a starboard turn to point 3. It can be easily seen that the state change magnitude $|\Delta\vec{V}|$ of resolution maneuver 2 is smaller than for solution 3. The heading band visualizes this magnitude and the HTF travel strategy tried to use this measure to form a travel strategy for cooperative efficient conflict resolution. However, since solution 2, the preferred resolution for the strategy, lies very close to the intruder vector $\vec{V}_{int}$, the resolution time t_{res} will be very large and the maximal deviation δ_{max} will be several times larger than for resolution maneuver 3. The FBZ visualizes both the state change magnitude $|\Delta\vec{V}|$ *and* the resolution time t_{res} so that deviation can be more effectively minimized. The resolution maneuver towards the point indicated by number 1 in Figure 2.5(b) is the best resolution option. Again note that this is identical to the resolution provided by P-ASAS [3].

Production and other constraints. The presentation of the FBZ can be further adapted by introducing other workspace constraints/affordances. Limitations to aircraft performance (constraint at physical level), such as maximum and minimum values for aircraft velocity can be applied. Due to productivity (a more functional workspace constraint), the heading change is limited to 90 degrees port and starboard in order to show travel opportunities that will decrease the distance between the aircraft and the destination. The resulting presentation is called the State Vector Envelope (SVE) and will be used as the interface concept related to the SHTF travel function. Figure 2.5(d) shows the SVE at the bottom of the Navigation Display (ND). Note that the SVE *contains* the FBZ and that its boundaries are imposed by aircraft performance and productivity constraints.

2-6-2 Multiple conflicts and implicit coordination

Multiple conflicts. When multiple conflicts occur simultaneously, several FBZ's can be shown superimposed on each other. Figure 2-6 shows a multiple conflict with two intruder aircraft. $\vec{V}_{own}$ is the speed vector of the ownship, $\vec{V}_{int1}$ and $\vec{V}_{int2}$ are the speed vectors of the two intruders. The SVE is shown at the bottom of the figure. The geometric relation between the beam position and orientation on the one hand, and intruder position and speed vector on the other hand, allows pilots to correlate FBZ's with aircraft symbols on the navigation display. The FBZ origin position represents the intruder speed vector. The direction of the opening of the beam reveals the intruder relative position.

Implicit coordination. 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. In Figure 2-7 one can see that because of the symmetry, the closer one's aircraft vector end-point is located to one leg of the FBZ, the closer the other aircraft's vector end-point will be to the opposite leg. Hence, the resolution of aircraft 1 (labeled with number 1) is complementary to the resolution of aircraft 2 (labeled number 2). Therefore, the motion of the FBZ due to the maneuver of aircraft 1 is in the opposite direction of the motion induced by the maneuver of aircraft 2. On the bottom of Figure 2-7, one can see two close-ups on the FBZ from the perspective of aircraft 1 before (left) and after (right) the resolution maneuvers are done. It illustrates the situation before (grey) and after (black) maneuvering. Because both aircraft maneuver, the magnitude of the resolution maneuver could be half of the indicated resolutions. In this way, each pilot can move to the FBZ leg that is situated closest, yielding simultaneous, cooperative maneuvers, *without* the need to exchange intent information.

2-6-3 Spatio-temporal FBZ dynamics

The changing relative aircraft positions cause the FBZ to expand. Both ownship and intruder maneuvers result in translation and/or rotation of the FBZ. A proper

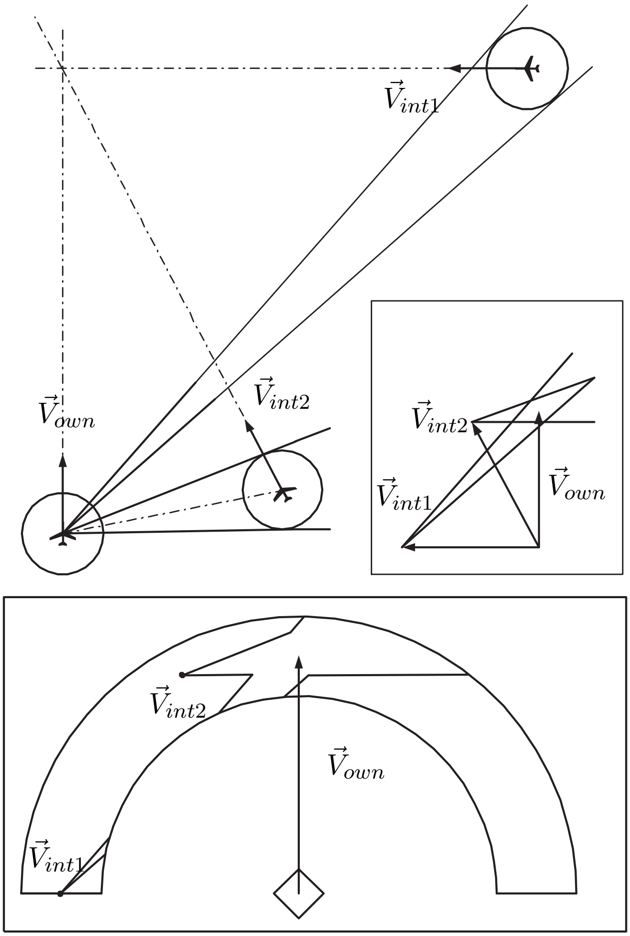


FIGURE 2-6: Combination of two FBZ's due to conflict with two intruders.

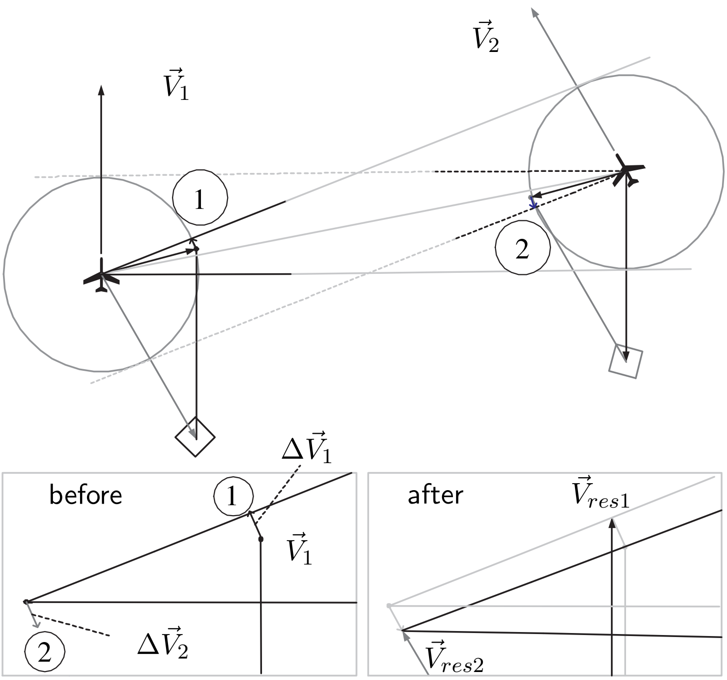


FIGURE 2-7: Implicit coordination between two aircraft.

analysis of the FBZ dynamics is needed to understand how these dynamics affect pilot decision making and conflict awareness.

FBZ expansion. In Figure 2.8(a), the ownship speed vector $\vec{V}_{own}$ at time t_0 lies inside the FBZ and during the time that the ownship is approaching the intruder aircraft, and therefore the PZ, the FBZ-beam width will expand. The different effects of the maneuver and the expansion are indicated with man and exp, respectively. The FBZ is drawn at the beginning (t_0) and at the end (t_1) of the maneuver in an intruder-fixed reference frame, Figure 2.8(a), an intruder-fixed speed-heading space, Figure 2.8(b) and an ownship-fixed speed-heading space as seen on a SVE, Figure 2.8(c).

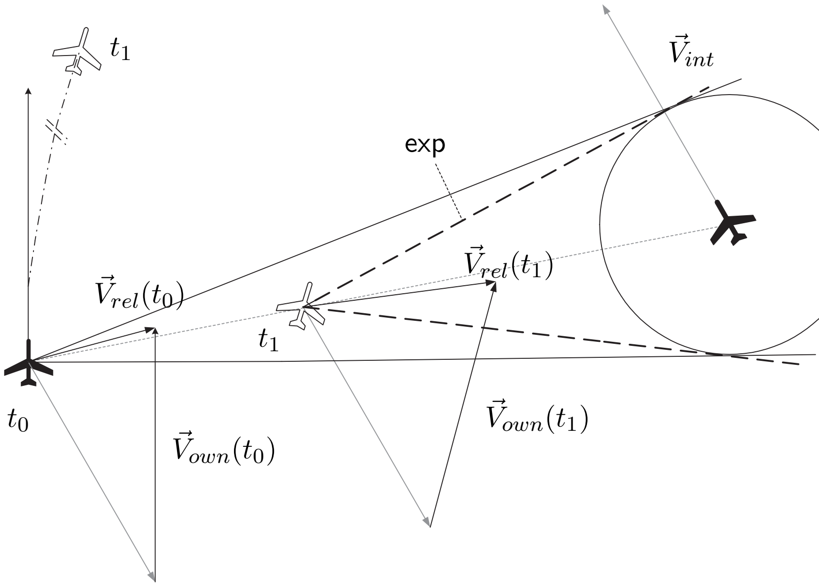
The closer the conflict comes to actual loss of separation, the more significant the expansion rate will be, resulting in a "sweep movement" at the end, illustrated in Figure 2-9. The FBZ is drawn for the conflict situation at current time t_0 and four instances in the near future (t_1 to t_4 using equal time steps) when both aircraft do not maneuver. Since the ownship's vector is located exactly on the upper FBZ leg, this leg will not sweep at all, at least not until the CPA point is passed. The perception of an increased expansion rate gives the pilot an indication of conflict urgency. A pilot could estimate whether it is still possible to go out of the FBZ, or trespass it. Note, however, that it does not guarantee that separation is indeed feasible, unless exact aircraft maneuver dynamics are used in the model. Furthermore, the expansion rate only becomes significant when time-to-CPA is very low (less than 1 minute), and by that time a collision avoidance system is employed.

Intruder maneuvers. Intruder maneuvers can also be directly perceived by translation of the corresponding FBZ. Due to the displacement of the intruder velocity vector $\vec{V}_{int}$, "fixed" to the origin of the FBZ, the entire FBZ is translated. When the intruder is inside the FBZ, a cooperative maneuver is intuitively realized by steering in the opposite direction of the intruder maneuver, resulting in a lower conflict resolution time or a larger separation. Similarly, when the intruder aircraft is outside the FBZ but makes a "hostile maneuver", i.e., towards a FBZ leg, the pilot can now prevent intrusion by initiating exactly the same maneuver as the intruder.

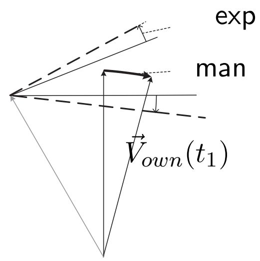
2-6-4 Hypothesis for a travel strategy with the SVE

Considering the above analysis, the following travel strategy will efficiently resolve and prevent a conflict situation with an intruder aircraft:

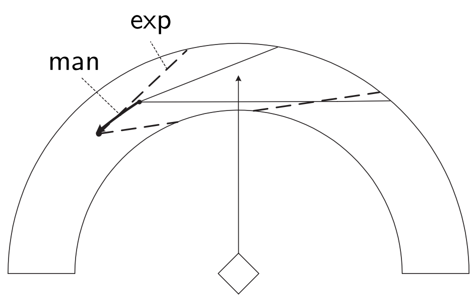
- safety: stay out and get out of the FBZ before the aircraft enters the PZ of other aircraft;



(a) Relative motion of ownship in an intruder-fixed reference frame.

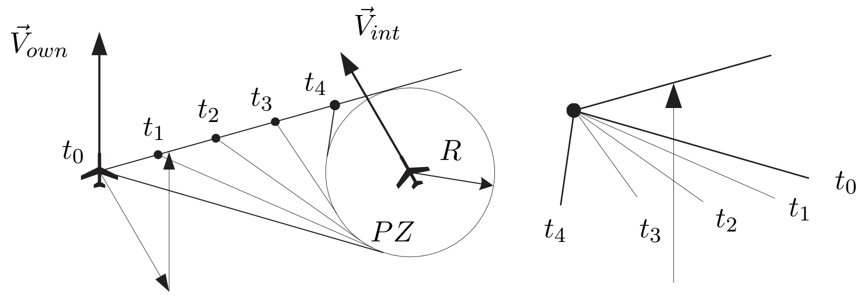


(b) Maneuver in intruder-fixed speed-heading space.



(c) Maneuver in State Vector Envelope (ownship-fixed speed-heading space).

FIGURE 2-8: Expansion of the FBZ when doing nothing (top), or when executing a resolution maneuver (bottom).



(a) Relative motion of ownship. (b) Ownship fixed speed-heading space.

FIGURE 2-9: FBZ expansion and sweep movement.

- production: keep or get the destination in front;
- efficiency: minimize the deviation of the original trajectory path by optimizing two factors:
  1. limit the heading and speed deviation for the resolution/prevention maneuver: *"for resolution (when intruder is not maneuvering), go to closest resolution state on the side of the closest FBZ leg"*; *"for resolution and prevention (when intruder is maneuvering), move against and along in the direction of the FBZ translation, respectively"*,
  2. limit the duration of the conflict resolution/prevention time: *"stay away from FBZ origin points"*.

Through the use of the efficiency travel strategy, implicit coordination of a conflict between two aircraft is guaranteed as long as the optimal resolution (or, at least, a resolution that lies on the side of the shortest FBZ-leg) is available. Though more complicated, this strategy can also be applied to multiple conflict situations. As long as the pilot takes a resolution that is situated on the side of the shortest FBZ-leg of each individual pair of FBZ-legs (one pair for each conflict), implicit coordination between each individual conflict is achieved.

Situations may occur, however, where the resolution space at the side of the FBZ is unavailable due to other mapped constraints. In such a situation, the pilot would have no other option than to perform a counteractive maneuver to the furthest FBZ-leg. Given the assumption that no intent information is exchanged, the intruder can not be informed about this maneuver. The addressed problem is inherent to the travel strategy. Therefore, an additional rule is needed: if the closest FBZ leg is not available, the ownship should not maneuver at all. The intruder aircraft resolves the conflict alone.

2-6-5 Presenting the SVE on the ND

The speed-heading travel function expresses possibilities for motion in terms of instantaneous speed-heading state changes. In the intruder-fixed reference frame, the FBZ visualizes how both the ownship and intruder speed vector afford efficient and cooperative conflict resolution and prevention. The FBZ geometry remains identical when translated to an ownship-centered speed-heading state space, e.g., Figure 2.5(b). Such presentation formats were also proposed for the design of maritime collision avoidance systems [19–21].

The State Vector Envelope interface is overlayed on the Navigation Display at the bottom, Figure 2.5(d). The main disadvantage of such an overlay is the risk of confusion between information on the plan view of the ND, a two-dimensional ownship-fixed spatial field, and the speed-heading space, a vector field. Still, the advantages seem to cancel out this disadvantage.

First, mapping the SVE on the ownship position of the ND relates the aircraft in the spatial space (the ND) with the FBZ in the speed-heading space. The pilot can observe speed, heading and relative position of aircraft in the vicinity and also how these intruder characteristics affect the ownship's travel options. The use of speed-heading space (motion) and plan view (airspace) for presenting constraints therefore *enhances* the natural ecology that pilots have and use when moving through airspace. Second, possible maneuvers in the speed-heading space can be translated to the ND by (mentally) plotting a course in the short/middle term (planning). Third, the mapping further enables the presentation of workspace constraints in the spatial plane, the speed-heading space, or both. For separation, the intruder aircraft symbol in the spatial plane shows how much the actual separation is, while in the speed-heading plane, the FBZ shows if separation will be lost in the future and by which actions pilots can efficiently resolve the situation. The interface designer now has two possible "spaces" in which to present constraints, paving the way for more extended or integrated support tools.

An alternative to mapping the envelope would be to decompose the speed-heading space into separate speed and heading bands, but then a part of the conflict information contained by the FBZ position and shape would be hidden: combined speed-heading maneuvers, intruder behavior, and multiple conflicts.

2-7 EID properties of the interface

EID addresses how information should be presented and how to support operators to deal with novelty and change. The Skills, Rules and Knowledge (SRK) taxonomy of Rasmussen is a framework for describing the mechanisms that people have for processing information [22]. It defines three levels of cognitive control when describing human behavior in reaction to available information. EID aims to support all three levels of cognitive control, while not forcing the operator to control at a higher level than necessary, saving cognitive resources [7]. In this section it will be discussed how the SVE interface supports these EID principles.

The SVE interface supports Skill-Based Behavior by enabling the pilot to act on directly perceivable constraints. The speed-heading state vector should be kept inside the envelope and outside the FBZs. Through the path control (speed and heading settings on the autopilot), the pilot can directly manipulate the goal state.

Ruled-Based Behavior involves associating familiar perceptual cues in the world with an action or intent. There should be a consistent one-to-one mapping between the workspace constraints and the perceptual information on the SVE interface. Domain constraints related to separation and path deviation are mapped into perceptual cues: the distance between FBZ origin and state vector, FBZ legs and state vector, and the movement of the FBZ, give input to the pilot's travel strategy for efficient conflict resolution and prevention. There is a one-to-one mapping between the type of conflict situation and the FBZ presented on the SVE interface. Over time, different avoidance strategies can be tested, selected or discarded depending on their efficiency. Heading constraints (production goal) and speed constraints (aircraft performance) mark the capabilities of the locomotion function and are mapped on the interface (boundaries of the SVE).

Knowledge-Based Behavior involves analytical problem solving based on a symbolic mental model. The interface should present the content and relations identified by the abstraction hierarchy model of the workspace. The separation function on the abstract function level of the AH is revealed by the FBZ, as explained earlier. The relation between the generalized functions (locomotion, path control) and the abstract functions lies in the formulation of separation in terms of aircraft (loco)motion. The locomotion prediction depends on the possible speed and heading settings given by the pilot (path control function). The presentation of the "functional information" through the FBZ is built up out of physical information of airspace elements (physical function level): the intruder's position is revealed by the FBZ orientation pointing towards the symbol on the ND. Because of this relation, each aircraft on the ND can be related to an FBZ on the SVE, also in case of multiple simultaneous conflicts. The position of the ownship speed vector relative to the FBZ also reveals how it will pass the intruder (front, back, left, right or a combination).

Intruder velocity is shown by the FBZ origin and can be directly compared to the ownship's velocity vector. Intruder maneuvers (vector changes) are visible by the movement of the FBZ. The effects of the intruder behavior on the constraints are clearly visible and allows the pilot to react properly, even if the behavior is unexpected and unanticipated for. Finally, the expansion rate of the FBZ is a measure for the time-to-CPA, i.e., a measure of "conflict urgency". The higher the expansion rate, the more critical it becomes to decide for and start a resolution manoeuver.

2-8 Pilot Evaluation

In a fixed-base, part-task flight simulator, the State Vector Envelope interface has been evaluated by a brief test experiment with six professional civil airline pilots.

The purpose of the evaluation was to verify the safety and efficiency of conflict resolutions, and to obtain a first impression of pilot acceptance and situation awareness. It is stressed that the evaluation was not aimed at covering all our claims made above. For example, it did not consider implicit coordination. Rather, scenarios included hostile intruder behavior, to test the robustness of our interface against unanticipated behavior.

2-8-1 Procedure and setup

A set of five conflict scenarios with two intruder aircraft was simulated. Each scenario had a specific conflict geometry. Pilots were asked to fly a track between two waypoints in cruise conditions. At a given moment, a conflict situation occured with two intruder aircraft. Pilots were instructed to conduct a maneuver that would result in a safe and efficient conflict resolution using the speed-heading maneuver strategy. When the intruder aircraft had passed by, pilots were told to start a recovery maneuver, i.e., going back to the original cruise speed and head towards the next waypoint in order to continue flight on the original trajectory.

2-8-2 Description of the simulation

A Boeing 747-200 aircraft was simulated, flying at 30,000ft. Initial velocity was 0.8 Mach, approx. 240 m/s ground speed. The autopilot was enabled; speed and heading could be set on a simulated Mode Control Panel using a mouse.

Given the actual speed, the "conflict detection" algorithm detected a future spatial separation violation (5 NM reference) within a 5 minutes look-ahead time. The "FBZ drawing" algorithm used a look-ahead time of 15 minutes in order to show less urgent conflicts inside the state vector envelope map when a resolution strategy was chosen for the actual conflict.

Each intruder was simulated with a propagation model that defined an initial trajectory by its position, ground speed and heading. At a given time, a resolution maneuver with a different ground speed and heading was triggered. When the intruders passed each other they headed back to their original trajectory path. The resolutions were pilot-like and caused a spatial separation between 5 and 10 NM. The maneuver dynamics included a simple turn geometry and a constant longitudinal acceleration. Both intruder aircraft only resolved the conflict with each other, and neglected the conflict situation with the owncraft. It was therefore possible for the intruders to make counter-intuitive or even hostile maneuvers at the time they initiated the resolution or recovery maneuver. Pilots were informed about this intruder behavior during the briefing.

Three "normal" scenarios were designed in such a way that using the travel strategy at detection time would lead to the most efficient resolution. In the two other scenarios, the intruder behavior during resolution, i.e., before passing the CPA point, changed the desired resolution strategy.

2-8-3 Results

Safety was measured by loss of separation and the minimum separation distance; efficiency by the maximum path deviation. In the normal scenarios, out of 18 runs, 14 times pilots applied the most efficient resolution strategy, and 1 time a sub-optimal one. The 3 less-efficient strategies resulted in a path deviation that was at least twice as high as necessary. In one of the scenarios, a hostile recovery maneuver near CPA instance caused a minor loss of separation of a few hundred feet.

In case the unexpected intruder behavior changed the optimal resolution maneuver strategy for the own aircraft, pilots would have to cross the forbidden area. However, our pilots did not feel confident enough to do this. In one scenario, two equally efficient resolution strategies existed, a port and a starboard maneuver. Four pilots decided to do a starboard turn maneuver. Due to the resolution maneuvers of the intruders, this resolution would lead to a path deviation δ_{max} three times higher than for the port maneuver. One out of four pilots decided to re-plan the strategy and cross the FBZ to take the more efficient option. In another scenario, the optimal solution was a small triangular area on the SVE that would disappear just before passing each other due to a hostile intruder recovery maneuver. Four pilots avoided this strategy from the start, taking a less efficient but more safe resolution strategy. One of the two pilots who did chose the optimal strategy eventually lost separation passing by at 2.3 NM.

2-8-4 Pilot comments; pilot acceptance

Pilot acceptance and conflict awareness were evaluated through the personal feedback of pilots and a questionnaire. All pilots indicated that the SVE interface was useful, but more practise and experience would be needed for a better comprehension and use of it. All indicated that they were able to correlate envelope lines to particular intruder aircraft and also reason about how aircraft will pass each other (back, front, left or right), but again mentioned that more practise was needed. Pilots recommended to keep the beam shape of each individual FBZ visible, i.e., draw the entire beam until the maximal velocity limit, including the part below the minimal velocity, and staple different FBZ on each other *without* merging the lines. The acceptability of, and confidence in, trespassing the FBZ area varied amongst pilots.

The FBZ expansion was easily perceived. All pilots acknowledged that the evolution of the envelope form was noticed better when the intruder aircraft came closer to the owncraft. However, it was difficult to predict the expansion rate of the FBZ. The lack of awareness about the future position of the beam edges made it difficult to exactly determine the right maneuver needed to get out of the FBZ.

All pilots commented to have a reasonable notion on conflict urgency. Three pilots indicated that they used the FBZ size to build up this notion. All pilots used spatial proximity of the intruder aircraft on the ND. Two pilots also used relative approaching velocity of the aircraft symbols on the ND. It was not clear to them how much time was left before collision, or alternatively, how much time was left to start a resolution maneuver. Pilots indicated that they especially wanted to perceive the relative velocity of the intruder aircraft.

During the experiment, most pilots did not explicitly state that the intruder aircraft were maneuvering. They spoke about movements of the envelope lines and how to react upon them. When a hostile intruder maneuver was done just before passing by, however, pilots clearly identified the maneuver.

2-9 Discussion

A work domain analysis was made of Airborne Trajectory Planning, identifying behavior-shaping workspace constraints, related to key functions like separation and path deviation. These were then translated into a visual representation by use of locomotion models that express travel options. During the design process, the workspace analysis was iterated several times, often in combination with the visualization step. In this way, the display was designed in an incremental, evolutionary way, allowing interface form and workspace analysis to give input to each other. EID is certainly not a recipe for the interface geometrical design, and a gap exists between analysis and display form. In the present context, pilots already have and use an existing, natural ecology of motion through space. Since we believe that interface forms should enhance this existing ecology, it led us to look for solution forms that used the dimensions of motion and space.

The paper shows that conflict situations are, depending on conflict geometry, most efficiently resolved by a speed change, heading change or a combination of both. Locomotion models such as the Heading Travel Function, that do not describe combined speed-heading maneuvers, fail to present travel options that minimize path deviation and support implicit coordination unless they use an explicit resolution advice. The use of heading bands or speed bands on the interface to prevent maneuvers that trigger new conflicts is unsatisfactory. The heading band only holds for the current speed and vice versa, the speed band for the current heading. Additionally, multiple conflicts may overlap each other, making it difficult to distinguish between the bands or relate individual bands with the appropriate intruder aircraft on the navigation display.

Separation can not be presented in a steady, meaningful way on a traditional plan view display. However, in an ownship-centered speed-heading vector field (such as visualized in the State Vector Envelope interface), separation can be expressed in terms of maneuvers based on instantaneous speed-heading changes. For each conflict, the FBZ visualizes efficient conflict resolutions (supporting conflict prevention) and intruder maneuvers (supporting implicit coordination).

Due to the time needed to maneuver, the FBZ beam width expands. Conflict urgency can be directly perceived by the expansion rate of the FBZ, a property that becomes more salient just before both aircraft cross each other. However, a pilot can not be completely confident that it is still possible to go out of, or trespass the FBZ, as it might expand faster than the aircraft can maneuver. Therefore, a time threshold should be determined, below which collision avoidance is activated.

The mapping of the SVE on the Navigation Display (pinpointed on the ownship position geometrically) relates the aircraft in the spatial space (the ND) with the FBZ in the speed-heading space. The pilot can not only observe the speed, heading and relative position of aircraft in the vicinity, but he can also observe how these intruder variables affect the ownship's travel options. Thus, the use of speed-heading space (motion) and plan view (airspace) to present four-dimensional spatio-temporal constraints enhances the natural ecology that pilots have and use when moving through space. The SVE "makes visible the invisible", perfectly in line with EID principles [15].

The direct visualization of workspace constraints in the speed-heading space, the "intelligence" behind the SVE envelope mapped on the ND, allows for a deeper understanding of travel options and conflict situations. This makes it an appropriate support tool for complex problem solving. On the other hand, a pilot can simply steer out of the FBZ and remain within the speed envelope without fully analyzing and understanding all aspects of the conflict situation, reducing cognitive workload. This results in supporting the skills, rules and knowledge levels of cognitive control.

Tentatively, the introduction of a display that enables the operator to accomplish his task with little cognitive effort, might lead to an erosion of skills [23]. Extrapolating the results observed in [24] to the present context, however, suggests that if pilots actively reflect on the feedback they receive from the EID display, they will have an opportunity to gain deeper knowledge of airborne conflict situations.

A brief pilot evaluation proved that pilots are able to perform safe and efficient conflict resolution maneuvers using the display. The experiment data and pilot comments primarily served as an input for further design steps and more extensive evaluations. The limited complexity of this experiment needs to be seen in this context, it was mainly intended to elicit pilot comments and provide initial feedback on the design. From the results it appeared that the FBZ expansion was readily observed by the pilots, and that some pilots used it to form an impression of conflict urgency. FBZ expansion rate was more difficult to observe, however, leading to difficulty in predicting the development of a conflict and uncertainty in the choice and timing of maneuvers in some cases. Pilots also can correlate the FBZ lines with the associated intruder aircraft, and are well able to predict how they will pass other aircraft. Movement of the FBZ is visible to the pilots, but they cannot relate that movement to the intruder maneuver causing it, unless that maneuver is a critical hostile maneuver. Pilots also indicated that they would need more practice with the display to achieve better comprehension and use it better.

2-10 Recommendations

The inclusion of aircraft dynamics into the travel models would make the FBZ presentation more accurate. In urgent situations, this guarantees a given resolution is feasible. In situations where unexpected intruder behavior alters the resolution strategy, the feasibility of the trespassing maneuver is then assured. Exchange of intent information should also be explored. The presentation of autopilot settings on the SVE would enable pilots to quickly assess the intruder's intentions. One planned path change in the near future could be accounted for in the (loco)motion prediction and the presentation of the FBZ. Including both dynamics and intent information, allows for more flexible travel strategies. At current a preliminary design including these features has been made [25].

Research is ongoing to experimentally compare current airborne separation systems like P-ASAS with the ecological design, focusing on the relation between display, conflict geometry and pilot performance and workload [26]. Since an ecological interface does not necessarily yield better performance, attention focuses on analyzing pilot problem-solving skills in exceptional situations, and pilot situation awareness.

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3

Introducing XATP, and comparing it with PASAS

In this chapter a second design iteration is presented, the eXtended ATP (XATP) display that accounts for turn dynamics when presenting the forbidden beam one (FBZ) areas. Whereas in the previous chapter an exploratory evaluation was done to check the validity of the design, this chapter discusses an extended theoretical and experimental comparison between the XATP design and a viable design alternative: PASAS. The comparison was restricted to the representation of 'no-go' maneuver constraints, in other words, the FBZ areas are compared with PASAS speed and heading bands. A theoretical analysis using the EID framework is given, and the results of an experiment measuring safety, performance and workload are discussed. Relations between display type, conflict geometry, and pilot decision making will be identified. Although the theoretical comparison indicates that XATP is better suited to promote pilot traffic situation awarenes, the ultimate self-separation performance metrics were found to be similar with both displays.

Paper title Comparison of Two Interfaces for Supporting Pilots in Airborne Self-Separation Tasks

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ABSTRACT

In future air traffic management concepts, pilots need an airborne separation assistance interface tool to help them separate from other traffic. Traditional tools provide pilots with explicit resolution commands, similar to the ones used for short-term collision avoidance. Earlier research indicated that (1) these tools fail to promote pilot traffic situation awareness and (2) traffic awareness is improved by showing pilots how their maneuver options are constrained by the surrounding traffic. Two viable support tool designs are presented. These tools show maneuver constraints, each in a different way. The first design is part of a conventional tool using explicit commands, the second one is an Ecological Interface Design that is used in a stand-alone manner. In this paper both visualizations are compared theoretically and experimentally with no further aid of automation in the form of explicit commands. A theoretical comparison based on the ecological framework analyzes how the designs support pilot traffic situation awareness. In a pilot-in-the-loop experiment, the safety, workload and performance of pilot maneuver behavior were measured. From the theoretical analysis it was expected that the second of the two displays would perform better in supporting pilots. The experimental results show that both systems perform equally well. A clear relation was found between the pilot's preference for a display type, the conflict geometry of a scenario, and the resulting decision making.

Nomenclature

ADS-B	Automatic Dependent Surveillance - Broadcast
$ASAS$	Airborne Separation Assurance System
AH	Abstraction Hierarchy
ATP	Airborne Trajectory Planning
CPA	Closest Point of Approach
EID	Ecological Interface Design
FBZ	Forbidden Beam Zone
ND	Navigation Display
$PASAS$	Predictive ASAS
SA	Situation Awareness
SVE	State Vector Envelope
$XATP$	eXtended Airborne Trajectory Planning

3-1 Introduction

Due to the congestion of airspace and the resulting delays, airspace authorities and governments (especially those in the United States and in Europe) have been investigating, and continue to investigate more effective and flexible ways to use the airspace. A number of Air Traffic Management projects such as Region Navigation [1], Free Flight (FF) [2–4], and Next Generation Air Transportation System [5] have indicated the benefits of such an approach. In certain parts of the airspace, e.g., during cruise flight, aircraft are expected to have more autonomy and freedom to optimize their trajectories by allowing ‘direct routing’ and ‘cruise climb’.

In the same way as for traditional airspace, aircraft may eventually lose separation with each other when flying these routes. Separation is defined by a Protected Zone (PZ), a virtual coin-shaped area, around each aircraft. This area is to remain free of other aircraft. At the moment another aircraft enters this PZ, an ‘intrusion’ or ‘loss of separation’ event occurs. Generally, the current radar separation minima are used: 5 NM horizontally, and 1,000 ft vertically. A conflict is defined is if two aircraft would enter each other’s PZ at some instance in the near future, if neither aircraft changes course [6]. Many different ways of detecting a conflict and providing potential resolution have been investigated, and a review of most Conflict Detection and Resolution (CD&R) modeling methods has been published, Ref. [7].

Due to the increased complexity of traffic flows in future airspace environment, the responsibility to maintain separation in cruise flight is shifted from the air traffic controller to the pilot, and will be referred to as airborne self-separation [8]. Airborne Separation Assurance Systems (ASAS) support the crew in this self-separation task. Numerous projects have been investigating such applications within this field, for an overview the reader is referred to Ref. [9]. An approach often taken is to provide pilots explicit automated solutions, i.e., specifically telling the pilot how to resolve the conflict. Although automated solutions have proven to be successful in resolving a conflict, they often fail to provide proper pilot situation awareness. With the ASAS system for example, pilots were unable to see if the evasive ‘resolution’ maneuver would cause (new) conflicts with other aircraft [10].

Predictive Airborne Separation Assurance System (PASAS) [10, 11] and eXtended Airborne Trajectory Planning (XATP), introduced in this chapter, are systems that deal with this issue by visualizing maneuver constraints, using so-called ‘no-go’ zones on the flight displays. The first, PASAS, is a traditional display design developed in an evolutionary fashion from ASAS [10], i.e., it was designed to prevent the pilot from performing resolution maneuvers that would cause other conflicts. The second, XATP, is designed following the principles of Ecological Interface Design (EID). EID is a framework that addresses the cognitive interaction between users and systems [12, 13]. As will be shown, XATP abandons the use of an explicit resolution command, and advocates that a clear presentation of maneuver constraints will promote sufficient pilot situation awareness as a basis for safe and conflict-free navigation. XATP is a follow-up design that builds on and enhances the earlier ATP design [14].

The 'no-go' zones employed in both systems have shown to be successful in presenting pilots which maneuvers will eventually lead to a loss of separation and which are conflict-free. Results from an earlier experiment with ATP indicate that pilots are indeed able to deal effectively with conflict situations using an interface that only shows these maneuver constraints [14].

The goal of the present work is to compare the no-go representation formats of both displays, both theoretically as well as experimentally. Any automation that would provide explicit resolution advices on the display, such as commonly added to ASAS, was omitted. It implies that PASAS is not evaluated in the way it was designed for, i.e., as an *complementary* function in addition to ASAS. To avoid confusion, it is emphasized that throughout this work the label 'PASAS' only addresses the visualization of the no-go speed and heading bands.

The EID framework principles, used for the design of the XATP display, can also be employed as a theoretical framework to analyze and compare both interfaces [12]. The theoretical comparison focuses on how well both interfaces convey information on the structure and content of the work that needs to be done. An experiment has been conducted to validate the findings of the theoretical survey. The experiment addressed both displays for two different levels of traffic density and three different conflict geometries, and measured the safety, performance and mental workload when resolving these conflicts. It was assumed that differences in pilot situation awareness with the two displays should become apparent in differences in performance, safety and workload.

The structure of the paper is as follows. First, the display systems will be described in detail, and it is specifically investigated how these systems differ in representing the separation problem and visualizing the maneuver constraints. Second, the visualization concepts are compared theoretically using the EID framework. Third, the experiment and its results are discussed.

3-2 PASAS: speed and heading bands

3-2-1 Airborne Separation Assurance System (ASAS)

At the Netherlands' National Aerospace Laboratory (NLR) a series of experiments has been conducted to investigate the feasibility of a Free Flight display concept [4, 10, 11, 15, 16]. The research consisted of three phases: design of an Airborne Separation Assurance System (ASAS), fast-time simulations to determine the feasibility of the developed algorithms, and human-in-the-loop experiments to determine if the concept was feasible from a pilot's perspective.

The initial aim for ASAS was to help the pilot to detect and resolve conflicts. To do the calculations for conflict detection and resolution, ASAS relies on the

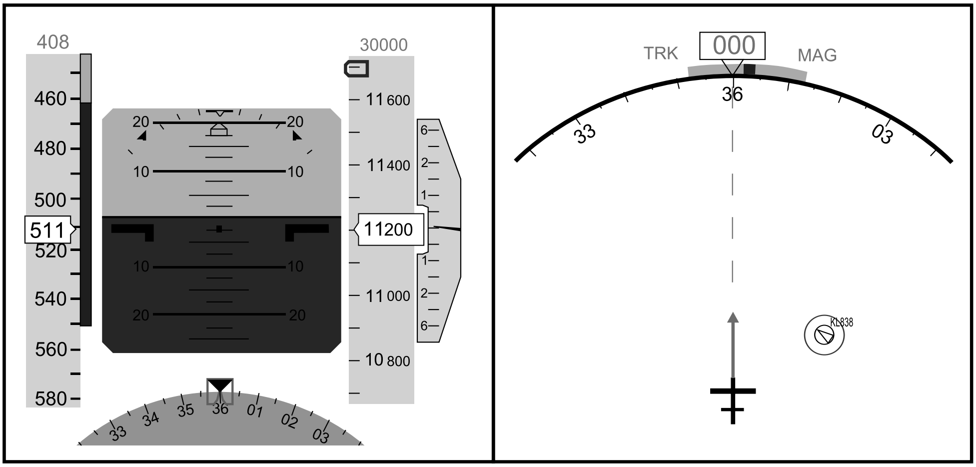


FIGURE 3-1: PASAS heading and speed bands are presented on PFD and ND. The figure is a greyscale drawing of a screenshot image. The light grey bands and the dark grey bands represent the orange and red bands, respectively, on the speed scale (PFD) and the heading scale (ND).

state information (position, height, track and groundspeed) of the surrounding traffic obtained using Automatic Dependent Surveillance - Broadcast (ADS-B) technology [17]. No intent information is used, that is, future turns of changes in speed that may have been programmed in the on-board computers, and the knowledge of which could be made available to other aircraft, is ignored. The surrounding aircraft are plotted on the Navigation Display (ND) with an outer circle around their position, representing the PZ, thus, the separation standard. The inner aircraft icon indicates the aircraft heading. Once a future intrusion is predicted, a single, optimal avoidance vector is calculated and presented on the Primary Flight Display (PFD) and ND as an explicit solution to the pilot. It is shown by speed and heading markers. For the aircraft in conflict, also a circle representing the PZ, at the position of Closest Point of Approach (CPA), and a track-line connecting the CPA position with the current position, is plotted. This is where both aircraft will pass each other.

During the first pilot-in-the-loop experiments testing this system, it was discovered, however, that the avoidance vector indeed correctly helped pilots to resolve a conflict, but nothing prevents them from triggering a new conflict [10]. Pilots were puzzled by the fact that resolving a conflict in some cases led to a new one, and although some pilots were able to deduce future conflicts from the traffic image on the ND, this task was considered to be too demanding.

3-2-2 Predictive ASAS (PASAS)

An improvement on ASAS, Predictive ASAS (PASAS) was designed to solve this problem. It does so by presenting 'no-go' state bands on the speed and vertical speed tapes of the PFD, and on the heading scale of the ND. Each of these bands is a one-dimensional presentation of maneuver constraints for the considered dimension, assuming the other dimensions to be constant: e.g., the heading band shows turn constraints for constant ground and vertical speed. All of these state bands come in an amber and a red version. If the pilot selects a heading inside an amber heading band, this turn maneuver will lead to intrusion in three to five minutes. A maneuver to a heading inside the red band will result in an intrusion in less than three minutes.

The PASAS display, as it was used in the study, is shown in Figure 3-1, showing the heading bands (1) and the speed bands (2), the aircraft icon and PZ (3), and the currently selected speed vector (4). The commanded airspeed is shown as a bug on the speedscale (5). Because the pilot does not have a reference of what the speed limits are, speed bugs were added. The vertical speed bands are not shown, as only horizontal maneuvers will be discussed in this paper. As mentioned in the introduction, the explicit resolution advisory is not drawn either.

In Figure 3-2 a conflict situation is presented in the relative plane (Figure 3.2(a)) and in the absolute plane (Figure 3.2(b)). In the relative plane, the relative speed vector $\vec{v}_{rel}$ indicates the motion of the ownship towards the fixed intruder aircraft. If the relative speed vector $\vec{v}_{rel}$ lies inside the so-called Forbidden Beam Zone (FBZ) [14], an intrusion in the Protected Zone (PZ) will happen in the future.

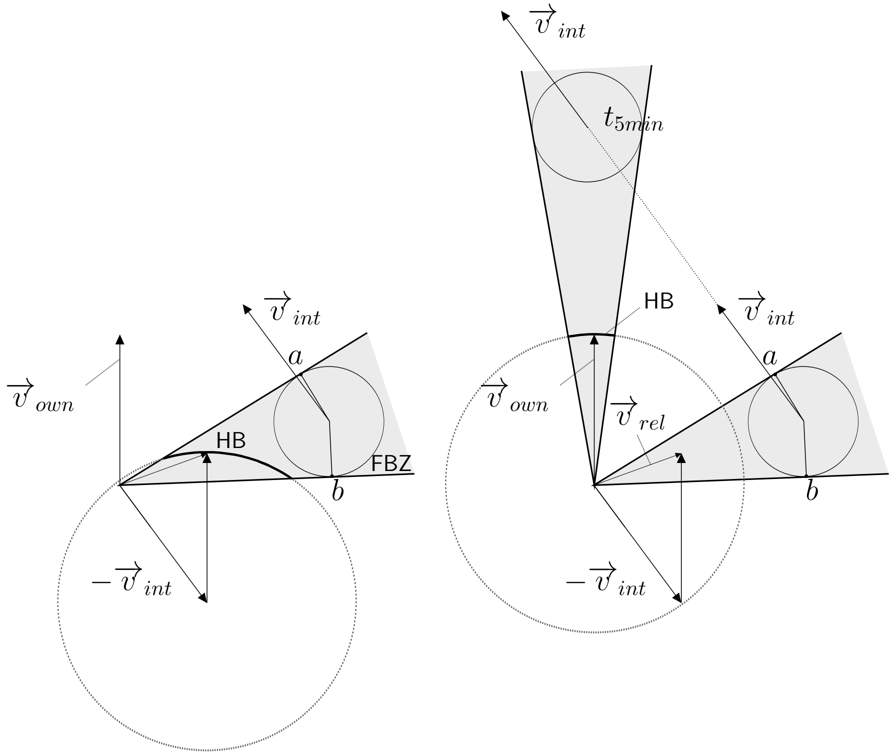
The calculations of the amber and red heading band (HB) edges are identical and consist of the following steps, taking into account the look-ahead times of three and five minutes discussed above:

1. Determine for each aircraft in the vicinity whether the future position of the other aircraft could be reached with an arbitrary (but valid) state within 5 minutes. If so, continue with step 2; if not, abort calculation.

2. For each FBZ leg separately, calculate heading changes (for a fixed current speed) needed to generate relative speed vectors that coincide with the FBZ leg, see Figure 3.2(a).

3. If one of the related relative speed vectors reaches the tangent points on the PZ (a or b) within 5 minutes, store the corresponding heading values as a solution. If not, calculate the position of the other aircraft in the absolute plane, Figure 3.2(b), at 5 minutes from now. Use this new position to calculate the lines tangential to the PZ related to the future intruder position. Using these lines, calculate the corresponding headings and store these values.

4. Order solutions, maintain the appropriate calculated values and combine overlapping heading bands from several aircraft.

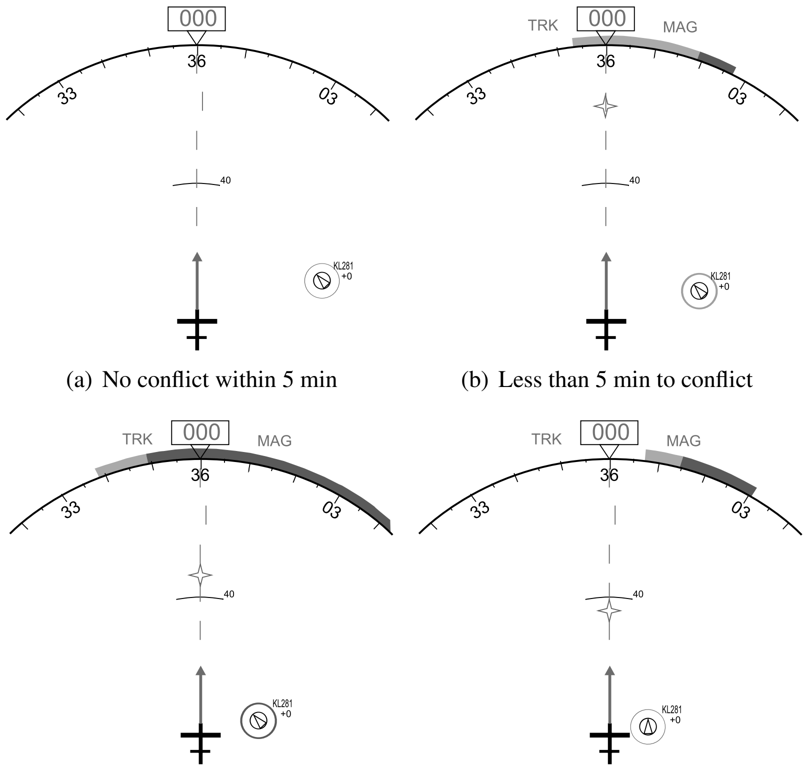


(a) $t_a < 5$ min. *or* $t_b < 5$ min (b) $t_a > 5$ min. *and* $t_b > 5$ min

FIGURE 3-2: Calculation of the Heading Band (HB): (a) normal calculation in the relative plane; (b) calculation in absolute plane using projected PZ when the time needed to reach point a or point b exceeds 5 minutes (step 3 of calculation algorithm).

The resulting heading band for the given conflict situation is labeled HB for each case in Figures 3.2(a) and 3.2(b), respectively. No maneuver dynamics are included in the calculation of heading (or speed) band edges. The speed bands follow a similar calculation, here the heading is kept constant whereas speed is changed. As a result, the speed bands and the heading bands *represent maneuver constraints in two separate one-dimensional locomotive state spaces*, namely, speed and heading. In each dimension, the no-go constraints are calculated assuming that the other variable remains constant.

The reader should note that the presentation and terminology employed in Figure 3-2, is not taken from the original PASAS literature [10], but sterns from our research into an ecological solution, discussed in the next section [14, 18]. It is introduced and used here to facilitate the investigation on the relations and differences between both formats, discussed in later sections.



(a) No conflict within 5 min

(b) Less than 5 min to conflict

(c) Less than 3 min to conflict

(d) Other aircraft has solved conflict by turning

FIGURE 3-3: The progression of a conflict on the PASAS display. Note that on the PFD also speed bands are plotted.

Some less favorable properties of the state bands were identified during experiments. First, when more than one conflict occurred simultaneously, the bands belonging to each conflict merge and it is very difficult, if not impossible, to relate parts of the band with the particular aircraft causing them. Second, the bands tend to move, shrink or split up when maneuvers are executed. In Figures 3.3(a) through 3.3(c) for example, the heading band grows and moves while both aircraft approach each other, but are not maneuvering at all. In Figure 3.3(d), the conflict has been resolved by a starboard turn of the intruder aircraft.

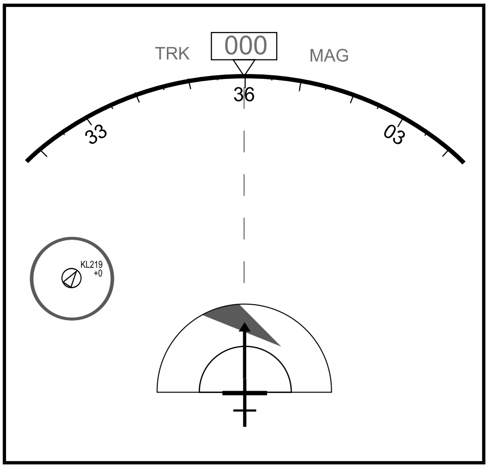


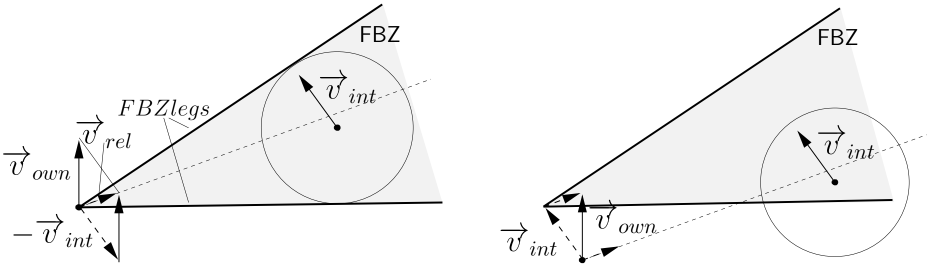
FIGURE 3-4: The XATP display including the State Vector Envelope (SVE) mapped on the own aircraft's position.

3-3 XATP: Forbidden Beam Zone

The irregular behavior of the bands and the inability to clearly differentiate between conflicts, raises the question whether this format is the most suitable for the presentation of maneuver constraints. At Delft University of Technology, a different approach was taken to tackle this design problem. By applying the Ecological Interface Design framework to vehicle motion problems, a pilot support tool, the Airborne Trajectory Planning system (ATP), was developed for the horizontal plane [14]. After a few analysis and design iterations, one of the main conclusions was that a description of separation in the relative velocity plane (in the form of the Forbidden Beam Zone, Figure 3.2(a)), is a very rich source of conflict information [19]. Such a description allows for an integrated 2-dimensional representation of maneuver constraints (1x2D), whereas speed and heading bands yield 2 separate singular dimensions (2x1D). These findings formed the basis for the resulting ATP design, the basic principles of which will be briefly described below. For a more detailed description the reader is referred to Refs. [14, 20]. The XATP display as shown on the ND is given in Figure 3-4.

3-3-1 Airborne Trajectory Planning (ATP)

The basic concept of ATP is to present to the pilot which combinations of his own aircraft heading and speed will result in an intrusion into the Protected Zone (PZ) of another aircraft, and at what time such an intrusion would happen. Pilots can then reason about and decide upon the speed-heading combination that keeps them free



(a) Conflict situation calculated in relative plane

(b) Moving FBZ to absolute plane

FIGURE 3-5: The presentation of a conflict situation by use of a Forbidden Beam Zone (FBZ) in the relative and absolute vector plane, respectively.

of conflicts. However, in addition to the basic need to avoid other aircraft, pilots may have secondary reasons to prefer a certain path over another, such as passenger comfort, the most efficient path to reach the destination, and so forth.

In the same way as with PASAS, the state information of the own aircraft and the surrounding aircraft are obtained through ADS-B, and no intent information is used. The calculations of (X)ATP are done primarily in the relative vector plane, see Figures 3.2(a) and 3.5(a). The use of a vector plane to present separation, has already been explored in the field of vessel navigation [21, 22]. As said before, if the relative speed vector $\vec{v}_{rel}$ lies within the "legs" of the Forbidden Beam Zone (FBZ), at some point in the future an intrusion will happen, unless action is taken that moves this vector outside the FBZ. The relative speed $\vec{v}_{rel}$ is calculated by subtracting the speed vector of the intruder aircraft $\vec{v}_{int}$ from the own speed vector $\vec{v}_{own}$.

Because pilots can not intuitively alter the relative speed, the FBZ presentation is centered around the ownship's speed vector in the absolute speed plane. This is possible because the relative and absolute speed planes can be overlaid, given that the tip of the relative speed vector and the ownship's speed vector are always connected, Figure 3.5(b). Pilots can now change the own speed vector in the absolute plane, and simultaneously keep the relative speed vector out of the FBZ in the relative speed plane.

The point where the two FBZ legs meet is called the "origin" of the FBZ. The location of the origin is determined by the other aircraft speed vector. Therefore, the other aircraft speed, its heading and its maneuvers are all implicitly visible through the location and translation of the FBZ's origin. When the own speed vector is chosen close to the origin, the relative velocity is small and resolution maneuvers will take a lot of time. If the pilot maneuvers the own speed vector out of the FBZ, i.e., by selecting a speed vector on the FBZ leg that lies closest to the actual

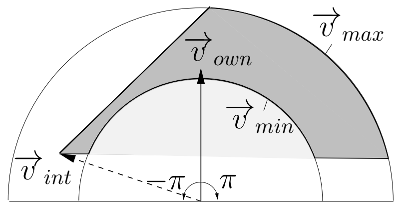


FIGURE 3-6: The Forbidden Beam Zone (FBZ), with state limits added yields the State Vector Envelope (SVE).

state, while avoiding the FBZ origin, an efficient conflict resolution in terms of path deviation distance can be realized [14].

Since the FBZ is a symmetrical presentation of separation, moving the own speed vector to the closest FBZ leg also yields coordinated maneuvers in case both pilots apply this strategy. The options for speed vector changes are bound by certain limits. First by the aircraft flight envelope, which limits the vector magnitude. Second, the known destination of the aircraft (the next waypoint) excludes headings that turn the aircraft away from the destination. If the FBZ is shown within these limits, our end result, the so-called State Vector Envelope (SVE) is created, illustrated in Figure 3-6. The SVE can be shown on the aircraft ND, linking the origin of the ownship speed vector to the ownship aircraft symbol at the bottom of the ND.

3-3-2 eXtended ATP (XATP)

The original ATP design assumed that a state change of the own aircraft can be executed ‘instantaneously’. Obviously, this is a simplification, because in practice, depending on the aircraft and engine dynamics, aircraft heading or speed changes will take time. During this time, both aircraft move and the shape of the FBZ becomes wider as, generally, the aircraft move closer together. Especially when predicted intrusion is nearby, the expansion rate of the FBZ legs becomes quite significant as compared to the rate at which the ownship speed vector can be changed.

In the time it takes the own aircraft to move the own speed vector out of the FBZ, the FBZ will expand, and may include the previously ‘safe’ target state. This may lead to an increased pilot mental workload, because it forces the pilot to iterate the target state of the solution. With eXtended ATP, or XATP for short, this problem is solved for heading maneuvers with a constant speed. Assuming certain typical aircraft turning characteristics, such as a maximum bank angle or a rate-one turn, the time needed to turn to each FBZ leg can be calculated, and the corrected leg for the FBZ can be calculated. An example of the difference between ATP and XATP is given in Figure 3-7.

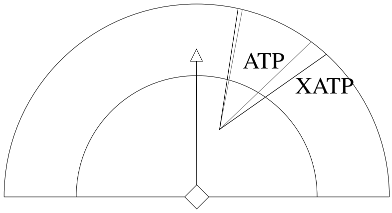
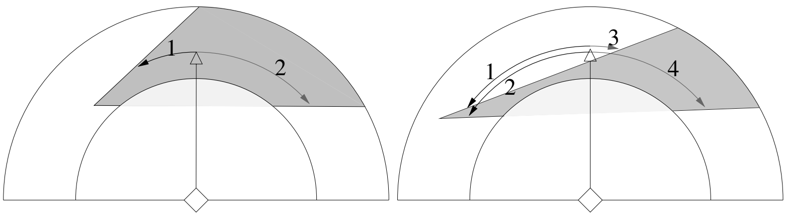


FIGURE 3-7: Adjusting the FBZ legs to accommodate the change of the FBZ over time.

As long as the current state is in conflict (thus, inside the FBZ as shown in Figure 3-6), one of these calculations is a left turn, and the other is a turn to the right. On the other hand, when the two aircraft are not currently in conflict, there are often conflict geometries where two ways exist to get into a conflict: one of these would lead to an almost parallel course (close to the origin of the FBZ), the other would be a course which points partially towards the other aircraft, see Figure 3.8(a). In such cases, for a constant speed, two points on the same leg can be reached, one with a turn to the left, the other with a turn to the right. In the current implementation only one correction is applied to the leg: the solution pertaining to the largest relative speed (i.e., not the almost "parallel" but the "crossing" course) is used, thus the points 3 and 4, not 1 and 2 in Figure 3.8(b).

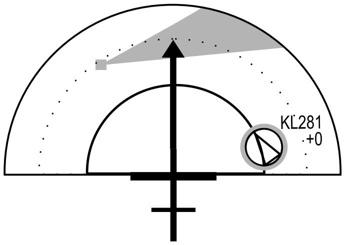
In Figure 3-9 a progression of screenshots of the bottom part of the final XATP ND is given. In this image the FBZ (1) and intruder aircraft symbol (2) are visible. The PZ and FBZ are colored in the same way as the PASAS bands, thus, orange and red means less than five and three minutes to intrusion, respectively, otherwise the FBZ is colored gray.



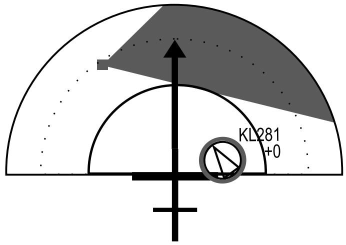
(a) (b)

FIGURE 3-8: Depending on the current situation there can be two or four boundary conditions.

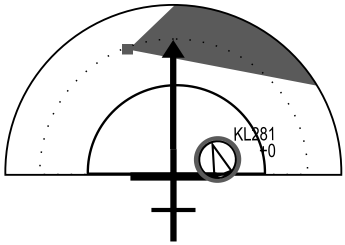
Before starting off with the theoretical comparison, it is important at this point to acknowledge some fundamental differences between the no-go zones employed in both display systems. The PASAS no-go bands were added to the existing ASAS



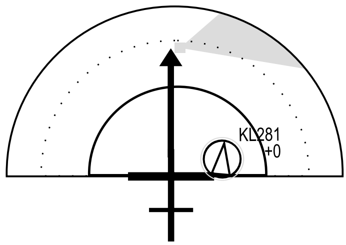
(a) Less than 5 min to conflict: FBZ orange



(b) Less than 3 min to conflict: FBZ red



(c) Other aircraft is turning: FBZ red



(d) Other aircraft has solved conflict by turning

FIGURE 3-9: The progression of a conflict on the XATP display zoomed in on the SVE at the bottom of the ND. With respect to the FBZ color; light gray represents orange color whereas dark gray stands for red.

design to prevent the triggering of new conflicts, while the ASAS system already covered conflict resolution by the use of explicit resolution advice. In XATP on the other hand, the no-go zones, i.e., FBZs, are employed as a support tool for conflict-free manoeuvring, which involves conflict resolution *and* prevention.

Following the latter approach, no explicit resolution is presented in either display in the experiment. The underlying philosophy is that the presentation of such a resolution would prevent pilots from exploring maneuver options other than the (possibly, optimal) one presented and therefore would prevent them from interpreting the no-go areas as a decision-making tool.

In this context, the ASAS information, in particular the resolution advisory and plots of the intruder PZ at their respective CPA position, is deliberately not presented in the PASAS display. This way, it is also sure that the pilots' situation awareness and maneuver strategies are only based on the information contained by the no-go bands. As a result, PASAS bands are not employed in their original operational context, i.e., in conjunction with ASAS. The investigation focuses on their potential to improve conflict SA and support for both resolution and prevention.

3-4 Theoretical comparison using Ecological Interface Design principles

Ecological Interface Design (EID) is an interface design framework that addresses the cognitive interaction between users and complex sociotechnical systems, and was originally applied to process control [12]. The basic principles have been applied to develop the XATP design [14, 20]. Its approach to interface design gives priority to the worker's environment or ecology, concentrating on how the environment imposes constraints on the worker. It aims to identify and visualize the constraints and means-end relations in the work domain, at different levels of abstraction, on the interface. The approach is oriented towards the improvement of operator situation awareness. It supports worker adaptation and has proven better problem-solving performance when compared with current design approaches in industry [23].

There are two central questions in EID. 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? These questions are dealt with by two separate EID tools which try to, respectively, identify and visualize work domain constraints: the Abstraction Hierarchy (AH) and the Skills, Rules, Knowledge taxonomy (SRK). In the following, these EID tools will be used to compare PASAS with XATP.

Before the analysis is described, it is important to clearly set out the boundaries of the work domain. The work is defined as the tactical maneuvering and planning of aircraft motion. So, in a temporal sense, the domain excludes the (very) short-term collision avoidance application, e.g., Traffic alert and Collision Avoidance System TCAS [24] as well as the strategic long-term planning of trajectories. In terms of the control task, the work is limited to the navigation of the aircraft, that is, excluding all control and guidance related issues involved with keeping the aircraft in the air.

3-4-1 Work domain content and structure: Abstraction Hierarchy

In the EID framework, the AH is a tool to reveal content and structure of the work domain, focusing in particular on the identification of the work domain constraints. The AH is a stratified hierarchy [25]: it shows the system from different perspectives going from a functional (top) to a physical description (bottom). Each level describes the system behavior with its own set of functions. From the functions and the relations that exist between them, the aim is to identify work domain constraints that shape the worker's behavior. EID advocates a direct visualization of these constraints on the display.

What distinguishes the AH from other stratified hierarchies is that it is explic-

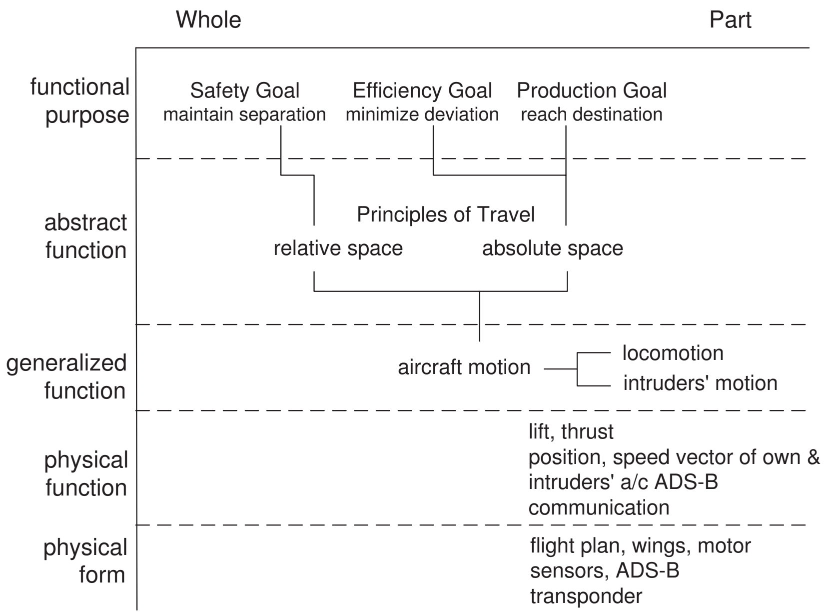


FIGURE 3-10: Abstraction Hierarchy for self-separation.

itly goal-oriented: each level provides the means for the ends identified at the next higher level. Therefore, it corresponds directly to how an operator would want to use a particular chunk of information to perform certain tasks to achieve specific goals. In Figure 3-10 an AH is given for the task of self-separation.

A pilot's top level goals are to safely fly the aircraft, according to its flight plan, to arrive at his destiny, or next waypoint, at a specific time. Hence, we have three separate goals pertaining to safety, efficiency and production. Although in this research mainly the *safety goal* is explored, the other goals stand in close relation to each other. The safety goal is achieved by maintaining spatial separation at all times and results in the spatial-temporal constraint that one aircraft is never allowed to enter the PZ of another aircraft. When an intrusion does happen, the separation distance itself is a measure for the severity of the intrusion, with smaller distances being more severe. The specific pieces of information that the pilot needs to be aware of while realizing the safety goal are, first the time that is left before separation is lost if no action is taken, *time to intrusion*, and second, the time that is needed to resolve the conflict situation, *time to avoid*. The difference between the time to avoid and the time to intrusion, results in the *time to certain intrusion*. This is the time before loss of separation becomes inevitable. When conflict situations have to be prevented or resolved, preference is also given to those maneuvers that limit the deviation (*efficiency goal*) of the current path (*production goal*).

The next level, the abstract function level, describes the system in terms of the principles of travel in both absolute and relative space. These principles govern spatial-temporal, i.e., four-dimensional constraints to moving aircraft. For example, separation in relative space requires that the relative speed vector has to be moved away from the PZ in such a way that it does not intercept the PZ of the other aircraft at the current location, thus out of the FBZ. This must happen before the vector origin enters the PZ, and is therefore also related to the time to intrusion. The relative velocity vector can be decomposed along the line connecting the position of ownship and intruder. The along-track component is the *closure rate*, and the perpendicular component is the *lateral rate*, both in relative space. In absolute space, the deviation from the path is expressed by the magnitude of the avoidance maneuver and the conflict resolution time that is needed before a return maneuver can be started towards the original path.

At the generalized function level, the individual behavior of aircraft is described. The aircraft motion function describes the aircraft trajectory resulting from possible maneuvers. Both the ownship's locomotion and the motion of intruder aircraft are described within this function. A primary element of aircraft motion models is the description of aircraft kinematics, e.g., a turn maneuver. The kinematic constraints have an important relation with the process of getting the relative speed vector out of the FBZ, see the separation function at abstract function level, before separation is lost, the safety goal at the functional purpose level.

The lower levels of the AH, i.e., physical function and physical form, describe the physical implementation of the pilot-aircraft system and depend on the aircraft type. Since the display concepts analyzed here do not consider specific aircraft type characteristics, the lowest levels are not included in this comparison study.

COMPARISON

Generalized Function Neither visualization explicitly expresses aircraft kinematics on the display. As a result, pilots can not assess the exact resulting motion path, meaning that the *time to maneuver* is not directly visible in either display. However, whereas PASAS bands are based on instantaneous aircraft state changes, XATP uses turning kinematics internally for the calculation of the FBZ-legs, and therefore the presentation of these legs implicitly show aircraft turn kinematics. This implies that with PASAS, pilots have to rely on their estimation on aircraft kinematics and maneuver time based on their own flight expertise.

XATP also explicitly reveals information on the behavior and position of the intruder aircraft inside the SVE as the origin and form of the FBZ represent the speed vector and relative position of the related intruder aircraft, respectively. The PASAS bands do not provide this information. In multiple conflict situations, PASAS bands overlap and it is usually impossible to relate band parts with the intruder aircraft on the ND that is causing this particular band part. With a limited number of simultaneous conflicts, XATP is still capable of preserving a clear relation between different FBZs and the respective intruder aircraft.

Abstract Function This level describes the principles of travel in relative and absolute plane. Both visualization forms show how to keep or change speed to have the relative speed avoid the PZ. Both displays show this in the absolute plane in terms of absolute velocity and heading. Neither the *closure rate* nor the *lateral rate* are explicitly presented in either display, although they can be derived from the relative intruder motion in the ND. That is, the change in distance between the ownship and intruder gives a notion about closure rate, and the angular change of the intruder position with respect to the owncraft allows an estimate of the lateral rate. In XATP the relative velocity vector can be seen by the position of the FBZ-origin relative to the ownship's speed vector. Still it is a demanding task to get an accurate notion of the lateral and closure rate, however. The same holds for the exact notion of time variables such as the time to intrusion.

Related to the efficiency goal, the path deviation caused by a certain conflict resolution maneuver is not directly shown in any of the displays. Using PASAS, pilots are likely to assume that the heading or speed band edge that is closest to the actual heading or speed leads to the most efficient resolution of the conflict. Though this assumption could lead to efficient maneuvers in most cases, it is incorrect. For some conflict geometries, where the resolution target state lies close to the intruder state, this may lead to parallel courses and very large deviations. Using XATP, however, this strategy is unlikely to occur as it would bring the own speed vector towards the FBZ origin. Thus, path deviation can be obtained from the presentation of the FBZ origin (relative velocity, time to avoid) and the distance to the nearest conflict-free areas (maneuver magnitude).

Functional Purpose At this level, the visualization should show whether goals are achieved. The distance with the intruder aircraft visualizes the safety goal, whereas the PZ is the visualization of the safety goal constraint. The *time to intrusion* can be deduced from the color of the state bands in PASAS and the FBZ in XATP. The *time to certain intrusion* is not explicitly available in neither PASAS nor XATP, although in XATP the pilot can deduce this from the change of splay angle of the FBZ legs over time.

Another important distinction between the two displays is that PASAS only shows the conflict bands if the intrusion is less than 5 minutes away, whereas XATP shows the FBZ in grey as soon as the intruder aircraft comes within ADS-B range.

Both displays present all possible conflicts: PASAS by simply integrating the bands and create a large band, and XATP by layering FBZs over each other [14]. Hereby, XATP has an advantage over PASAS: the separate aircraft are always clearly visible because the FBZs of different aircraft are different and therefore distinguishable.

3-4-2 Display form: SRK taxonomy

The second phase of EID deals with how information about the work domain constraints should be visualized in such a way that it is adapted to human behavior. The Skills, Rules and Knowledge taxonomy (SRK) is proposed as a tool for describing the mechanisms that humans have for cognitively processing information.

Three levels of cognitive control, skill-, rule- and knowledge-based behavior, are distinguished when describing human behavior in reaction to available information [12]. These levels cover a range of behaviors going from direct, (time-critical) control with little cognitive effort up to complex problem solving. Ecological designs aim to accommodate *all* levels of control, and at the same time, to not force control to a higher level than necessary, hereby saving cognitive resources of the human operator when desired [23].

COMPARISON

Skill Based Behavior (SBB) When displaying for SBB, operators must be able to directly act on the interface. In standard situations pilots quickly react on primary signals which allow them to maneuver safely without cognitive effort. Two issues must be addressed when comparing both concepts. First, the PASAS bands indicate that the current heading should be kept out of the heading bands, and the speed should be kept out of the speed bands. Finding a resolution means that the pilot must scan two separate one-dimensional solution spaces. The main advantage of a one-dimensional solution is that it is easy to understand and perform.

For XATP, the SVE envelope indicates how the current speed-heading state should be kept out of the FBZ. The SVE presents a two-dimensional field of states, hereby revealing the complete array of solutions involving combined speed-heading changes to the pilot, which is ‘hidden’ when using PASAS. The main advantage is that finding a combined speed-heading maneuver, being the most efficient solution in some situations, remains possible. Therefore, XATP supports these types of solutions at the SBB level, whereas for PASAS finding these (hidden) solutions is moved to higher levels of cognitive control.

Second, since the SVE includes turn dynamics, the final speed-heading solution is more accurately indicated (especially when it involves a significant heading change), whereas PASAS might require some incremental actions to achieve a successful resolution. This is likely to be a more demanding task for the pilot. On a psychological level, this may affect the pilot's trust in the support tool. Despite the unlikeliness of this event in the operational time horizon of the tool, the system can not completely assure that the area can be left before separation is lost.

Ruled Based Behavior (RBB) RBB involves the process of associating familiar perceptual cues in the world with an action or intent. This behavior allows the pilot to deal more efficiently with familiar problems by applying a fixed rule instead of analyzing them cognitively. There should be a consistent one-to-one mapping between the work domain constraints and the perceptual information on the SVE interface. RBB is supported by the fact that certain types of conflict situations will yield, in a one-to-one mapping, certain bands in PASAS and certain SVEs in XATP, meaning that pilots can rely on certain similarities learned in due course. Over time, different avoidance strategies can be tested, and selected or discarded depending on their efficiency.

In PASAS, however, several substantially different conflict situations can create similar bands, whereas in XATP each FBZ form represents a unique conflict situation. Although one may argue that this would not really be a problem as long as the same strategy could still resolve these different situations, XATP has a clear preference. In scenarios where multiple intruder aircraft impose constraints on the same speed-heading region, this effect is even more present. XATP also provides an additional cue related to the efficiency goal, namely, 'to stay away from the FBZ origin'. This prevents pilots from performing maneuvers that result in parallel path flight and therefore large path deviations.

Knowledge Based Behavior (KBB) KBB involves analytical problem solving based on a symbolic internal mental model. To support KBB, EID advocates that the interface presents the content and structure of the work, as identified with the abstraction hierarchy, as if it is an 'externalized mental model'. Both PASAS and XATP present separation zones (safety goal) in the absolute plane (absolute speed and heading) enabling pilots to see spatial relations between resolution capabilities (aircraft motion function) and the positions of reference path and destination (production goal).

The FBZ of the XATP, however, reveals additional domain functions and relations, as mentioned in the AH analysis. First, from the heading or speed band forms of PASAS only, pilots can not always know if the intruder aircraft is on port, starboard side, in front or behind the ownship, whereas the direction of the FBZ in the SVE clearly indicates the intruder position relative to the ownship position. Therefore, XATP enables pilots to link intruder aircraft motion and behavior (physical function) with separation (safety goal). In case of simultaneous conflict situations with a limited number of intruder aircraft, this linking is still possible with XATP whereas PASAS bands are simply combined to one heading and speed band, making linking already difficult when only two intruders are causing a conflict.

Second, the intruder behavior can also be perceived from the translation of the FBZ, as the FBZ origin is determined by the intruder speed vector in the SVE. And third, the expansion rate of the FBZ legs is a qualitative measure for time to intrusion, and pilots will (learn to) understand that an increasing rate indicates that both aircraft will pass each other relatively soon.

3-4-3 Conclusions from the theoretical comparison

Summarizing for display content and form, it would seem that, although both display designs provide sufficient information, the XATP design provides a more accurate final solution, due to using turning kinematics, but in particular as it presents the full array of possible speed-heading maneuvers. Whereas the geometrical form of the FBZ to present separation is unique for each conflict situation, with PASAS two different conflict situations may result in exactly the same heading or speed band configuration.

The FBZ leg expansion further provides information about how long it will take until an intrusion is inevitable. Different aircraft are clearly visible in the SVE, including their position, speed and, when looked for some time, even maneuver intentions. XATP is able to show aircraft at a larger range, thereby giving pilots more time for action.

It is, however, questionable whether this information-richness of the XATP design can be absorbed by the pilot with the current design format and size. PASAS bands have a larger presentation size, and their presentation of maneuver constraints in a one-dimensional state space, might be considered easier by pilots to use, because the related actions are also one-dimensional, i.e., speed *or* heading changes. From the above, a moderate advantage can be given to the XATP design, but experimental evidence is needed to back up these findings.

3-5 Experiment

An experiment was conducted to assess the differences in pilot workload, performance and safety between the two visualizations introduced above. It is assumed that a direct relationship exists between pilot traffic situation awareness and performance (and workload) in conflict resolution tasks. Since the theoretical analysis indicated some advantages in the XATP presentation regarding situation awareness, our main hypothesis was that conflict resolution performance improved with the XATP display, accompanied with lower levels of pilot workload.

TABLE 3-1: Pilot characteristics.

	age	hours	aircraft types
pilot A	66	12,700	DC3, CV640, F28, DC8-50/63, B747-300/400
pilot B	39	7,000	B737
pilot C	53	14,000	F28, DC10, A310, B737, B747-400
pilot D	28	1,100	C550
pilot E	31	7,000	J31, B757, B767
pilot F	45	11,600	B737-200/300/400, B747-400, B767-300
pilot G	40	6,800	C152/172, F406, B737
pilot H	30	4,200	BE-99, FA-227, EMB-120, B737-700/800

3-5-1 Method

Subjects and instructions Eight professional airline pilots participated in the experiment. All pilots were male, and aged between 29 and 66 years. The number of flight hours ranged from just over one thousand to over twelve thousand. All pilots were familiar with TCAS, see Table 3-1.

Subjects were asked to keep the initial aircraft heading and speed, and to fly towards the next waypoint (also shown on the ND) while avoiding other traffic. In case a conflict situation was detected the pilot was instructed to resolve it by changing heading and/or speed. When the conflict was resolved, pilots were instructed to return to a course that would intercept the original path before or at the next waypoint.

Apparatus The experiment was performed in the fixed-base flight simulator of the Control and Simulation Division, with no outside visuals. Subjects were seated in the co-pilot position. Flight instruments (PFD and ND) were displayed to the pilot on two 18" LCD screens. A virtual Mode Control Panel (MCP) and the ND were shown on the center screen which was vertically oriented, the PFD was shown on the right screen (directly in front of the pilots). Pilots controlled the virtual MCP with a touchpad.

To measure workload objectively, a secondary task consisting of a critical tracking task was shown on the same screen as the PFD. This tracking task, discussed in more detail below, was conducted using an electro-hydraulic stick mounted to the right side of the pilot.

Aircraft characteristics and experiment conditions The experiment was conducted with a non-linear B747-200 model. This model was controlled through an autopilot, manipulated through the virtual MCP, which only reacted to horizontal state change commands. The autopilot remained engaged during the entire run. ICAO standard atmosphere was used; no wind was present.

The range of the XATP display was artificially reduced during this experiment so that it could be more readily compared with the PASAS display, since PASAS can only give information about short-term conflicts. Each scenario had the subject flying in en-route, uncontrolled airspace at a constant altitude of 30,000 ft and an initial groundspeed of Mach 0.8 (approximately 240 m/s).

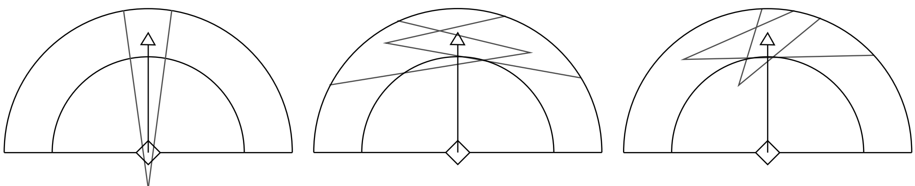
Independent variables The experiment tested three independent variables: two displays, two traffic densities, and three conflict geometries.

Display The PASAS and XATP displays were tested. The displays presented solutions to conflicts in two dimensions, respectively separated (speed and heading band) and integrated (speed-heading space). Both displays augmented the ND with the traffic surrounding the own aircraft, showing the aircraft PZ which was colored if in conflict. The current heading of the other aircraft was also shown.

Traffic Density Traffic density was set similar to current real life traffic density, or to a value three times higher. This was done to investigate how the displays would perform in future traffic densities.

Conflict Geometry Three different conflict geometries were tested (see Figure 3-11). These geometries were designed to encourage different resolution maneuvers. The first geometry was a head-on scenario, during which a heading maneuver is the desired resolution. The second geometry was such that a heading change was either unavailable, or very large. This would prompt the subjects to make a change of speed. The third geometry was a combination of the above; both a speed change and a heading change were possible, but a combination of the two would be a more efficient solution.

All the experimental data were analyzed using analysis of variance (ANOVA).



(a) Heading change (b) Speed change (c) Combination

FIGURE 3-11: Different conflict geometries and their SVE.

Experiment and scenario design The three independent variables led to $2 \times 2 \times 3 = 12$ possible experiment conditions. After a detailed briefing and several test runs, 12 different scenarios (each condition once) and two "emergency" scenarios were flown. The scenarios were distributed in two blocks. The first block contained all scenarios with the PASAS display, the second block all scenarios with the XATP display. The order of the blocks was balanced over subjects.

In the emergency scenario another 'intruder' aircraft would suddenly change course so that an intrusion would happen within two minutes. Subjects would need to take immediate action to resolve the conflict. This scenario was performed once with both displays, in high-density traffic, at the end of each block.

In all scenarios, the subjects would encounter a conflict caused by one or two intruder aircraft which would prompt the subject to take action. The intruder aircraft would also take some predetermined action. This action would aid the subject in the solution if the subject had taken the ideal solution to the conflict. If the subject had taken a different solution, the course change of the intruder aircraft might not make a difference, or might make matters worse.

In addition to these conflicting aircraft, other traffic was simulated to give a realistic (or future realistic) traffic view. These other aircraft were situated at least 7 flight levels above or below the current level, or with such a position and heading on the own flight level, so as not to interfere with the conflicting aircraft or the own aircraft.

Procedure At the start of the experiment, each subject was given a short briefing on the different displays. After this introduction a number of test runs was flown to familiarize the subjects with using the displays. The warmup runs were identical pairs, differing only in the display used. Subjects made at least four test runs, and afterwards, if they indicated that they were not entirely comfortable with the displays, an additional two test runs were available.

Each subject performed fourteen runs lasting approximately nine minutes each. Subjects were instructed to keep the heading and speed of the aircraft to what it was at the start of the run, and to fly towards the next waypoint (also shown on the ND). If the speed or heading needed to be changed in order to avoid other aircraft, then after the conflict had passed, the subjects should return the speed to the original value, and the heading to such a value that the original path would be intercepted at or before the next waypoint.

A run was terminated once the following conditions were satisfied:

- the conflict had been solved, or:
- the other aircraft were passed, so that only an absurdly large state change could cause a new conflict, or:
- the state had been changed so no more changes were necessary until the original path was intercepted at or before the next waypoint.

Subjects were *not* asked to return to the original path immediately after the conflict, because in a real situation this would not happen either. They would instead fly directly to the next waypoint.

To get an objective measurement of workload, subjects were asked to perform a critical tracking task. The primary task, self-separation, was to be considered the most important at all times.

At the end of the experiment, pilots were asked to fill in a questionnaire.

Secondary task To measure workload objectively, a critical tracking task was conducted as secondary task. [26] In this task, subjects had to maximize the time until the position of a controlled element, an inverted pendulum, goes out-of-bounds (referred to as the *fall-time*). The fall-time gives an indication of the secondary task performance and as such also how much attention the pilots are giving the tracking task. If the fall-time is short, and the next fall-time is also short, then it is hypothesized that the attention of the subject is with the primary task. A single shorter time could be caused by momentary inattention (blinking eyes, twitching, etc.), an extremely brief glance at the displays, or being too slow to get the side stick back to the rest position. When the tracking task went out of bounds, the task was suspended for 1.4 seconds.

The difficulty of the secondary tasks slowly increased during the first 20 seconds of successful control, after which it remained steady. The increase over the first 20 seconds was done to allow the subject to partially control the secondary task if the primary task takes some attention, but not all attention. A higher difficulty after 20 seconds would assure that only a subject who has all his attention with the secondary task would be able to be successful in keeping the task going.

Dependent measures The most important instruction in the experiment was that subjects were not allowed to enter the PZ of other aircraft at any time. The *distance* between the controlled aircraft and the other aircraft is therefore the first dependent measure, representing 'safety'. Only aircraft with the potential to create a conflict were considered. Therefore all aircraft flying at the other flight levels were ignored. As hypotheses for safety, it was expected that an increase in traffic density will lead to lower safety measures (#2) whereas it will not be influenced by the traffic display (#1) not by the conflict geometry (#3), since both displays have proven to be useful and safe systems in earlier experiments.

The second measure was called 'performance' and was measured by the needed *number of autopilot commands* and the *maximum lateral off-track deviation* from the original trajectory. The number of autopilot commands given is a measure of how well the subject can interpret the situation. If the subject has a good situation awareness, better performance is reflected by fewer state changes to get to a safe course. A state change is defined as a new selection of heading and/or speed on the MCP by the subject, but only if the change remains constant for at least 2 seconds and is different from the previously selected value.

The maximum lateral off-track distance measure will be largely dependent on how close the subject wishes to pass the other aircraft, and how far away he is willing to deviate from the original track. It was expected that both performance measures would have little bearing on how well the subject understood the situation, or how much concentration the display requires.* As hypotheses for resolution performance, effects were expected from the traffic display (#4), traffic density (#5) and conflict geometry (#6).

From the secondary task measurements, two 'workload' measurements were defined. The *mean-time-to-fall* is the time that the complete run lasted divided by the number of falls. The *percentage of up-time* gives the ratio between the time the tracking task was successfully going and the total run time. For each time the task fails, 1.4 seconds is subtracted. The percentage gives an indication of how much time the subject is dedicating time to the secondary task. It was hypothesized that display (#7), density (#8) and geometry (#9) would affect the workload.

Based on the theoretical comparison, our main expectation was that the XATP concept allows a better SA and this will become the most apparent in the measurements for performance (which would then improved) and workload (which would be lower).

Hypotheses Table 3-2 summarizes the hypothesized effects. Here, for each combination of independent variable and dependent measure the first column gives the hypotheses ID number, the second column 'H' gives the hypothesized effect, and the third column 'R' indicates whether a significant effect has indeed been found in the experiment, or not. An 'x' indicates that an effect is hypothesized (or found), whereas a dot '.' indicates that no effect was hypothesized (or found).

Pilot acceptance At the end of the experiment, pilots were asked to complete a questionnaire that contained questions to allow for a more subjective evaluation of the displays. It also invited pilots to state their personal comments. The questionnaire addressed pilot acceptance, situation awareness, and ultimately, their preference of one concept over the other. Table 3-3 summarizes some of the questions that were included.

*It is also acknowledged that along-track deviation was neglected in the metric for track deviation. A more precise metric should ideally also account for along-track deviation and moreover, take into account that recovery from a deviation along track takes more effort and time than recovery from the same deviation in lateral direction.

TABLE 3-2: Experimental hypotheses regarding the effects of the independent variables display type, traffic density and conflict geometry on the various dependent measures reflecting safety, performance and workload.

	Safety	H	R	Performance	H	R	Workload	H	R
Display type	#1	.	.	#4	x	.	#7	x	.
Traffic density	#2	x	.	#5	x	.	#8	x	.
Conflict geometry	#3	.	.	#6	x	x	#9	x	x

3-6 Results and discussion

3-6-1 Safety

Figure 3-12 shows boxplots of the minimal distance between aircraft (at the CPA), for both displays and both traffic densities, for the three conflict geometries.

Overall, the safety was high. In just five runs the distance between two aircraft became less than 5 NM. Three of these intrusions happened with the same subject, and two of those occurred during the first two runs in which the pilot chose a path which was slightly too close to the PZ of the other aircraft. Because of pre-programmed last-minute maneuvers of the intruder aircraft, the aircraft subsequently entered the PZ. In the end, all intrusions still had a distance of more than 4.5 NM. Three intrusions happened with the PASAS display, and two with the XATP display. Two occurred in high-density runs, and three in low-density runs.

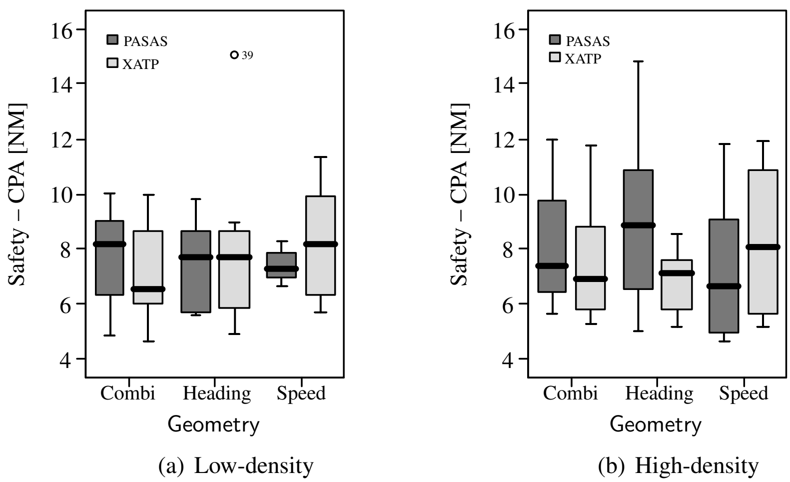


FIGURE 3-12: Safety performance, minimal distances at CPA.

The results indicate that for the heading change scenario, both displays perform

TABLE 3-3: Example questions of pilot questionnaire.

Acceptance	
both	*What is your general opinion of the {PASAS, XATP} display?*
Awareness	
both	*Did you know how much time you had until the conflict took place?*
PASAS	*Did you feel you could go through the bands to attain a better solution?*
	Did you know which aircraft caused which band?
XATP	*Did you feel you could go through an FBZ to attain a better solution?*
	Did you know which aircraft caused which FBZ?
Comparison	
	Which display did you find the most useful for conflicts which required a heading change to solve?
	Which display did you find the most useful for conflicts which required a speed change to solve?
	Which display did you find the most useful for conflicts which required both heading and speed changes to solve?
	Which display helped your situation awareness most?
	Which display did you prefer and why?

the same in low-density traffic. Whereas XATP yields similar performance in the high-density environment, PASAS appears to induce larger separations; it is unclear why this happened. For the speed scenario, XATP results in a larger CPA distance than PASAS in both traffic densities. For the combination scenarios, the situation is reversed, with XATP having a lower CPA distance. This latter result is expected because the 2D nature of XATP gives more information in such geometries, thereby allowing the subjects to pass other aircraft with a smaller safety margin.

ANOVA shows that none of the effects of conflict geometry, display type and traffic density are significant, see Table 3-4. Results did show a significant difference in separation distances between the various pilots, however. Hence, different pilots adhered to different safety distances.

The results therefore indicate that hypotheses #1 and #3 can be accepted: safety was not affected by the display nor by the geometry. Neither was safety affected by the density, however, and hypothesis #2 must be rejected for the density levels used in this experiment, see Tables 3-2 and 3-4.

TABLE 3-4: Results of a full-factorial ANOVA, with the statistically significant results underlined.

	performance[1]	safety	workload
main effects			
display	$F_{1,7}$=0.452, p=0.523	$F_{1,7}$=0.181, p=0.683	$F_{1,7}$=1.304, p=0.291
geometry	$F_{2,14}$=8.588, $\underline{p=0.004}$	$F_{2,14}$=0.049, p=0.952	$F_{2,14}$=7.629, $\underline{p=0.006}$
traffic density	$F_{1,7}$=0.658, p=0.444	$F_{1,7}$=0.289, p=0.607	$F_{1,7}$=0.854, p=0.386
2-way interactions			
disp × geom	$F_{2,14}$=0.291, p=0.759	$F_{2,14}$=1.972, p=0.176	$F_{2,14}$=0.081, p=0.922
disp × dens	$F_{1,7}$=0.049, p=0.831	$F_{1,7}$=1.281, p=0.295	$F_{1,7}$=0.846, p=0.388
geom × dens	$F_{2,14}$=1.924, p=0.183	$F_{2,14}$=0.123, p=0.885	$F_{2,14}$=4.157, $\underline{p=0.038}$
3-way interaction			
disp × geom × dens	$F_{2,14}$=0.189, p=0.830	$F_{2,14}$=0.913, p=0.424	$F_{2,14}$=1.355, p=0.290

[1] expressed in number of commands

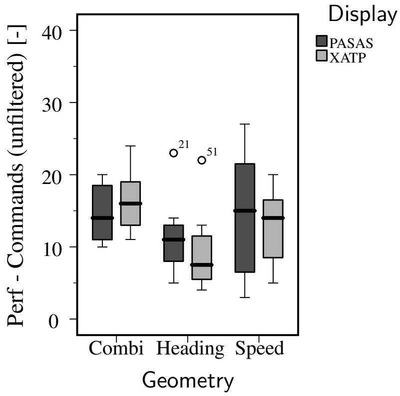
3-6-2 Performance: number of commands

Figure 3-13 shows boxplots of the number of commands selected by the pilots, for both displays and both traffic densities, for the three conflict geometries.

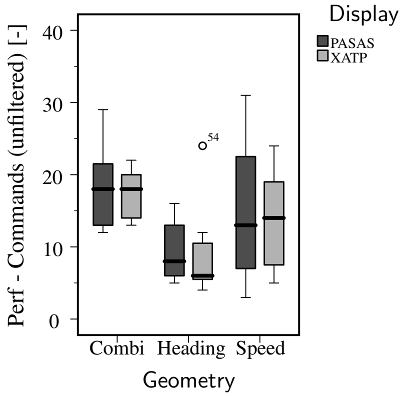
An autopilot command was defined as a new selection of heading and/or speed on the MCP by the subject which remained constant for 2 seconds. However, some pilots made a large number of commands, as they sometimes adjusted the state by only small amounts. The questionnaire revealed that seven of the eight pilots commented that, with PASAS, in an effort to increase the efficiency of the maneuver, many small commands were made to stay close to the bands, in particular when returning to the original track.

Post-hoc, results were filtered to mitigate this effect. Commands that changed the heading by less than 4 degrees or the speed with less than 4 knots and were given within 7 seconds of the previous command, were all excluded from the calculations of the commands. These commands were simply not considered really ‘new’ trajectory change commands.

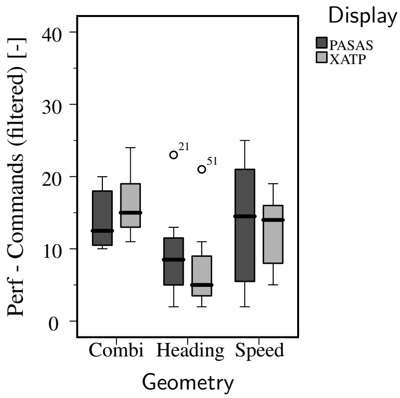
The number of commands was roughly equal for the speed and combination scenarios, in the heading scenario less commands were given, Figure 3.13(d)). Unlike the other scenarios, the heading scenario easily allows pilots to perceive the best solution since the only safe solution was a heading change, Figure 3-11. ANOVA showed that whereas the effect of the conflict geometry was indeed significant, the effects from traffic density and display type were not, see Table 3-4. Note that the variability in the number of commands was indeed much smaller with XATP, in particular for the speed scenario, and in the high-density scenarios.



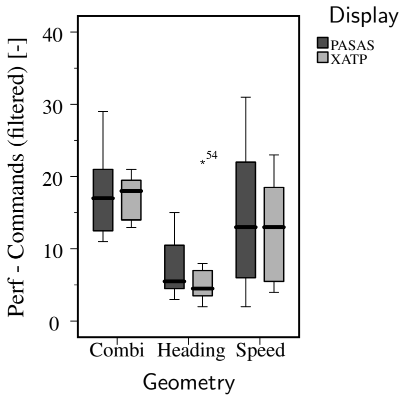
(a) Low-density, original



(b) High-density, original



(c) Low-density, filtered



(d) High-density, filtered

FIGURE 3-13: Performance: number of commands, unfiltered (top) and filtered (bottom).

3-6-3 Performance: deviation from the track

Figure 3-14 shows boxplots of the maximum deviation from the track, and the integrated track deviation, for all experimental conditions.

The results for maximal off-track distance are quite similar to the results for autopilot commands, Figure 3-13. The lateral off-track distances are extremely spread out for the speed scenario. Here, a deviation from the track was in principle not necessary as the scenario was setup in such a way that a change in speed was sufficient to resolve the conflict. Indeed, some pilots did find the solution since the bars start at 0, but many did not and actually made heading changes that resulted in very inefficient conflict resolutions and extremely large (lateral) off-track distances. This

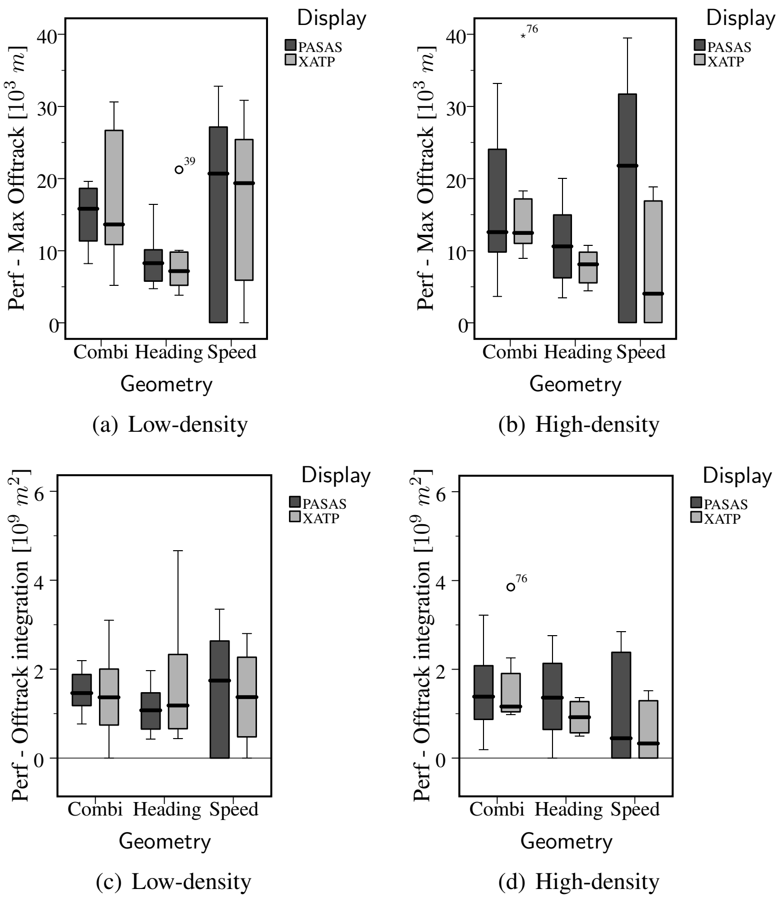


FIGURE 3-14: Performance: maximum off-track distances (top), and integration of the track deviation (bottom).

behavior possibly indicates a pilot's intuitive preference for a turn maneuver over a speed change.

For all scenario geometries, PASAS results in a much wider spread in off-track distances and integrated off-track distance, which indicates that, overall, XATP encourages a better use of speed as (part of) the solution command. This occurs in particular in the high-density scenarios. These effects were, however, all not significant.

Summarizing, hypotheses #4 and #5 should be rejected: performance was not significantly affected by the display nor by the traffic density. The conflict geometry, however, did affect performance, and therefore hypothesis #6 is accepted, see Table 3-2.

At the end of this chapter, two figures are included that show some of the tracks flown. Figure 3-17 shows the tracks flown by the aircraft, and the aircraft heading, for all 'heading-change' scenarios. Figure 3-18 shows the distance between the own aircraft and the intruder, with the minimal separation of 5 NM indicated. Clearly, no conflict occurred in the scenarios.

The crosses in Figure 3-17 show the "ideal" conflict resolution maneuver, yielding the smallest off-track deviation and the shortest time to resolve the conflict. The figure shows the tracks flown for the XATP and PASAS displays, in both low- and high-density traffic. Overall, it is clear that in all conditions except one, pilots chose the right heading resolution direction (to the left), but that the heading changes were larger than absolutely necessary. The variability in tracks and resolutions chosen by pilots are typical for the other results found in the experiment.

3-6-4 Pilot workload

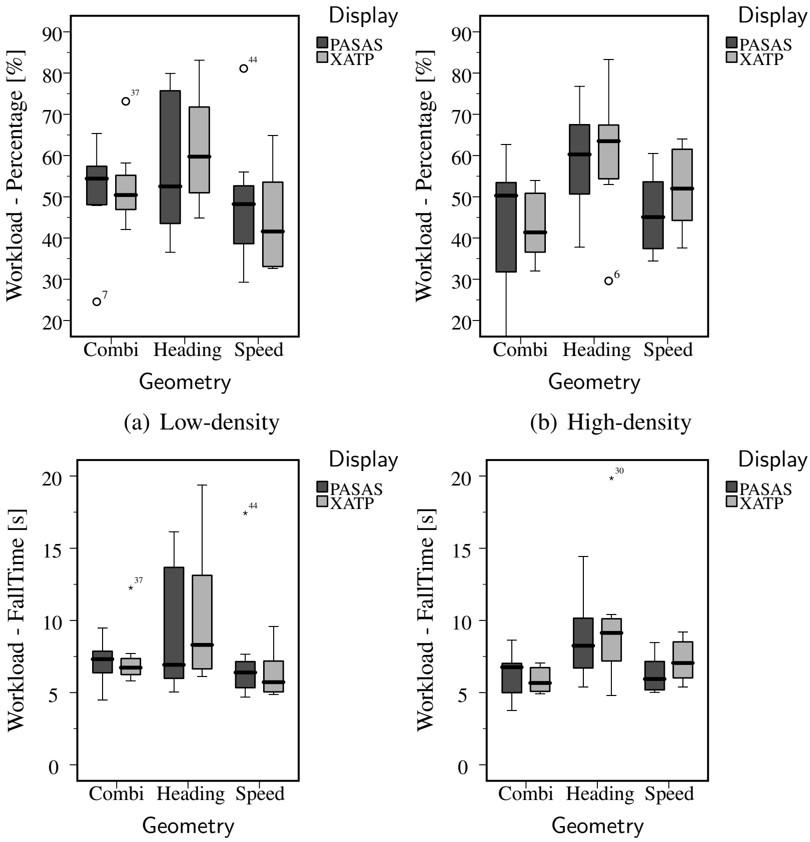
Figure 3-15 shows boxplots of the percentage of the total time of a run spent on the secondary task, and the fall-time measurements obtained in the secondary task. For both metrics, a higher value indicates that more time could be spent on the secondary task, meaning a lower workload of the primary task of self-separation.

Results regarding the percentage of time spent on the secondary task and the fall-time measurements agree quite well. The median time spent on the secondary task seems fairly constant across densities and displays, so hypotheses #7 and #8 must be rejected. However, results are different with respect to geometries. Higher values are found for the heading geometry, indicating that pilot workload is *lower* here than for the other geometries. Hence, geometry had a significant effect on workload, see Table 3-4, supporting hypothesis #9.

Furthermore, workload is higher for the speed scenarios in low-density airspace, and higher for the combination scenarios in high-density airspace. This causes the significant interaction between geometry and density, see Table 3-4.

The workload measures variations between different runs are also the largest in the heading scenarios. This spread could be caused because some pilots flew closer to the other aircraft, and therefore needed to pay more attention to the displays. When analyzing the data a little closer, this indeed was the case: if the CPA distance increased, so did the attention on the secondary task, indicating a lower workload of the primary task.

Summarizing, hypothesis #9 is accepted, since the geometry did indeed affect the workload. Hypotheses #7 and #8 are rejected, as workload was not significantly influenced by the choice of display, nor by the traffic density, although the latter depended on the conflict geometry as well.



(a) Low-density (b) High-density

(c) Low-density (d) High-density

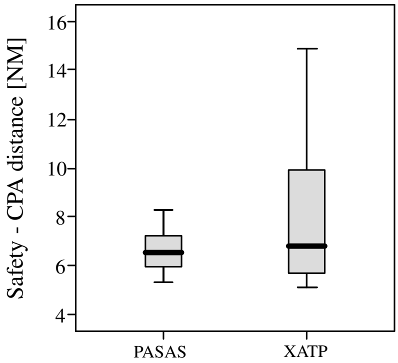
FIGURE 3-15: Percentage of time spent on the secondary task (top) and the average fall-times, the mean-time-to-fall (bottom).

3-6-5 Emergency scenarios

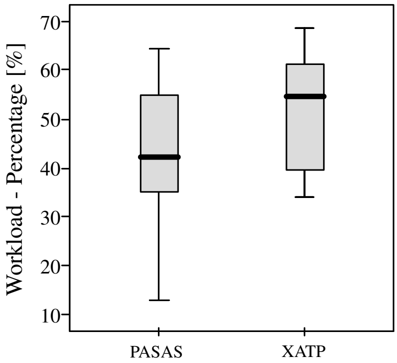
The emergency scenarios were included to see how subjects would react to a sudden and unexpected conflict situation; they were only flown in high-density airspace.

The results of these 16 runs are shown in Figure 3-16. From this figure it is clear that both displays performed equally well. Most important in this scenario is of course the safety. In none of the runs did an intrusion actually happen; apparently all subjects were able to successfully avoid the other aircraft. The results of runs with the XATP display had a larger deviation in distance at CPA than those using the PASAS display, Figure 3.16(a). Workload was lower with the XATP display, Figure 3.16(b), and was the number of commands given, Figure 3.16(c).

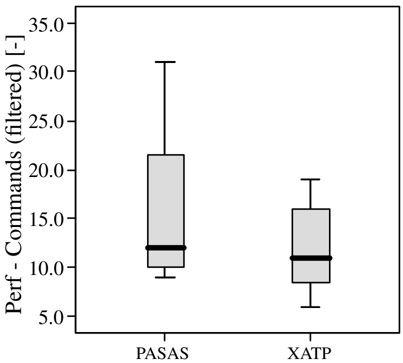
It is unclear why the XATP display would need less attention in the emergency



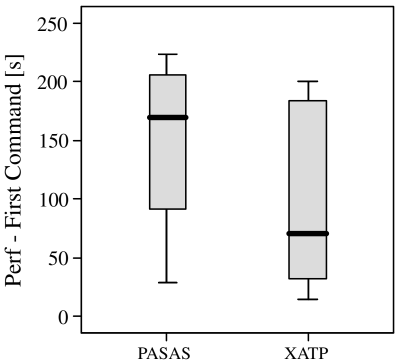
(a) Performance: safety



(b) Workload



(c) Number of commands



(d) Time-to-first-command

FIGURE 3-16: Safety, performance, workload, and time to first command, for the emergency scenarios, conducted in the high-density traffic.

case, since the PASAS display is in fact somewhat more straightforward, and especially gives better detail in sudden changes. Once we take a look at the last graph in this series it becomes clear, however. It appears that the XATP display allowed pilots to take action much earlier; almost 100s earlier for the median values (70.7 and 169.2), and almost 50s for the mean value (98.6 and 148.3). When comparing the times at which the conflict is first presented to the pilots, the XATP display shows the conflict significantly earlier: 63 seconds for XATP vs. 24 seconds (speed-band) and 184 seconds (heading-bands) for PASAS. Although the speedbands for PASAS are visible earlier, these only indicate that no acceleration should be made, and here the most important maneuver was the heading change. And this only becomes visible two minutes after it is visible in XATP.

TABLE 3-5: Summary of pilots' answers to some questionnaire items.

	PASAS by far	PASAS a bit	Neither	XATP a bit	XATP by far
better in heading conflicts	1	3	3	0	0
better in speed conflicts	1	2	1	2	1
” in combined speed/heading conflicts	0	0	1	5	1
needs less concentration	1	2	2	1	1
helps in situation awareness	0	0	1.5	3.5	2
main preference	1	1	1	4	0

Overall, in none of the runs an intrusion occurred, which means that for this experiment, both displays remained functional in unexpected short-term situations.

3-6-6 Pilot questionnaire

In the questionnaire, all pilots indicated that both displays were very useful and worth integrating into the flight deck. All subjects agreed that the XATP display takes more time getting used to. Asking subjects for a direct comparison between the two displays resulted in a preference for PASAS for heading changes, equally separated preferences for the speed-change geometry, and a preference for the XATP display for combination geometries. Overall, 4 out of 7 subjects (one pilot did not complete the questionnaire) ultimately preferred XATP, and 2 preferred PASAS. Table 3-5 summarizes some more answers of pilots to the questionnaire.

In all cases, the displays were used to select a safe state which was near the edges of the no-go areas rather than further away, indicating that pilots had confidence in the display presentations. XATP seemed to provide a slightly better indication of the time to intrusion. Pilots indicated that it was easier to link the other aircraft to FBZs (XATP display) than to link them to speed and heading alert bands (PASAS display). Some subjects used the XATP display to get a clearer image of the traffic, whereas fewer subjects did this with the PASAS display. Finally, all subjects noted that speed info of the other aircraft was missing. Since this information is in fact implicitly presented in the XATP display, this comment is an indication that pilots indeed need more time to adjust to the information-richness of the presentation.

3-7 Discussion

The theoretical comparison showed that the PASAS display and the XATP display provide information from different levels of the AH. The XATP display has some distinct advantages: a larger warning time for more tactical use, and the fact that as soon as an intruder is within range, the ‘final’ solution can be found. With PASAS, the pilot may start the avoidance maneuver, but he can not be sure if the chosen maneuver is large enough until the intruder aircraft is closer.

Both displays have elements that are superior to the other. The size of the PASAS bands make these a clear presentation, and speed and heading bands can be easily used to make conflict-free speed changes and turns, respectively. The small size of the SVE on the XATP display makes it hard to discern the same level of detail. However, the SVE provides a two-dimensional speed/heading space that is a richer source of conflict-specific information and allows for a stronger correlation with traffic information on the plan view of the ND. For example, the FBZ points to the actual position of the intruder causing the conflict, and allows the pilot to clearly discern between the behavior of different aircraft. Therefore, the XATP display was expected to be superior in terms of SA.

From the experimental results, it becomes clear that both displays use well-suited, safe visualization forms for the task of self-separation. Neither display was found to be superior in terms of task performance, workload, or safety. The effects of traffic density were overall not significant. Task performance and workload were primarily influenced by the conflict geometry.

The pilot questionnaires affirm these findings as it indicated a pilot preference for one of the display types, depending on the personal preference, but also on the specific conflict geometry of each run. Experimental results for the speed scenario affirm that pilots avoid speed maneuvers, sometimes leading to very inefficient turn maneuvers. This behavior seems to be even more explicit with the PASAS display.

When comparing the theoretical analysis with the experimental results, the hypothesized superiority of the XATP display could not be validated experimentally. Several explanations are possible. First, the *choice of metrics* for safety, task performance and workload might have to be enhanced or even changed. As an example, it might be more meaningful to develop a metric where along-track path deviation is also penalized accordingly, or a metric including fuel-burn or time differences at some arrival point. Second, the scenarios employed may have been too simple, resulting in small differences in decision making between both displays. The use of a baseline display that would only provide traffic information and conflict warnings could have provided insight in to what extent pilots are already capable of dealing with these conflict scenarios even without any constraint visualization. The scenarios were also quite standard pre-defined situations that are perhaps not well-suited for the evaluation of ecological displays.

Task performance, workload and safety measurements mostly cover skill and rule-based pilot behavior. However, EID aims at display design for enhancing SA in order to give effective support for dealing with situations beyond the design scope of automated pilot-aircraft systems. This is mostly reflected through the performance in terms of knowledge-based behavior. Although some relation is likely to exist, task performance and workload metrics are no *direct measures of SA*. In this context, an evaluation of an ecological display might call for better-fitted scenarios and direct measures of SA.

Future research should therefore give more attention to the definition of what situation awareness exactly means in this problem domain, and what experimental scenarios, measurements, and SA assessment techniques could be the most appropriate to obtain more meaningful, objective and quantitative results on conflict SA. It seems that too few attention is given to assess to what extent pilots are aware about the conflict situation: e.g., which maneuver options are available, how urgent is the situation, and which conflict aircraft needs more attention?

3-8 Conclusions

In this paper two separation assistance interfaces, XATP and PASAS, were compared. It was analyzed how both displays visualize maneuver constraints imposed by the need to separate from other traffic in the surrounding. From this analysis it was concluded that XATP is more suited to promote pilot traffic awareness. An experiment with professional airline pilots indicated that both displays perform equally well. Better metrics for safety and performance could change the outcome, however. Additional research should be done to identify what exactly traffic situation awareness means, and how it can be measured.

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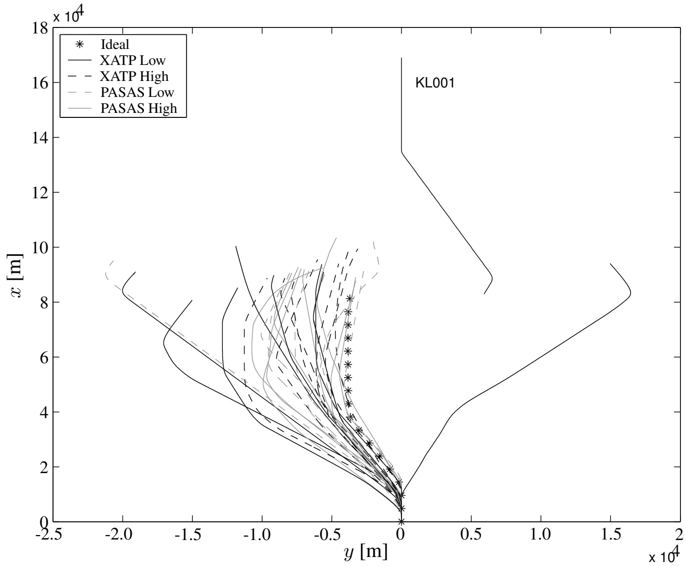
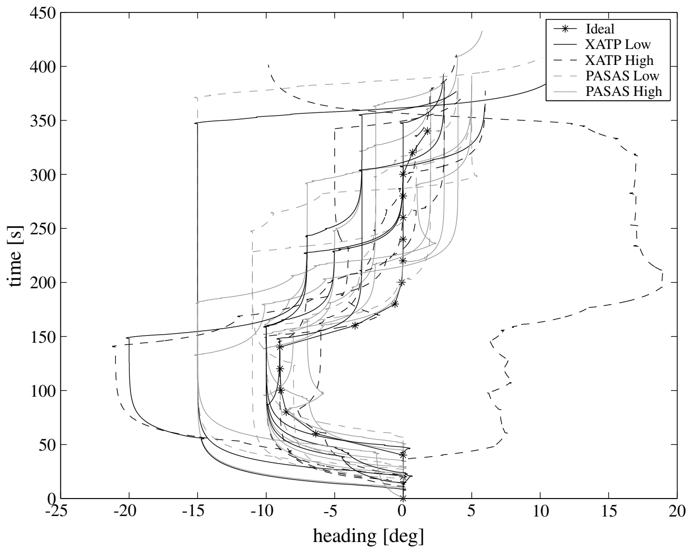


(a) Tracks flown (top-down view)



(b) Aircraft heading

FIGURE 3-17: Example of the tracks flown in the experiment, for the heading scenarios (data for all subjects). Part one: top-down view, and heading data.

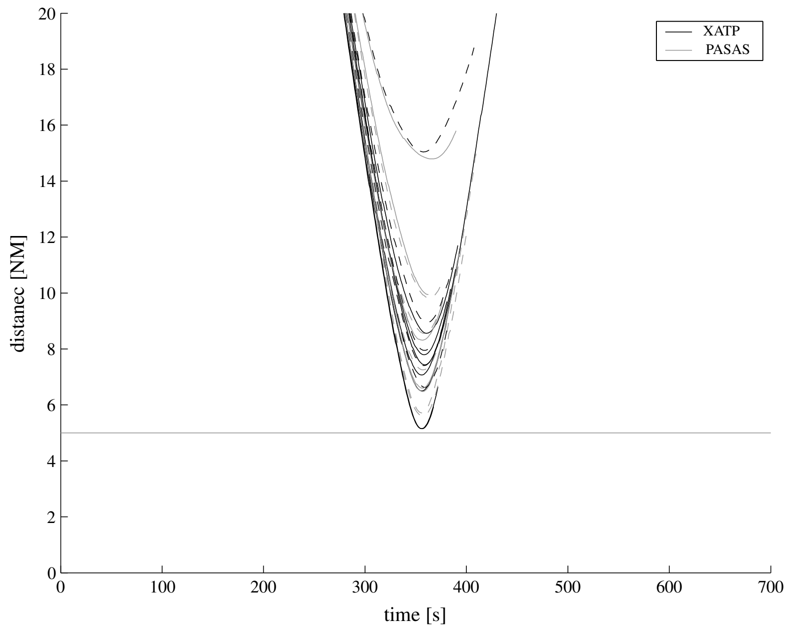


FIGURE 3-18: Example of the tracks flown in the experiment, for the heading scenarios (data for all subjects). Part two: distance between aircraft.

4

Evaluating conflict situation awareness

In the previous chapter, the expected differences from the analytical comparison are not reflected in the results of the pilot experiment. These findings acknowledge that measuring pilot subjective workload and performance may be less suitable when evaluating the ecological features of an EID against alternative designs. In this chapter, a second comparative evaluation applies a more situation-oriented approach by developing objective, explicit measures and measurement techniques for traffic SA. In addition to the former comparison, the automated ASAS resolution advisory is added to the PASAS bands, i.e., the complete PASAS design is used. A new experiment using the most promising SA measures and techniques is set up and discussed.

Paper title Comparing Situation Awareness for two Airborne Separation Assistance Interfaces

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ABSTRACT

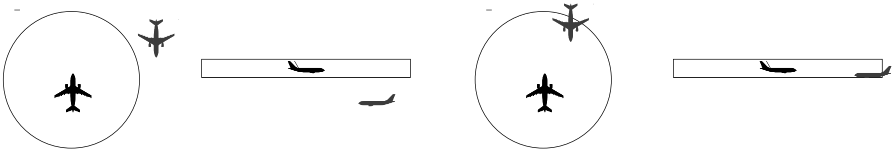
In future airspace environments, there is a need for on-board self-separation interfaces that support pilots in the resolution and prevention of aircraft conflict situations. Current designs offer pilots explicit evasive maneuvers, but it is questionable whether such a design approach promotes conflict Situation Awareness (SA) and task-independent support. As an alternative, an ecological display was designed to promote pilot SA. This display maps functional overlays on the Navigation Display (ND) that show pilots how their manoeuvring is constrained by the need to separate from the surrounding traffic. This paper discusses a comparison between the ecological display and a viable design alternative using explicit resolution commands. The comparison, including an online pilot experiment, used a situation-centered and user-centered approach to evaluate how well both displays promote SA during conflict situations. Results confirm that the ecological display improves SA. As in previous research however, no significant differences in pilot behavior in terms of safety and performance measurements were found.

Nomenclature

$ASAS$	Airborne Separation Assurance System
AH	Abstraction Hierarchy
ATP	Airborne Trajectory Planning
CPA	Closest Point of Approach
EID	Ecological Interface Design
FBZ	Forbidden Beam Zone
ND	Navigation Display
NLR	National Aerospace Laboratory
$PASAS$	Predictive ASAS
SVE	State Vector Envelope
$XATP$	eXtended Airborne Trajectory Planning

4-1 Introduction

In future airspace environments [1, 2], pilots will be responsible for separating their own aircraft from others in parts of the airspace that are unmanaged by Air Traffic Controllers. So called Airborne Separation Assistance Systems (ASAS) provide pilot support to deal with aircraft conflict situations [3]. Separation is defined by the PZ, a virtual coin-shaped area, around each aircraft. At the moment another aircraft enters this PZ, an ‘intrusion’ or ‘loss of separation’ event occurs, Figure 4-1. A ‘conflict’ occurs when two aircraft would enter each other’s PZ at some instance in the near future, if neither aircraft changes course.*



(a) Separation (b) Separation is lost, intrusion of the protected zone

FIGURE 4-1: Definition of the separation criteria.

Separation assistance Most of the conventional designs such as ASAS [5], use explicit automated commands to resolve conflict situations. These commands are similar to the ones used in short-term collision avoidance systems. Although they have proven to be very effective in resolving detected conflict situations, it is questionable whether they sufficiently support pilot conflict SA, especially in situations beyond the scope of the designed automated solutions.

An additional way to help pilots deal with conflicts is to present maneuver constraints imposed by the conflict, i.e., show how an intruder aircraft constraints the maneuver possibilities of the own aircraft. Predictive Airborne Separation Assurance System (PASAS) [5–7] and eXtended Airborne Trajectory Planning (XATP) [8, 9] are systems that visualize maneuver constraints, using so-called no-go zones on the flight displays.

First, PASAS is a traditional display design developed in an evolutionary fashion from ASAS [5], i.e., it was designed to prevent the pilot from performing explicit ASAS resolution maneuvers that would cause other conflicts. Second, XATP was designed following Ecological Interface Design (EID) principles. EID is a framework that addresses the cognitive interaction between users and systems [10, 11]. XATP advocates that an ecological presentation of maneuver constraints will promote sufficient pilot situation awareness as a basis for safe and conflict-free navigation, hereby alleviating for the need to use an explicit resolution command on the display.

Both constraint-based interfaces were evaluated against each other in earlier work [8], The results affirmed that pilots were able to safely and effectively deal with conflict situations based on support tools that only presents manoeuvre constraints. However, whereas the theoretical comparison using EID tools indicated that XATP

*The current separation minima are 5 NM horizontally, and 1,000 ft vertically. An overview of the many different ways of detecting a conflict and providing potential resolutions can be found in [4].

is better in supporting SA than the PASAS bands, negligible differences were found between both displays in terms of safety, task performance and workload.

The work presented in this paper adds a new iteration to the comparison study between both displays, and differs from it in two ways. First, the ecological design is compared with the *complete* PASAS system, i.e., the predictive ASAS heading and speed bands *and, in case a conflict situation exists,* the explicit ASAS resolution commands together with a plot of the Protected Zone (PZ) of the aircraft causing the conflict at the location where both aircraft would be closest to each other. Second, instead of focusing on task-oriented metrics, the comparison study includes a pilot experiment that intents to analyze and measure the *pilots' insight in the conflict situation*.

Situation Awareness In this paper, EID tools such as the Abstraction Hierarchy (AH) and the Decision Ladder (DL) are used to make a theoretical comparison. Then, a discussion is made about the role and meaning of *Situation Awareness* and what *measurement techniques* are available to assess SA in an experiment. The construct of SA can be approached both from a cognitive as an ecological point of view focusing on the *awareness* and *situation*, respectively [12]. The cognitive approach is adopted by using Endsley's levels of perception, comprehension and projection [13] whereas the ecological approach consists of defining meaningful chunks of information that describe conflict situations. These chunks of information will serve as *direct* explicit SA measures as opposed to *indirect* implicit SA-measures such as safety, task performance, workload, and pilot debriefings used in former experiments.

A pilot experiment is set up with scenarios that also include complex situations and unexpected events specifically targeted to identifying differences between both displays. It is expected that in general both systems will perform equally well but the ecological design will better promote conflict SA and therefore have better results regarding the SA measurements.

4-2 Predictive Airborne Separation Assurance System (PASAS)

At the National Aerospace Laboratory (NLR) Predictive Airborne Separation Assurance System (PASAS) has been developed [5–7]. In the initial phase of the supporting system development, NLR created the Airborne Separation Assurance System (ASAS). ASAS was the *draft version* of PASAS and was limited to two tasks: conflict detection and conflict resolution. The conflict detection and resolution functions are based on predictions based on the current state (position and velocity vector). ASAS uses the Navigation Display (ND) and the Primary Flight Display (PFD) to represent the resolution. This resolution advisory consists of a combined speed-heading maneuver represented by bugs on the heading scale of the ND, and on the velocity taper of the PFD.

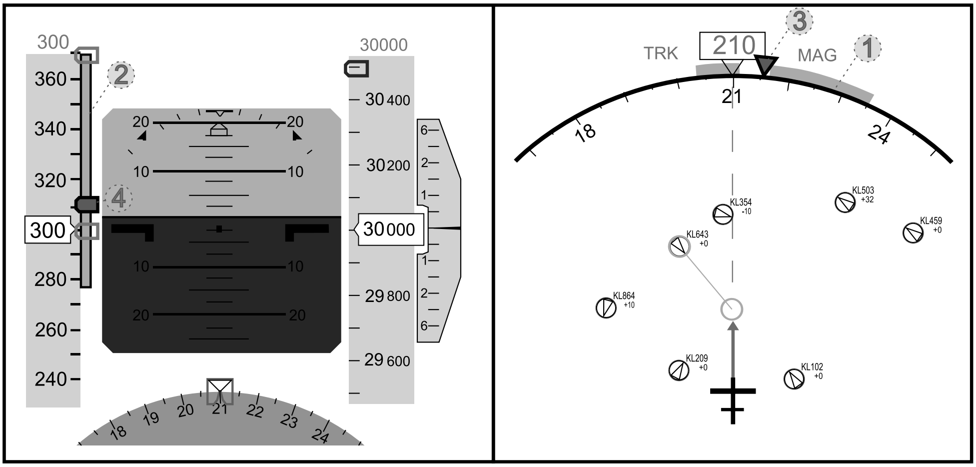


FIGURE 4-2: Predictive Airborne Separation Assurance System.

Experiments showed that an extra functionality within ASAS was needed: conflict prevention. This addition to ASAS created the current PASAS display. The goal of the conflict prevention function is to assist pilots in avoiding triggering new conflicts when maneuvering. PASAS uses two individual one-dimensional solution spaces to present maneuver constraints in each dimension separately: heading bands ① on the heading scale of the ND, and velocity bands ② on the velocity taper of the PFD, represent the no-go zones, Figure 4-2.

The display also presents the own aircraft speed and heading state markers. When these markers lie inside the bands, a conflict situation exists. The color of the bands indicates the urgency level of the situation. An orange band means that separation will be lost within 5 minutes or less, and a red band indicates that an intrusion will happen within 3 minutes.

On Figure 4-2 also the ASAS resolution advisory is depicted by bugs on the heading scale ③, and on the velocity taper ④. Note that in this work only the horizontal part of PASAS is taken into account, vertical resolutions are not included. The used configuration of PASAS corresponds with the version of the display as described in Hoekstra's PhD thesis [5]. In multiple conflicts the PASAS markers use the principle of superposition of individual conflict resolution advisories.

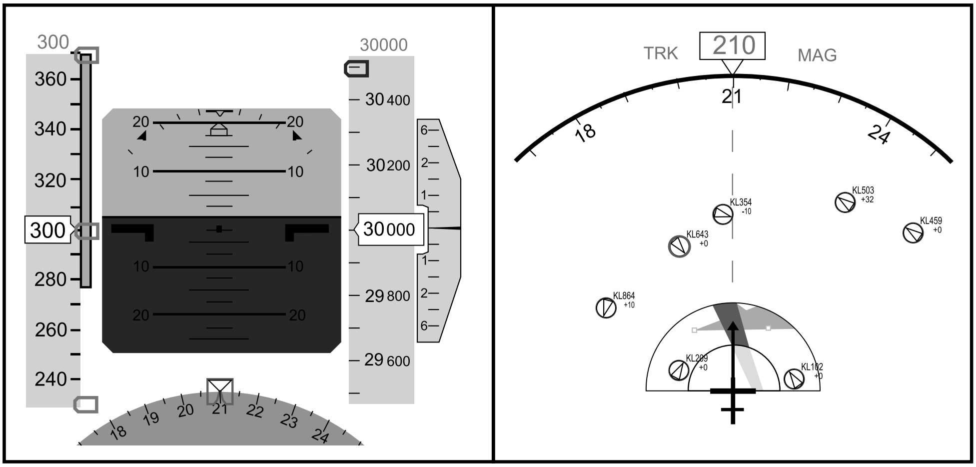


FIGURE 4-3: Extended Airborne Trajectory Planner (XATP).

4-3 eXtended Airborne Trajectory Planner (XATP)

At Delft University of Technology an alternative display, the Extended Airborne Trajectory Planner or XATP was developed. A more complete explanation of this display can be found in Van Dam [9] and Appleton [8].†

XATP is a planning tool to prevent a loss of separation from happening in the intermediate-term. The display shows no-go zones in the horizontal plane, in terms of turn maneuvers and speed changes. In contrast with PASAS, XATP shows a combined two-dimensional representation of possible resolutions, in which the pilot is free to choose a speed-heading state. The absence of an explicit resolution advisory, allows pilots to take into account other safety, efficiency and production goals when deciding how to resolve the situation.

As shown in Figure 4-3, the XATP overlay is presented at the bottom of the ND. It shows the combination of heading and speed state. When a conflict is detected, the display shows which aircraft are involved and how they impose maneuver constraints on the owncraft in terms of 'forbidden' combinations of speed and heading, represented by triangular Forbidden Beam Zones (FBZ) on the state vector envelope (SVE).

The SVE is a two-dimensional solution space, Figure 4-4, where ① is an example of the FBZ's caused by the intruder ②. If the own velocity vector lies inside one or more of these FBZ's, separation will be lost if no maneuver is made. Not only the current state of the subject aircraft is indicated, a projector indicates the future

† Chapters 2 and 3 of this thesis

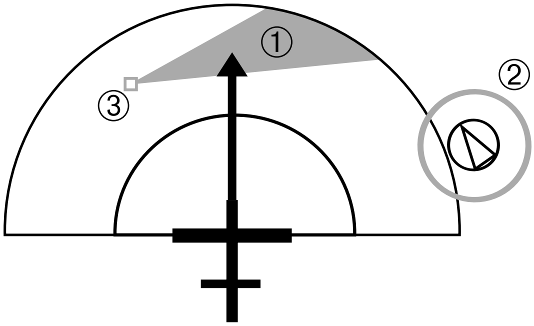


FIGURE 4-4: XATP: State Vector Envelope.

position of the state vector as it represents the autopilot speed and heading settings that are manipulated by the pilot on the Mode Control Panel (MCP).

The boundaries of the SVE solution space represent the *performance* limitations of the owncraft: the minimum and maximum velocity restrict the state envelope into a semi donut-shape. The color of the FBZ's indicates the urgency level of the conflict: orange means 5 minutes or less to intrusion, red means 3 or less minutes to intrusion. When the own state vector is located inside grey FBZ's it signifies more than 5 minutes until intrusion. When the own state vector is located outside the grey FBZ's, it is advised to stay out of these grey zones. When maneuvering into the grey area, an intrusion will happen. If the intrusion will happen within 5 minutes, this maneuver creates a new conflict and the color of the grey FBZ's will change into orange or red.

The white square at the end of the FBZ's is called the FBZ-origin ③. It signifies the state of the owner of the FBZ's: it reveals the heading and the speed of the intruder. This origin also indicates a speed-heading state to avoid: when the own state vector is located close to the FBZ origin, the own aircraft and the intruder fly at nearly the same speed and direction, and the relative velocity of the own aircraft with respect to the intruder aircraft approaches zero.

Maneuver strategy. The coupling between the FBZ and the intruder state forms the basis of a maneuver strategy for efficient conflict resolution. When deciding upon a resolution maneuver, the strategy can be simply contained by the following rule of thumb: stay away from the FBZ-origin, and, maneuver towards the closest FBZ-edge. A more in-depth description of the strategy can be found in Van Dam [9].

4-4 Workspace Analysis

Rapid advances in technologies along with economic demands have led to a noticeable increase in the complexity of engineering systems [14]. As a result, it is becoming more and more difficult for designers to anticipate events that may occur within such systems. Unanticipated events by definition cannot be predicted in advance and thus cannot be prevented through adaptation of training, procedures or automation. If the design of a complex sociotechnical system is based solely on known scenarios, it frequently does not possess the flexibility to support unforeseen events. Hereby, system safety is often compromised by the operators' inability to adapt to new and unfamiliar situations [10]. EID attempts to provide the operators with the necessary tools and information to become active problem solvers as opposed to passive monitors, particularly during the development of unforeseen events.

EID tools There are two central questions in EID. 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?*" These questions are dealt with by two separate EID tools which try to, respectively, identify and visualize work domain constraints: the Abstraction Hierarchy (AH), a tool for Work Domain Analysis (WDA), and the Decision Ladder (DL), a tool for Control Task Analysis (CTA). To investigate whether from a theoretical perspective there is a difference between the PASAS with XATP, the displays will be compared using the these EID tools.

Work domain boundaries Before the domain analysis is conducted, however, the work domain and its boundaries have to be further specified. The work being analyzed in this paper is tactical navigation in the horizontal plane during cruise flight. In a temporal sense, the domain excludes the (very) short-term collision avoidance application, e.g., Traffic alert and Collision Avoidance System TCAS [3] and the more strategic planning of trajectories. In terms of the control task, the work is limited to the navigation of the aircraft, that is, excluding all control and guidance related issues involved with keeping the aircraft in the air. The pilot task consists of the on-board path (re-)planning of turn and speed change maneuvers, with the main goal of *separating themselves* from other traffic in the vicinity.

This work domain was already investigated in an earlier publications [8, 9] and has also similarities with the work domain analyzed for the design of a support system for pilot terrain awareness [15, 16]. Whereas in terrain awareness support systems the environmental constraints are fixed in the world, traffic awareness systems deal with fast-moving intentional constraints.

4-4-1 Abstraction Hierarchy

In earlier research the AH was already used to compare how both systems present maneuver constraints on the display [8]. The AH presented in this paper, represents an updated AH. No fundamental changes have been made. The discussion on the AH with respect to both display types mostly outlines earlier findings that are relevant in this work. A new element in the AH however, is that two different groups of constraints can be identified from the domain analysis: *internal* and *external* constraints. On the lower levels of abstraction, the content of the AH can be clearly separated into internal *owncraft-related* domain functions and relations (left-hand side of Figure 4-5), and external *environment-related* functions and relations (right-hand side of Figure 4-5).

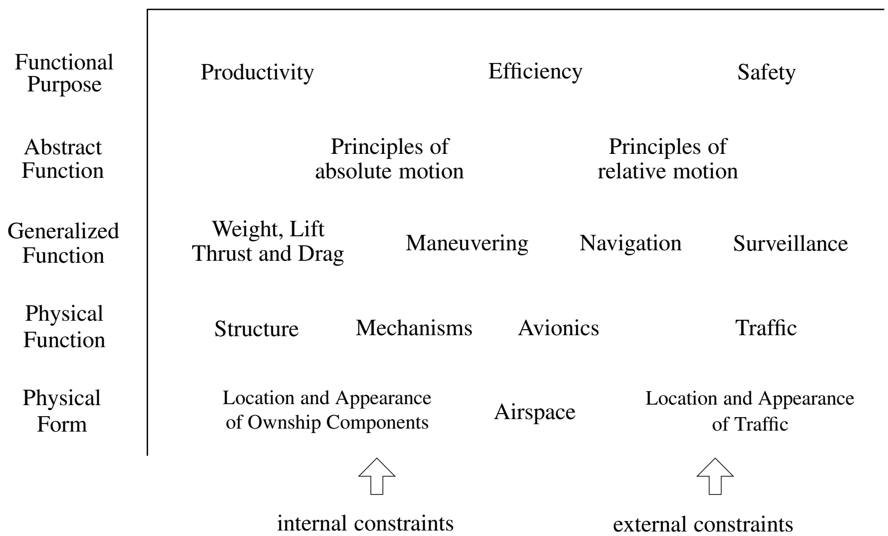


FIGURE 4-5: Abstraction Hierarchy for self-separation in the horizontal plane.

Functional Purpose As for most transportation systems, three main purposes can be identified at this level, production, efficiency and safety. The *safety* purpose is twofold: to stay in the air, i.e., stay in the *performance* envelope, and to *maintain separation*. The *efficiency* purpose is to resolve and prevent conflict situations by minor deviation of the planned flight path. The *efficiency* purpose is to fly towards the destination of the programmed flight path.

Abstract Function This level describes the underlying principles that are necessary to meet the purpose of the system. For the transport domain, this level is best described by the laws of physics. The *energy laws*, describing kinetic and potential energy, govern the vertical motion of the aircraft, but are omitted in this analysis due the limitation to the horizontal plane. The second set of physical laws is given by the kinematic *principles of absolute motion* and *motion relative to other vehicles or other objects in the environment*.

Generalized Function It describes how the laws at the abstract function level can be achieved independent of the physical implementation of the system. *Weight, lift, thrust and drag* functions, *maneuvering* (aircraft kinematics, dynamics and performance) and *navigation* (in the sense of determining ones own position) . *Surveillance* means determining the position and path of surrounding aircraft.

Physical Function The states of system and their capabilities are described. The states and configuration of the aircraft structure such as wings or fuselage, and aircraft mechanisms such as engines and control surfaces are part of the aircraft components that realize the internal functions on the generalized level. The states of the other aircrafts in the environment are described by *traffic*. A particular function is *avionics* which measures and receives state information related to both *external* traffic and *internal* aircraft system.

Physical Form The lowest abstraction level in this analysis, the physical form level, describes the physical details of the systems, such as shape, material use, etc. This level contains the appearance, location, shape, condition of the components of the *own* aircraft as well as the location and appearance of other aircraft (the latter from a complete aircraft perspective). Especially in aerodynamics, the details on shape determine all functionality. The *airspace* contains several physical properties such as the area's position and volume, air density and wind conditions.

4-4-2 Discussion on the displays

Safety, in terms of separation, is realized on the abstract function level by locomotion *relative* to the aircraft or other obstacles in the vicinity. This means that the motion relative to an other aircraft should be thus that the protective zone of that aircraft is not entered, Figure 4.6(a). Productivity and efficiency are realized by *absolute motion*, since absolute motion describes whether and how efficiently the aircraft approaches its destination.

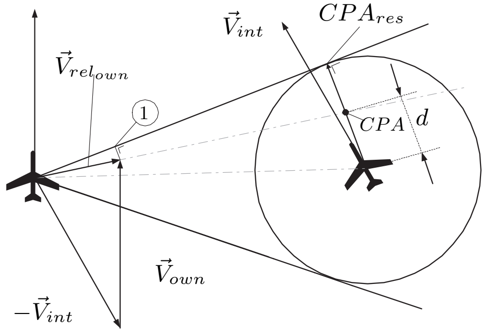
Maintain separation Separation is neatly coupled to productivity and efficiency by transposing the constraints from the relative plane, Figure 4.6(a) to the absolute plane, Figure 4.6(b) and Figure 4.6(c) for XATP and PASAS, respectively. Both the PASAS bands and XATP's FBZ directly show how to keep or change the own speed and heading so that the *relative speed avoids the PZ*. They both show this *in* *the absolute plane* in terms of *absolute velocity and heading*. XATP uses the SVE where speed-heading constraint areas are shown, Figure 4.6(b) whereas PASAS uses single speed and heading bands *and* speed and heading markers (advised resolution) on the speed and heading tapers, Figure 4-2.

If a conflict exists PASAS also shows the location where the intrusion will happen by means of a plot of the intruder's PZ at the position where both aircraft will be closest to each other, the Closest Point of Approach (CPA). This informs pilots where separation will be lost if no maneuvers are made, but can not be used to resolve conflicts as its location moves, often unpredictably, when the owncraft maneuvers [9]. Alternatively, the PZ plot at CPA location gives pilots a notion on how close a conflict is situated, meaning, a notion on how urgently the conflict needs to be resolved.

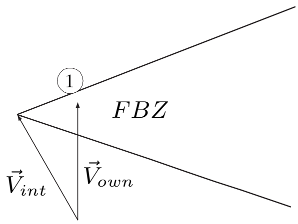
Conflict Urgency An important piece of information for pilots to *maintain separation* is indeed to be aware of the conflict urgency, i.e., the time that is left before separation is lost if no action is taken. Both displays use two levels of conflict urgency, represented by the use of orange, meaning intrusion of the PZ within 5 minutes, and red, intrusion within 3 minutes. This intrusion is predicted based on the current speed and heading of the aircraft. XATP colors the FBZ completely in one color where as PASAS splits up the bands in orange and red parts. That means that XATP does not reveal which parts of the FBZ will result in an orange conflict (less than 5 minutes) and which parts in a red (less than 3 minutes). The PASAS split-up on the other hand, informs pilots which parts of the no-go area will lead to more urgent conflicts.

In XATP however, urgency can also be deduced from the *change of splay of the FBZ legs* over time; the rate of change will increase when approaching the intruder aircraft. PASAS speed and heading bands may also expand due to the approach, but this behavior is far more difficult to identify. Finally, urgency can be interpreted from the relation between the magnitude of the *relative velocity* (i.e., the distance between the FBZ-origin and the actual state vector) and the *distance between both aircraft*, visible on the ND: the closer the aircraft and the higher the relative velocity, the faster intrusion will happen. An accurate notion on the exact urgency in terms of time to intrusion of PZ is still expected to be a very demanding task.

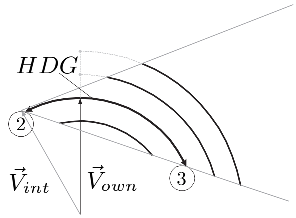
As long as no conflict exists for the actual state, the FBZ will already be shown in grey *if* there exists a speed-heading maneuver with the aircraft *maneuver performance* limits that would cause a conflict situation. Pilots can already use the FBZ characteristics to interpret the situation and come up with resolution maneuvers when required. PASAS speed and heading bands will only capture those maneuvers that already would trigger a conflict situation with the 5 minute look-ahead horizon, and it is impossible to use these bands to interpret the conflict since they



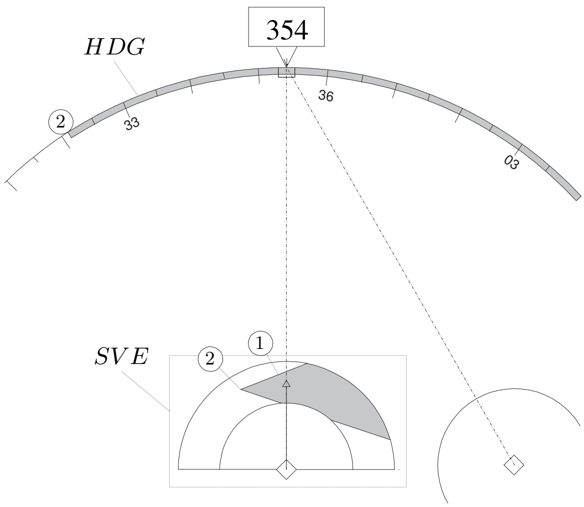
(a) Relative motion of ownship with respect to intruder in an intruder-fixed reference frame.



(b) Forbidden Beam Zone (FBZ)



(c) Heading bands (HDG) for different speeds



(d) State Vector Envelope (SVE) and Heading Band (HDG) on a Navigation Display (ND)

FIGURE 4-6: Presentation of a conflict situation: numbers ① to ③ represent possible conflict resolution maneuvers based on Forbidden Beam Zone (FBZ) ① and Heading Band (HDG) ②③. The Closest Point of Approach (CPA) indicates the predicted minimal distance between both aircraft [9].

are still growing and moving. PASAS resolution markers will not be shown, unless the actual speed and heading causes a conflict situation.

Path deviation In the context of conflict situations, the *efficiency goal* can be described by using the metric of path deviation. Efficient conflict resolution will result in maneuvers that minimize the deviation from the path that was foreseen before the conflict occurred. Using XATP, the *efficiency* of a resolution maneuver can be obtained from the FBZ characteristics: the location of the FBZ origin (relative velocity) and the distance to the nearest conflict-free areas (maneuver magnitude), see Section 4-3 [9].

Applying a similar steering strategy to the PASAS bands: e.g., steering towards the closest heading band edge might result in very inefficient resolution maneuvers with large path deviation [9]. In Figure 4-6, this is illustrated with a parallel conflict situation. Moving to the closest edge would result in moving the own speed vector $\vec{V}_{own}$ to the state indicated by ① with XATP whereas it would move to point ② with PASAS. In this situation moving the own speed vector $\vec{V}_{own}$ to ③ would result in a more efficient conflict resolution [9].

In the scenario that $\vec{V}_{own}$ will move to point ①, moving to the closest FBZ edge, the CPA point will move to the CPA_{res} point, Figure 4.6(a). This resolution represents exactly the PASAS maneuver advisory. As a result, both PASAS, explicitly by use of the markers, and XATP, implicitly by use of the maneuver strategy, provide pilots information to perform the most efficient maneuver.

Turn dynamics On the generalized function, *maneuvering* realizes relative and absolute motion. XATP accounts for the turn dynamics when the constraints are calculated and drawn whereas PASAS calculations assume state changes are made instantly [8]. Simple kinematic models of aircraft climb/descent capabilities and acceleration and deceleration profiles should be included [17].

Location and appearance of traffic The location of other aircraft in the vicinity determine wether separation is maintained, or not. In both displays a circle representing the PZ is drawn according the urgency level of the conflict the aircraft creates. The color of this circle can help pilots to relate a no-go area with the intruder aircraft that creates it. Using XATP, the FBZ appearance provides additional cues to relate a no-go area with the location and speed vector of the respective intruder aircraft.

4-4-3 Decision Ladder

After a Work Domain Analysis (WDA) a Control Task Analysis (CTA) is performed [14]. The WDA captures information about the constraints in the work environment, or, conversely, about what is possible. The CTA, on the other hand, outlines how the constraints in the work domain should be actually handled in order to effectively perform tasks within the boundaries of the work domain. We describe the Decision Ladder (DL) as a modeling tool that can be used to develop Control Task models. The Decision Ladder is built in the Skills, Rules, Knowledge (SRK) framework [11]. This framework decomposes human activity into a (combination of) behavior at three different levels, the Skill Based Behavior (SBB), such as displayed in continuous control tasks for example, the Rule Based Behavior (RBB), which consists of the triggering of learned or create rules, and the Knowledge Based Behavior (KBB), in which the operator must reason about the system and task using basic principles.

All three levels of cognitive control should be supported by the displays during all control tasks, but the level should not be pushed higher than necessary. The control tasks performed by the pilot are identified as conflict detection, conflict resolution and recovery and conflict prevention. To model the actions of the pilot during the tasks and the formation of a decision regarding these tasks, a Decision Ladder for both XATP and PASAS was constructed. Via these Decision Ladders the level of cognitive control can be derived, but also the level of support can be measured.

The decision ladder for the control task ‘conflict detection’ with the PASAS display is given in Figure 4-7 as an example of the DL’s. The boxes in the Decision Ladder correspond to information-processing activities, whereas the circles represent the states of knowledge. The information-processing activities correspond to activities in which the participants should engage. The states of knowledge are the product of the information-processing activities.

There are no fixed run-throughs in the ladder; different shortcuts are possible. In general the actors tend to run through the shortcuts instead of *processing* the entire ladder, thus limiting the KBB, and making use of the (more efficient) RBB. It is important to discover the reasons for taking these shortcuts and to check if these shortcuts are valid in all cases, and sufficiently supported by the display. In case of an unforeseen or hard-to-anticipate event, the pilot will run through the entire ladder, searching for information assisting him to make the correct decision. Therefore it is vital to check the level of display support and check whether the pilot is able to anticipate properly on all possible events.

From the decision ladders the following conclusions can be drawn regarding the level of cognitive control.

Skill-based behaviour is the lowest level of cognitive processing. It represents a type of behaviour that requires very little or no conscious control to perform or execute an action once an intention is formed [18]. The Decision Ladder does not give much information on when and why the pilot’s behaviour corresponds to SBB.

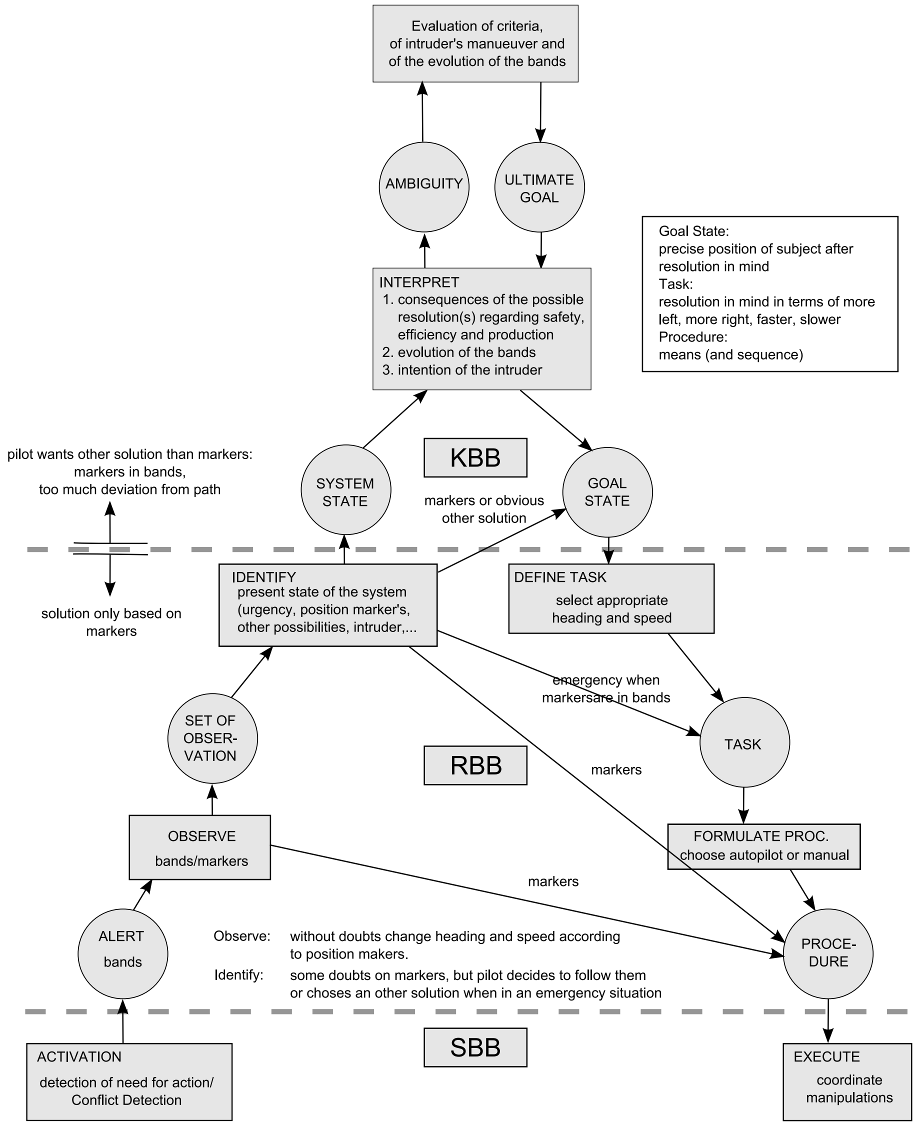


FIGURE 4-7: Example of Decision Ladder: conflict detection task using the PASAS display.

It only occurs after sufficient training of the pilots with both displays and during familiar events.

Rule-based behaviour is characterized by the use of rules and procedures to select a course of action in a *familiar* work situation. Information revealing these familiar situations is recognized as *signs*. The rules can be a set of instructions acquired by the operator through experience or given by supervisors and former operators [18]. From the decision ladder we can conclude that under normal circumstances the pilot's behaviour will be limited to RBB in both displays. Pilots are provided with rules and procedures in PASAS as well as X-ATP. These rules can be applied during familiar situations, but are not always adequate to resolve unfamiliar or unforeseen conflicts.

In PASAS the resolution markers are concrete signs for the pilot to select the optimal resolution speed and heading. The markers simplify the trade-off for the best resolution and thus limit the level of cognitive control to a very low level. The pilots are not required to know the underlying principles of a system, they only have to follow the advised resolution.

In XATP no advisory tool is present, still some simple rules or standard procedures are prescribed or can be discovered by the pilots: the FBZ's indicate the states to avoid and the FBZ-origin indicates the state to avoid in order to prevent inefficient parallel flight. Looking at the FBZ legs and origin, the pilot can perceive the resolution state that requires the least effort or deviation from the flight path. Again the pilots are not required to comprehend the underlying principles of the FBZ's and its shape, but probably they consider more constraints of the situation in their trade-off to achieve the best resolution, for example, it is expected that the pilots will consider the surrounding aircraft, able to trigger new conflicts.

The *shortcuts* with PASAS will be lower than the shortcuts with X-ATP: when the pilot performs a rule-based control with X-ATP, the cognitive demand is slightly higher than with PASAS, since no indicated resolution is present and more information on the situation is taken into account.

The RBB of the pilot was already tested in Appleton [8] and was found to result in the same performance for both XATP and PASAS. As mentioned earlier, in this experiment the PASAS display design did not include explicit resolution markers.

Knowledge-based behaviour represents a more advanced level of reasoning. This type of control must be employed when the situation is novel and *unexpected* and when there is no know-how or rules available. Dealing with such a situation requires on-the-spot decision making. Since operators need to form explicit goals based on their current analysis of the system, cognitive demand is typically greater than when using skill- or rule-based behaviours. During KBB in both displays, the pilot should interpret the entire conflict situation, the consequences of the possible resolutions for safety, efficiency and production and regarding the intruder's present and future state. Pilots should receive sufficient support from the display to do so.

In PASAS the pilot is required to increase his level of cognitive control to KBB when the markers do not indicate an adequate resolution. He or she will shift his attention from the markers to the bands and to the behaviour of the surrounding aircraft. Under normal circumstances the pilot is not required to understand the underlying principles of the indicated resolution and is thus less familiar with information retrieval from the display. In X-ATP more information sources are available to the pilot to extract the needed information of the situation from.

During RBB pilots generally take into account more constraints of the situation than with PASAS, so they are more familiar with information retrieval from the X-ATP. Since XATP provides more information on the situation, e.g., the information provided by the FBZ origin and its shape, it is assumed that XATP will support the pilot better during KBB. An experiment is needed to test this assumption. To assess the KBB of pilots it is necessary to include unfamiliar and unforeseen events during the runs of the experiment.

4-5 Situation Awareness

SA could generally be described as 'seeing the big picture'. Pilots often describe it as "knowing what is going on and what to do". The most commonly cited and academically accepted description is Endsley's definition of SA: "*the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" [13].

However, many researchers do not accept this definition of SA. In fact, many different definitions have surfaced as a consequence of the difficulty of describing the same psychological construct. An example of them is Rousseau's definition: "*Situation Awareness is fully understanding what is going on in a given situation, seeing each element within the context of the overall goal, and having all pieces fit together into a coherent picture. It is defined in terms of goals and decision tasks for a particular job*" [12].

User- & situation-focused approach The remaining challenge is to understand which fundamental elements compose the 'big picture' [19]. This would help to identify what exactly constitutes high or low levels of SA, and how to address them. In other words, if SA is properly modeled, human decision-making and action can be properly supported. In classic literature, about 26 definitions of SA exist that either see SA as a *process* or a *state*.

More recently, studies on SA have shifted the classical process-state distinction to a distinction between *user*- and *situation*-focused approaches, respectively [12]. The term 'approach' indicates that SA can be much more considered an approach than a definition. In analogy with the 'user-situation' distinction, the construct 'situation awareness' itself is twofold and can be approached by asking questions centered around 'situations' or 'awareness'.

A situation-focused approach is characterized as driven by the properties of the situation within the SA construct. On the other hand, a user-focused centers on the properties of the operator. According to Endsley, Situation Awareness is essentially a cognitive construct whereas ecological psychology explicitly rejects cognitivist considerations [20]. Endsley claims these two approaches differ a lot to connect. She considers Situation Awareness as a theory of human performance as is the ecological psychology approach. Rousseau on the other hand, defines SA as a concept that can be approached in a ecological or in a cognitive way. Thus, Rousseau's [12] point of view is contradictory with Endsley's point of view.

In this work, Situation Awareness will be treated as a concept that can be considered from a ecological or cognitive viewpoint. It will be approached focusing on the "Situation" in Situation Awareness (ecological approach) or focusing on the "Awareness" in SA (cognitive approach). Of course both cannot be fully de-coupled, but during the analysis we will focus first on the pilot and later we will focus on the situation.

4-5-1 Cognitive Approach: Endsley's levels

From the definition of Situation Awareness according to Endsley [13], three different levels can be derived: perception, comprehension, projection. Endsley's levels were applied on a conflict situation: focusing on the awareness of the pilot.

The first level, *perception*, contains all elements the pilot can perceive when observing the display. The information derived from all these elements is grouped in the *comprehension*-level. Subsequently this information serves as a mean to predict the future state of the situation. The predictions made by the pilot define the *projection*-level.

Data-driven & Goal-driven If the pilot gains insight in the situation running through the above steps, it is called data-driven: starting at level 1 (perception) and climbing up to level 3 (projection) to form a mental model of the situation. For example, from the color of the bands or legs, the pilot can extract the time to intrusion. With the time to intrusion he can derive the level of urgency of the conflict. In reality this rather simple process is not an efficient processing tool in a complex and dynamic system, which is where expertise and goal driven processing come into play. In these situations another approach is needed: goal-driven [20].

Based on their goals or their current understanding or projections (level 2 or 3) the individual will go looking for data to either confirm or deny this assessment or to collect extra information. Using the same example, one can see that the pilot will look at the display to obtain the necessary information to conclude the level of urgency. He will perceive this information looking at the color of the bands/legs, but also looking at the distance between the own aircraft and the intruder and looking at the (color of the) PZ of the intruder.

Evaluation The method of Endsley's levels immediately exposes some differences and mutual shortcomings of the displays. Overall three main conclusions can be drawn. First of all, Endsley's levels reveal that XATP provides more information resources to the pilots, making it easier to deduce relevant information. For example, the origin of the FBZ's reveals valuable information like the owner of the FBZ's and the intruder's relative velocity, while PASAS does not represent such information. Secondly, the levels expose gaps in the level-sequence, meaning the information retrieval can heavily be hindered. In PASAS the pilot should, for example, extrapolate the position of the intruder with respect to the own aircraft in order to retrieve the intruder's relative velocity. And finally, not all links between the levels are clear, meaning the pilot can experience problems with understanding the meaning of the perceived elements on the displays or with predicting the future state due to limited information. For both XATP and PASAS the intention of the intruder should be derived from the movement of PASAS bands or FBZ's, or alternatively, from the history of the position and velocity of the intruder, which can be complex to obtain.

A disadvantage when using Endsley's cognitive approach, is that we tend to look at what pilots perceive and understand. By doing so certain elements of the situation might be overlooked or not understood, because pilots perceive these elements unconsciously. Endsley's levels can therefore only be useful if the entire conflict situation is defined. Without a complete determination of the situation, some elements or features can be unintentionally omitted from the analysis. The absence of some of these elements will become transparent after the situation is defined. This is where the ecological approach comes into play.

4-5-2 Ecological Approach: Situation Focused

Zooming out on the problem, the term *situation awareness* should be revisited with respect to these displays. It appears that the concept of *situation* is almost completely missing in discussions of Situation Awareness. It seems that the dialogue has crystallized around questions of *awareness*. Flach [21] defines a situation as a nested set of constraints that have the potential to shape performance. In this context, high skill or high situation awareness will reflect a tight coupling to these constraints. Low skill or low situation awareness will reflect de-coupling from the constraints, so that the complex stimuli do not cohere into a structured whole. This all comes down to an ecological approach of Situation Awareness, a rather unusual approach looking at previous research.

Main chunks of information In general a situation is defined as the general state of things at a certain moment. From this definition two main components of a situation can be established: the things, namely the *actors* involved in the situation and the *state* of the situation. The actors in this case are the subject aircraft and the surrounding aircraft. The status of the situation is a conflict. It is also important to include the dynamic behavior of this situation and involve all events in the future. Basically this means that the *strategy* of the actors and/or the state changes need to be included as well as the *consequences* of the strategy or the future state of the situation. The strategy of the pilot is in this case the pilot's resolution or maneuver. The consequences of this resolution determine the future state of the situation. This method of defining a situation is applicable to any situation without overlooking components. Table 4-1 gives an overview of the main chunks of information that define a conflict situation.

TABLE 4-1: Main chunks of information (elements) that define a conflict situation.

Main Elements	Information
Actor: Subject aircraft	Heading, position, speed, trajectory, aircrafts' limitations or possibilities
Actor: Intruding Aircraft	Relative heading, position and speed, intruder's behavior, intruder's FBZ or Bands
Conflict State & Geometry	Conflict status, (level of) urgency, time to (certain) intrusion, position legs/bands, absolute image of conflict, possible resolutions, trade-off, time to action
Maneuver Strategy (Resolution)	Maneuver time/magnitude, resolution/maneuver feasibility
Consequences	Conflict resolved, efficiency, production, evolution of bands/FBZ

Evaluation All these features and elements were examined looking at different aspects. First, a comparison was made to discover the differences and similarities between XATP and PASAS. Secondly, the available information was investigated to assess where gaps in the information-process existed, and where extra support was needed.

The evaluation also revealed some bottlenecks and uncertainties. First of all, the pilot's knowledge concerning the aircraft's maneuverability and consequently the duration of a resolution maneuver was questioned. Furthermore it was unclear whether the pilots would be able to derive the intention of the intruders and to estimate the evolution of the legs/bands from the information provided by the displays. Extra research is needed to reveal whether extra information is needed. This analysis also demanded special attention for the ranking of urgency levels and the assigning of the legs/bands to an intruder. It is not yet clear if sufficient information sources are present in both displays to assist the pilot well during these tasks. On the other hand it was clear from the analysis and Endsley's levels that these tasks form an important basis for the trade-off of conflict resolutions. In the trade-off a correct pilot's three-dimensional mental model of the conflict geometry is crucial and must be examined as well.

Table 4-2 gives an overview of all bottlenecks and uncertainties of conflict situation information with respect to both display types. Note that throughout this work the label intruder position and velocity are used in a reference frame where the own aircraft is fixed. Thus, velocity vector represents the movement that the intruder aircraft makes on the ND.

TABLE 4-2: Bottlenecks and uncertainties of conflict situation information with respect to both display types.

intruder's behavior
evolution of PASAS bands or FBZ legs
trade-off for best resolution
assigning PASAS bands or FBZ legs to related aircraft
urgency level of individual conflicts
3D mental model:
conflict geometry
intruder aircraft (position and) velocity (vector)
time of passing the intruder aircraft
way of passing intruder aircraft

4-6 Measuring Techniques for Situation Awareness

Over the last 20 years, many methods for measuring situation awareness are developed, some more successful or accurate than others [19]. The chosen method will serve as a tool to approach the measuring of SA in the best possible way. Previously, the question "*What will we measure when assessing the SA of the pilot?*" was largely answered, in this section the question "*How will we measure this?*" will be answered. The majority of SA measuring methods can be assigned to one of the following categories: implicit, explicit, and subjective.

Implicit measures of SA utilize task performance to infer SA. Possible measures are the deviation of the actual flown trajectory from the predetermined trajectory, CPA or *passing-by*-distance, total time in a conflict situation, etcetera. Implicit measures are different than other types of SA assessments in that the awareness of operators is not assessed directly but merely is implied by their performance. The main disadvantage of this method is that there is often no proven relationship between the performance measure and the SA measure. Low or high performance measures do not always mean low or high SA measures, respectively. Results from an earlier experiment seem to confirm this since no significant differences between both displays were found [8]. whereas based on the theoretical analysis differences in SA measures are expected. Therefore this method will not be selected.

Explicit measures require pilots to self-report variables associated with the present situation. For example, pilots may be asked to recall aircraft state variables or the location of intruder aircraft. These measures are objective as SA is directly assessed by comparing the participants view on the situation to the exact reality-based baseline situation. Questions can be asked to the pilot during or after the experiment. Commonly three different techniques are applied.

The first is the *retrospective measure*, used *after* the task is completed, and requires participants to recall specific events and describe decisions made during an experimental scenario or simulation. These measures are useful because they allow the participants ample time to respond to the questions. However, the answers strongly depend on the (selective) memory of the participant, i.e., the answer can contain the participant's retrospective diagnosis of the situation rather than what actually happened [19]. Another issue with explicit SA measures is that the probed questions must be task-related which can be difficult to assess as pilots may use alternative cues than those probed. This method will be used in this research: the experiment leader will conduct a post-run analysis with the pilot after the runs.

The second technique is the *concurrent measures* and is used *during* the runs. These measures assess SA during the course of the task. Concurrent measurements have the advantage to be not memory-dependent, however this technique tends to increase workload, particularly when questions are probed to the pilot. Using *online probing*, the experiment leader plays the role of an air traffic controller and asks questions to the pilot during the runs. The questions are posed by an experiment leader, who plays the role of the air traffic controller. The use of a confederate minimizes the unusual character of online probing. A less intrusive alternative to probing questions is the use of *verbal protocols*, where participants are asked to think out loud during the run.

A third well-known measure technique is the *freeze technique* in which participants are required to answer questions after the simulation is frozen and the participant is deprived of relevant information. During this interval the participant is interrogated on the task. The mental workload is decreased, but the unnatural character of the interrogation remains.

A trade-off had to be made between the concurrent measures and the freeze technique, since both cannot be applied in the same experiment. Two reasons determined a preference for the concurrent measures: freezing allows the pilot to extensively overlook the situation or make a decision, while in reality the time pressure is a key player. Secondly, the dynamic character of the simulation plays an important role: with online probing it is possible to anticipate on the actions of the pilot and deviate from the predetermined questions. Thus, more relevant questions can be posed online compared to offline. After each run a picture will be presented to the pilot to allow him ample time to respond to questions concerning critical phases in the runs.

Subjective measures is the last category of methods to assess SA.These measures are distinct in that SA is measured either by self-assessment rating or by the assessments of the observer, meaning the measure are solely based on subjective opinion. They are easy to implement but difficult to compare across raters. Again three different techniques are available.

Direct Self-rating requires the participant to rate his/her own SA using a Likert-scale ranging from 1 to 7. The disadvantage of this method is the reliability: the results can be influenced by the performance of the pilot during the runs and/or by the self-esteem of the pilot. *Comparative self-rating* requires the pilot to compare self-assessed SA from one trail to another. It can be useful since it encourages within-participant consistency. Finally, an experienced and neutral *observer* can be asked to evaluate the SA of the subject. Due to the lack of unbiased and neutral experts, this measure is not used. Both other subjective measures are used, but as secondary measures rather than primary.

4-7 Experiment

The experiment goal is twofold. One, it aims to measure the pilot's insight in the conflict situation using SA measuring techniques. Two, it aims to assess the related pilot behavior, i.e., to reveal the cognitive processes pilots use to obtain these required chunks of conflict information

4-7-1 Method

Subjects and instructions. Seven pilots participated in the experiment. The background of these pilots largely differed: some were very skilled with flying hours up to 12,300 hours and some were less experienced with limited flying hours in a glass cockpit, as can be seen in Table 4-3. All pilots were familiar with the Electronic Flight Instrument System (EFIS). This was the main criterion for the pilots, since experimenting with unfamiliar situations requires some familiarity with the supporting displays.

The pilots were briefed about the experiment and were instructed on the technical and procedural parts by the experimenter. During this briefing they were taught that safety, not intruding the protected Zone of the surrounding aircraft, was given the highest priority. They were also expected to pay attention to the efficiency, head towards destination, and the productivity, head back to original velocity.

Apparatus. The experiment was executed in a fixed-base flight simulator consisting of a cabin mockup, situated in a darkened noise-free room. The cabin has two 18 inch LCD screens. One is situated in front of the pilot and displays the PFD. The other display is situated to the left of the pilot and showed the ND and Mode Control Panel. No outside visuals were presented to the pilot.

Aircraft characteristics & experiment conditions. For the simulation a B747-200 aircraft was simulated through a realistic non-linear model, flying at 30,000 ft. ICAO standard atmosphere was utilized. No wind was present. The autopilot was engaged during the entire experiment. The pilot could select autopilot airspeed and heading on the MCP by use of a mouse pad. Vertical aircraft control was disabled. The experiment leader acted as an air traffic controller, through online probing via the intercom. The entire communication during the runs was recorded.

4-7-2 Independent Variables

Two independent variables were varied, the *display type*, PASAS or XATP, and the experimental *scenarios*. For PASAS the configuration was based on the descriptions in Hoekstra's PhD thesis [5], for XATP the in-house model was used [8].

TABLE 4-3: Pilot experience.

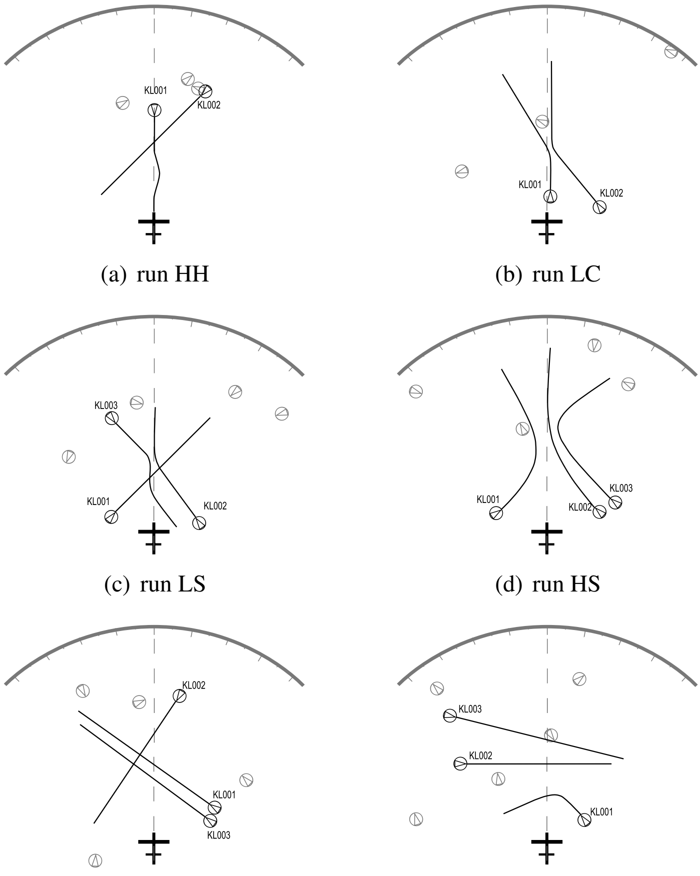
Pilot	Year of Birth	Aircraft Types	Flying Hours
1	1956	B737-BA146-DC10	13,000
		A320-military jet	
2	1939	B747-C550-DC3-DC8-light	13,200
3	1984	TB10-PA28-DA42	190
4	1982	B777-Be36/58	1,230
5	1973	B757/767-others	7,000
6	1977	PA34-TB-C150-B737	290
7	1976	C550-B737-MEP-SEP	1,550

Scenario Design In total the pilot completed 6 different scenarios per display. The similarity between the runs of PASAS and XATP was concealed for the pilots by mirroring the conflict geometry, adjusting the airspace density or changing the scenario line-up. The conflict geometry of each scenario was set up with two reasons in mind: the diversity of conflict situations possible, and the evaluation of the situation elements pointed out as bottlenecks and uncertainties in the analysis of Section 4-5-2. The runs also consisted of unexpected or hard-to-anticipate events such as multi-conflict situations, hostile maneuvers, and reduced conflict prediction time, in order to evaluate Knowledge Based Behavior (KBB).

The intruder aircraft were programmed not to cooperate with the subject aircraft when resolving conflict situations. Cooperation would significantly simplify the conflict interpretation and decision making of the subject pilot. Intruders would rather maintain their current flight path, resolve a conflict with other aircraft, or make an arbitrary maneuver. This behavior added complexity to the conflict situation, and was considered more appropriate approach to measure the pilot insight in conflict situations.

Head-on Scenario HH The first intruding aircraft is located ahead of the own aircraft and flying towards the own aircraft, Figure 4.8(a). This intruder will make an own resolution maneuver to its left. Another intruder is located at the right side of the subject. During this run, the trade-off of the best resolution is evaluated, regarding triggering a second conflict and the pilot's insight in the intruder's intentions.

Overtake Scenario LC The first intruder aircraft is located in front of the own aircraft, with the same heading but a lower speed. A second intruder in located at the right, as shown in Figure 4.8(b). In this scenario the main focus is on the



(a) run HH (b) run LC
(c) run LS (d) run HS
(e) run LH (f) run HE

FIGURE 4-8: Conflict Geometry scenarios.

pilot's three-dimensional model of the conflict geometry and the trade-off for the best resolution: will pilots overtake the slower intruder or stay behind him?

Multiconflict Scenario LS Three intruders cause a conflict simultaneously, Figure 4.8(c). In multiple conflicts the PASAS markers use the principle of superposition of individual conflict resolution advisories. This principle only works when all aircraft involved perform the superposed resolution as presented on their respective PASAS advisory markers. Since in this experiment intruder aircraft only resolve their mutual conflict regardless of the conflict with the subject aircraft, the proposed PASAS advisory may not resolve the multi-conflict situation and the subject pilot may have to abandon the markers in order to resolve the conflict. This is the case for the multi-conflict scenarios in this experiment. The pilot's insight in the different urgency levels and the trade-off for the best resolution are evaluated.

Multiconflict Scenario HS In this scenario also three intruders cause a conflict simultaneously. However, the heading of the intruder aircraft vary from the previous scenario, Figure 4.8(d). The conflict geometry is constructed as to provoke the enclosing of the state vector in the FBZ's in X-ATP. The knowledge of the pilot on the urgency levels of the conflicts and the pilot's three-dimensional mental image of the conflict geometry is tested.

Different Flight Level Scenario LH Different intruders are located around the own aircraft, again with different headings than previous scenarios, Figure 4.8(e). Some intruders are located on different flight levels. This scenario evaluates whether the pilot filters the higher or lower intruders and thus builds up a correct three-dimensional mental image of the conflict situation. Secondly the pilot's insight in the urgency levels is examined.

Hostile maneuver Scenario HE In the final scenario three intruders are present, the first one makes a 80 degrees turn maneuver, causing an unforeseen conflict with the own subject. The bands and FBZ's will immediately color red instead of orange and therefore reduces the lookahead time to 3 minutes, Figure 4.8(f). Depending on the chosen resolution maneuver for this conflict, up to two other aircraft may trigger an additional conflict. The pilot's insight in the evolution of the bands/legs and in the intruder's intention will be examined, and also the pilot's three-dimensional mental model of the conflict situation.

4-7-3 Dependent measures

In the discussion about SA, Section 4-5, the main chunks of information that define a conflict situation were given, Table 4-1. These elements were evaluated in the experiment to assess SA scores: the larger the deviation between the pilot's estimation on one of the situation elements and its actual state, the smaller the SA score for that element. A theoretical analysis of these elements with respect to both display types, indicated some information bottlenecks and uncertainties, Table 4-2. The experimental evaluation of these critical elements was given priority assuming that their scores would point out whether they are true bottlenecks and whether there is a significant difference between X-ATP and PASAS.

Secondly the Closest Point of Approach (CPA) distance between the intruders and the own aircraft was measured. From this distance we can retrieve information on the safety and efficiency of the runs. The separation minima should be respected, therefore a CPA distance of 5 NM should never be intruded, indicating a safe run.

4-7-4 Procedure

Pilots were briefed about the experiment and the functioning of both displays. To familiarize the subjects with both displays, test-runs were performed until the pilot was confident enough to proceed to the actual experiment. The actual experiment consisted out of 12 runs, 6 per display. Most runs were built out of unfamiliar or unforeseen events to test the situation awareness of the pilot. The geometry of the scenarios are shown in Figure 4-8 and they are further discussed in the results Section 4-8. Four pilots flew with the PASAS display first and afterwards with XATP, while the other pilots did the experiment in the reverse sequence.

The experiment leader communicated in the same way as an air traffic controller, through *online probing* via the intercom. The entire communication during the runs was recorded. During the runs the pilot was asked to answer the questions posed by the experiment leader. Secondly the pilot was requested to comment all actions made (*verbal protocol*). Since the moment of decision-making was short, it was considered less disturbing to let pilots provide information immediately themselves.

After each run, a *post-run analysis* was done to compensate for the lack of time of querying during decision-making. A screenshot of the conflict situation is presented to the pilot to provide ample time to respond to questions concerning critical phases in the previously-handled conflict. Finally, pilots filled out a *post-experiment questionnaire* that queried them on information retrieval, the acceptability of the display and its components, and other remaining uncertainties.

4-7-5 Measurement techniques

Online-probing The pilot was interrogated during the runs on the conflict situation. This method was chosen over the freezing method where the simulation is freezed when the experiment leader interrogates the pilot. Though it can increase pilot workload, online-probing is considered to have a more natural and less disturbing character when compared to the freezing method.

It was important that the questions are non-disturbing, non-suggestive and would anticipate on the possible actions of the pilots, i.e., different maneuver strategies were anticipated for in the set up of the probing schedule and the scenario design. The form of the questions differed: some questions were open questions that intended to unveil the retrieval of information and therefore the possible lack of assistance. Other questions served as a technique to compare the pilot's mental model of the situation and the actual situation. The answers to these questions were either right or wrong. Sample questions are given in Table 4-4. Note that most questions are related to a particular phase of the conflict.

Verbal protocol As mentioned before, the pilot was also requested to make comments out loud when not interrogated, especially at points of decision-making when the experiment leader prefers not not to disturb the pilot.

TABLE 4-4: Example of SA questions for online probing.

before detection:
"What aircraft are you paying attention to?"
after detection
"How many resolutions do you see?"
"To which aircraft do these bands belong?"
"Which aircraft do you consider the most important one?"
"What is your time to intrusion?"
"Does KL693 fly faster/slower or at the same speed as you?"
"Which conflict is most urgent?"
during resolution maneuver:
"Will you trigger a new conflict?"
"How will these bands evolve during the maneuver?"
after resolution maneuver:
"Do you have a notion on time to pass by the intruder aircraft?"
all phases:
"Does KL693 pass in front or behind you?"

Post-run analysis To compensate for the lack of time of querying during decision-making when using online-probing, *post-run analysis* was used to ask the pilot to analyze a display screenshot of the previously handled conflict at the point of decision making. The experiment leader on his turn, could also pose all remaining on-line probing questions and questions on the decision-making without any time pressure.

Post-experiment questionnaire Pilots were asked to rate the difficulty of retrieving conflict information from the display such as distance to the intruder, intruder behavior, conflict urgency, duration of maneuver, etcetera. Furthermore display acceptance was evaluated by rating of representation elements such as conflict presentation, markers, state vector, color, size and movement of the bands or legs.

TABLE 4-5: Example of open questions for post-experiment questionnaire.

"When did you start a maneuver and why at that moment?"
"Do you prefer a 2D representation, when you opt for a 1D-resolution?"
"What are in your opinion the biggest advantages of PASAS?"
"What are in your opinion the biggest shortcomings of XATP?"

These rating were done using a Likert scale. Furthermore pilots were also asked to write down their point of attention during the different phases of the conflict situation. Finally a number of open questions were given regarding both displays and their comparison. Table 4-5 provides a few samples of the open questions.

4-7-6 Hypotheses

XATP is expected to perform better under unfamiliar or unforeseen circumstances, since it was ecologically designed and therefore supports the pilot better during Knowledge Based Behaviour (♯1). The information resources necessary for understanding the situation, are more available and easier accessible with the XATP display, as was derived from the evaluation according to Endsley's levels (♯2). Furthermore, decision making during single conflicts is expected to demand less effort with PASAS (♯3). On the other hand XATP is hypothesized to perform better during multi-conflict situations (♯4), especially regarding the pilot's general insight in the conflict situation.

4-8 Results & Discussion

The pilot answers and verbal statements on pilot behavior and pilot insight obtained during the experiment through on-line probing and post-run analysis are used in 2 different ways. First answers were used to establish the cognitive processes during the runs leading to so called information chains that describe *pilot behavior*. Secondly answers were used to evaluate the *pilot's insight* in the conflict situation itself and more specific in certain parameters using SA scores for the answers. Additionally, some *general conclusions* were drawn from the observation of pilot behavior. Finally, the results of the questionnaire after the experiment are discussed in the Section *pilots' opinion*.

The experiment results on pilot behavior and pilot's insight immediately revealed that the analysis could be narrowed down to the most significant elements of the situation. The retrieval of information of some elements appeared to be trivial and equal for both displays and were therefore excluded from further research. These elements are the own heading, position, velocity and flightpath and the intruder's position and heading. Pilots on their part, indicated that no extra information was needed on some other elements such as the aircraft's maneuverability or possibilities, the maneuver time and the maneuver feasibility. The pilot's knowledge on these elements is considered common knowledge, and therefore these elements were also excluded.

4-8-1 Pilot Behavior

One of the goals of the online probing and post-run analysis was to reveal the cognitive processes pilots use to obtain critical conflict situation information such as the resolution trade-off, the conflict geometry, the determination of the urgency levels, the evolution of the bands or legs and the estimation of the intruder's behavior, Table 4-2. The results from this analysis are represented in cognitive information-chains that show how pilots relate visual display information (perception) with conflict situation information (projection). Figures 4-9 and 4-10 show these information-chains for PASAS and XATP respectively.

Trade-off for the best resolution With XATP the pilots took into account the FBZ's, the surrounding aircraft, the own velocity and the predetermined flight path during the trade-off for the best resolution. They paid attention to avoiding triggering new conflicts, minimization of path deviation and arriving on time at the destination, regardless of single or multiple conflicts. During single-conflicts with the PASAS display the pilot blindly followed the markers. When the pilots discovered following the markers would not lead to a safe resolution during multi-conflicts, they neglected these markers and focused on the surrounding aircraft and the heading and speed bands.

Conflict geometry Creating a mental model of the conflict geometry differed also in both displays. In XATP the pilots used the own speed vector together with the FBZ-origin to derive the intruder's relative velocity, and could then determine the future conflict geometry, i.e., will the intruder pass in front, behind, at the left or at the right of the own aircraft. They decided on decreasing or increasing speed depending on the relative velocity of the intruder. For example, lowering the own speed if the intruder aircraft would pass in front. With PASAS no information was present on the relative velocity of the intruder. They estimated it from the relative closure speed of the other aircraft: they observe the movement of the intruder with respect to the own aircraft for a while and conclude the intruder's velocity on this

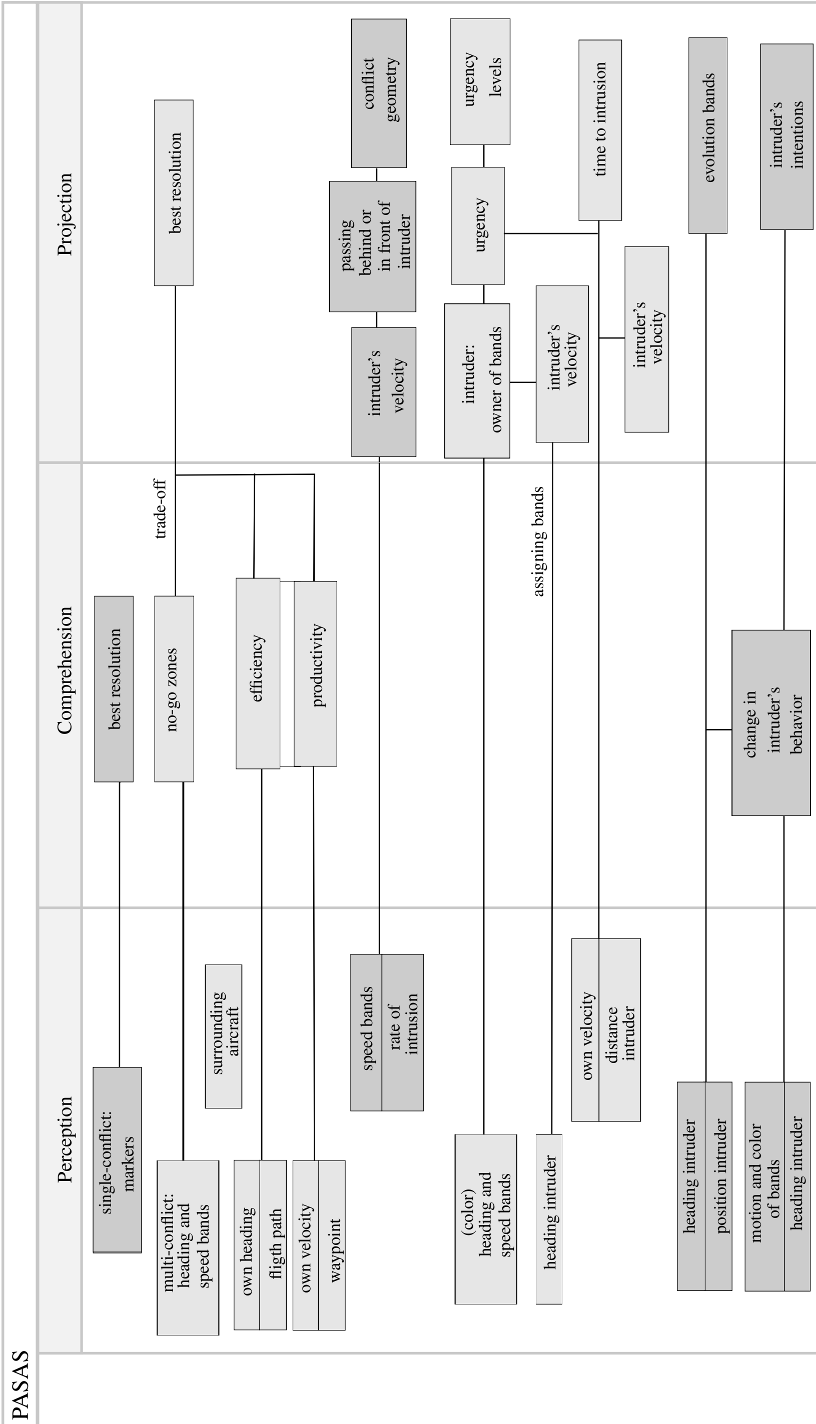


FIGURE 4-9: Information chains - PASAS.

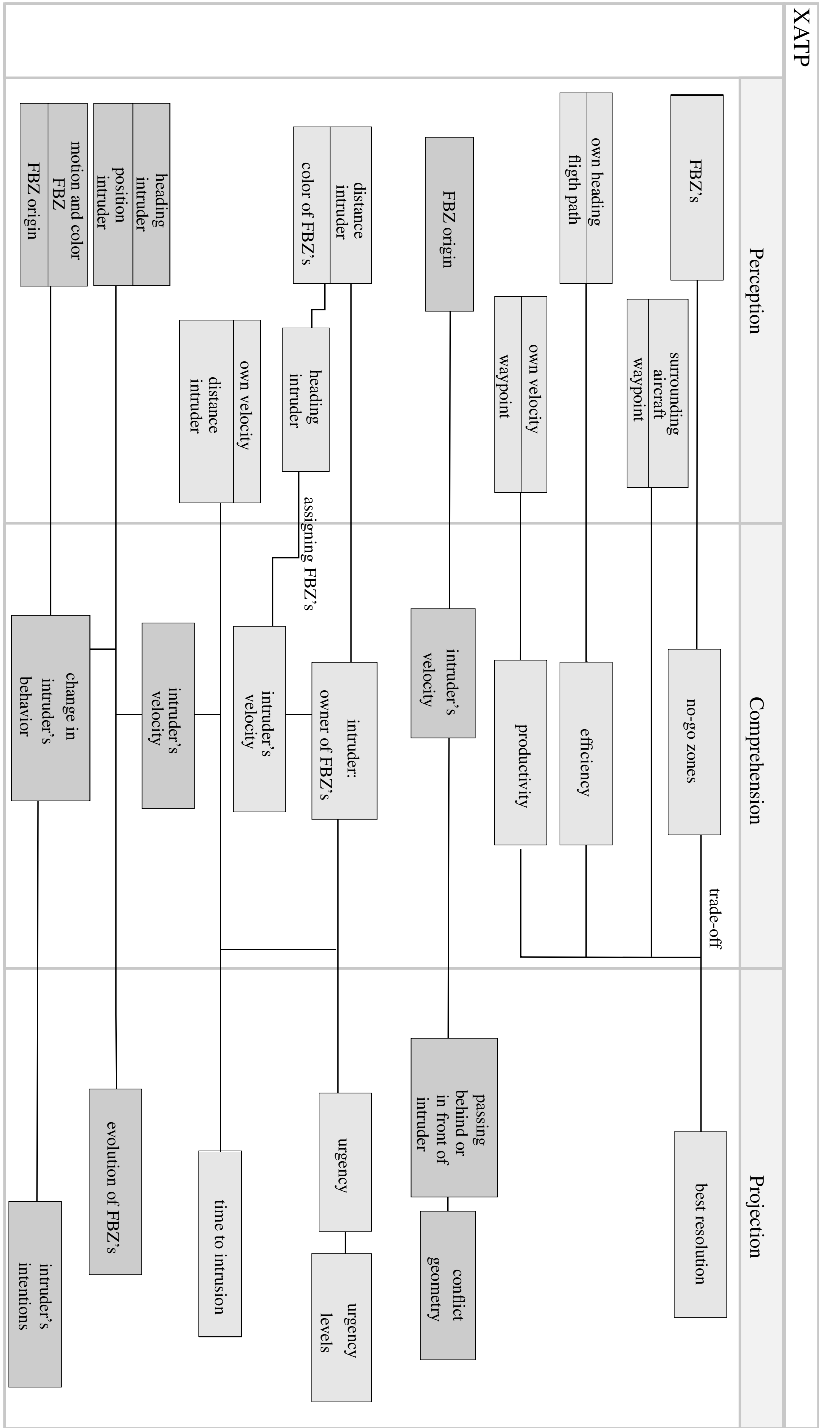


FIGURE 4-10: Information chains - XATP.

closure speed. This lack of information resulted in a decreased insight in the conflict geometry when flying with PASAS.

Assigning bands/legs When the state vector was located in orange or red no-go zones, it was easy to assign the bands or legs to an intruder on both displays since then the PZ of the intruder lit up in the same color as the bands or legs. However, when the current state vector was not creating a conflict (yet), or alternative, multiple conflicts caused multiple bands or legs in the same color, it became much harder to assign bands or FBZ's to individual conflicts. However with XATP, the subject used the position of the FBZ origin and direction of the FBZ legs to assign the FBZ's to an intruder before the FBZ's turned orange or red. They direction of the FBZ legs was used to narrow down the location of the intruder in the navigation display (left, right, front or behind?) whereas they observed the heading of the intruders and the heading indicated by the origin to couple the FBZ with a particular aircraft.

Levels of urgency This coupling was also used to determine the urgency of the conflict and in case of multiple conflicts, the levels of urgency. In this latter case the levels of urgency were well-defined when the FBZ's of two or more intruders had a different color. When two intruders both caused orange or both caused red FBZ's, they focused on the heading and the distance of the intruder to determine the most urgent conflict and encountered difficulties when performing this task. With PASAS the pilot observed the heading and distance of the intruder as well but also before a conflict warning. When the state vector was not located inside the bands, no assistance for this assigning process was available.

Determining the *time to intrusion* was a demanding process for both displays, they derived this time from the distance of the intruder and the own velocity. The information on the intruder's velocity in XATP was used as well and again simplified the process slightly. All pilots predicted the intruder's path as a straight flight path. When the intruders deviated from this path, the pilot was not able to predict this maneuver in advance. This resulted in a poor estimation of the future state of the situation but also in a poor prediction of the evolution of the bands or FBZ's. *The evolution of the bands or legs* was fairly predicted by the pilots without a maneuver of the intruders. When intruders did maneuver, pilots had difficulties identifying the maneuver, and predicting how the bands or legs would evolve due to the maneuver.

Scenarios. Since the scenarios were constructed to reveal the elements causing bottlenecks, some of the scenario's are further detailed to illustrate the findings on the pilot's behaviour with a concrete example.

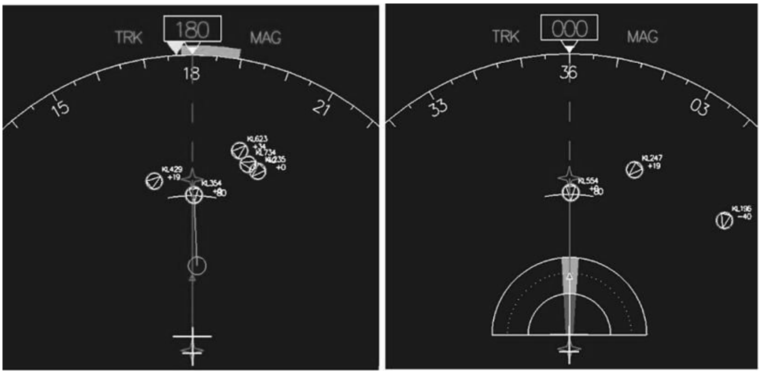


FIGURE 4-11: Scenario HH: Conflict Situation for PASAS and XATP.

Head-on Scenario HH: trade-off resolution maneuver In this scenario one intruder KL001 was located ahead of the own aircraft and flying head-on towards the own aircraft. A second aircraft KL002 was located at the right of the own aircraft and would trigger a second conflict when the pilot would choose a resolution maneuver to the left, Figure 4.8(a). Figure 4-11 shows the begin situation for both display types.

During this run, the trade-off of the resolution maneuver was evaluated, regarding triggering an additional conflict with KL002. The markers advised a turn maneuver to the left, since this involved the smallest heading change. Five pilots followed these markers and opted for a left heading change, triggering another conflict with KL002. With XATP the pilots chose a right turn maneuver, thus avoiding a second conflict. This scenario indicated the need for the algorithms of the markers to involve all surrounding aircraft.

Overtake Scenario LC: intruder's velocity The intruder aircraft KL001 is located in front of the own aircraft, with the same heading but a lower speed. A second intruder KL002 is located at the right, Figure 4.8(b). XATP shows a grey FBZ, Figure 4.12(b), indicating that currently no conflict exists. Since the state vector is located inside the FBZ, this means that a loss of separation 'will' happen if no maneuvers are made, but not within the next 5 minutes. All pilots were aware that in the near future a conflict situation would be triggered. All pilots were also able to assign FBZ's to the respective aircraft and to derive the lower velocity of the KL001 in front from the position of the FBZ-origin on the SVE.

The PASAS interface showed an orange speed and heading band but not covering the current state yet, Figure 4.12(a). Pilots failed to assign the bands to the intruders, and could not perceive if aircraft KL001 was flying slower. As a consequence, they did not know whether the situation would finally evolve into a conflict,

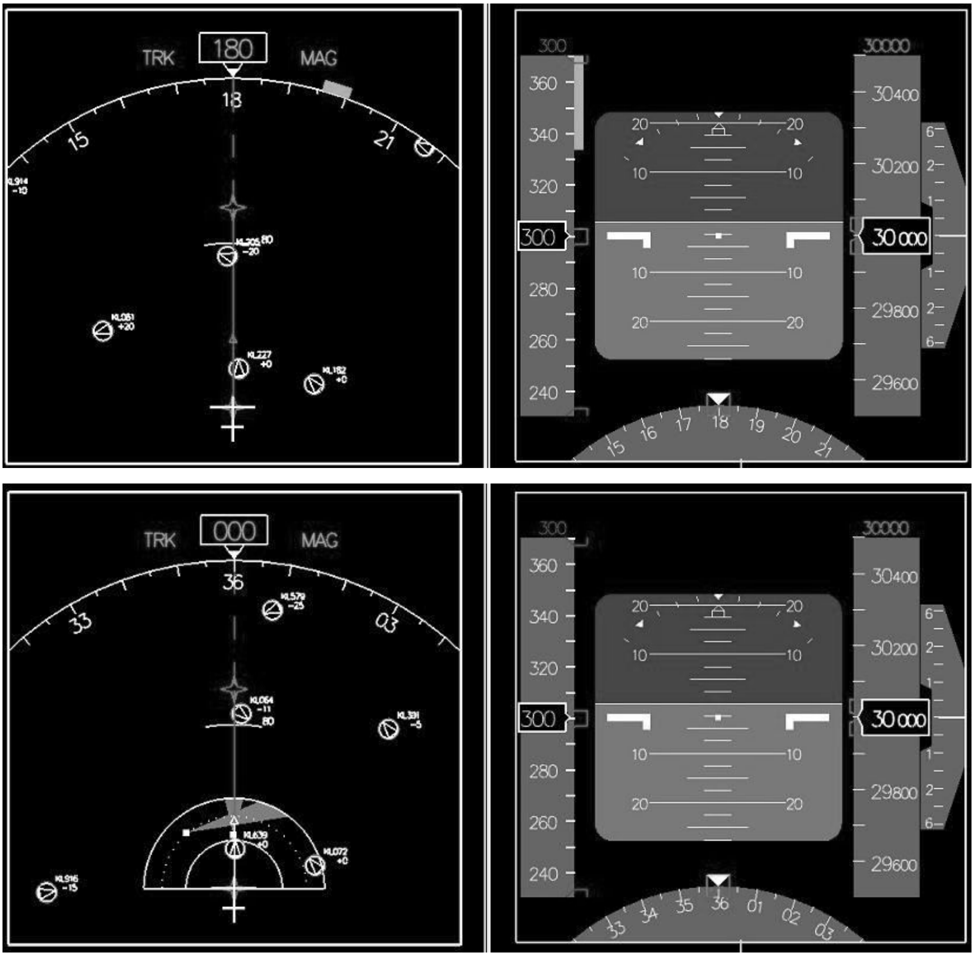


FIGURE 4-12: Scenario LC: Begin Situation of the Conflict for PASAS and XATP. PASAS bands are orange, FBZ's are grey.

nor what action would be appropriate to anticipate on this situation. As the conflict evolved and the speed band lowered, 5 out of 7 pilots erroneously concluded that this was due to a lower velocity of KL001. Pilots waited for the bands and markers to appear and then followed the advised state, without having a clear notion of the velocity of the intruder. Finally, this decision resulted in the same resolution behavior as with the XATP interface.

Multiconflict Scenarios LS & HS: assigning of the bands/legs & urgency levels In both scenarios three intruders cause a conflict simultaneously,

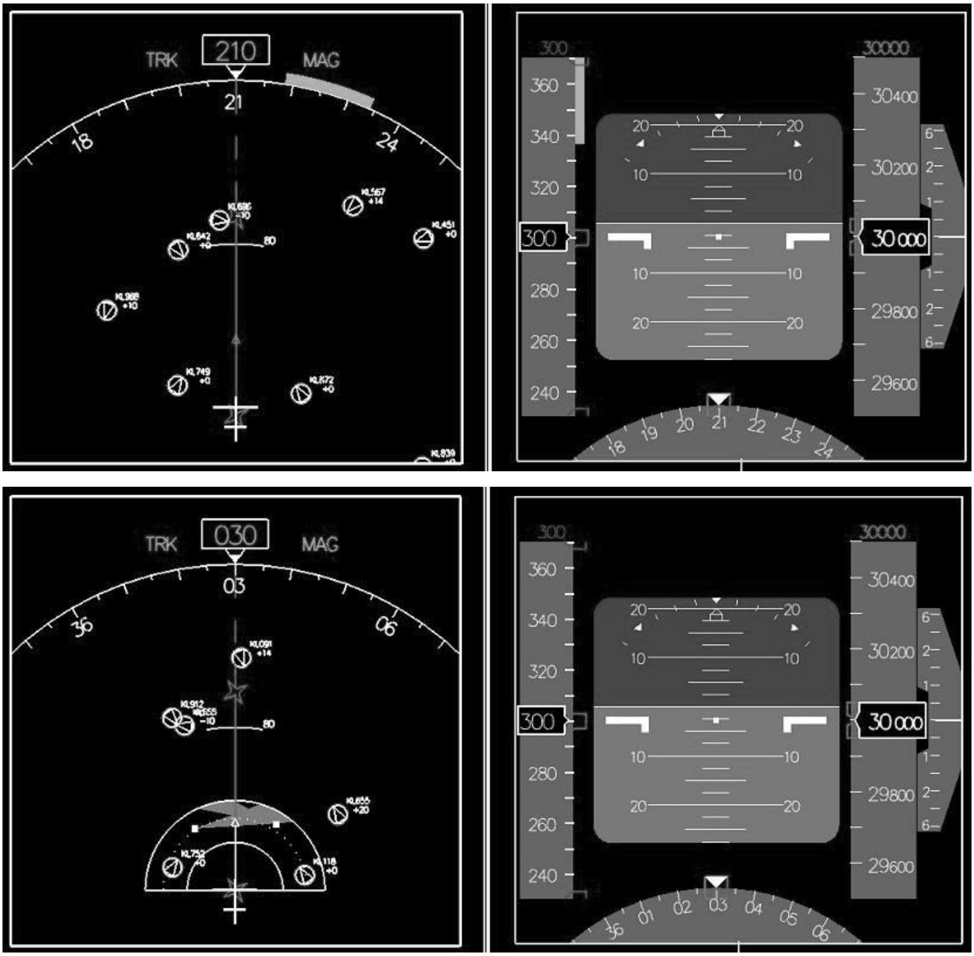


FIGURE 4-13: Scenario LS: Begin Situation of the Conflict for PASAS and XATP. PASAS bands are orange, FBZ's are grey.

Figure 4.8(c) and Figure 4.8(d), making it for the pilot hard to determine the different urgency levels. As in the former scenario, a clear difference in conflict presentation exists between XATP and PASAS: when the earliest loss of separation is still more than 5 minutes away, PASAS already displays bands on the ND and PFD, but not covering the state vector, Figure 4.13(a). XATP on the other hand, displays grey FBZ's and the state vector is already inside the FBZ's, Figure 4.13(b).

In this phase the pilot should be able to assign the grey FBZ's or the orange/red bands in order to determine the most urgent conflict and, thus, to determine which intruder aircraft needs most attention. With PASAS the pilots experienced difficulties to assign the bands, or part of the bands, to individual intruders. They could only do this after some time or when the Protected Zone of the intruder lit up in the same color as the bands. With XATP the pilots were able to perform this task through the coupling of the intruder's heading to the heading indicated by the FBZ-origin. When the difference between the heading of the intruder and the own aircraft was larger than 90 degrees, the FBZ-origin was not displayed on the SVE anymore, making it hard for the pilot to derive the intruder matching that particular FBZ.

The multi-conflict scenarios were also designed in such a way that the PASAS markers indicated a 'superposed' resolution that did not solve the conflict when the intruder aircraft ignored their advised resolution. The intruders resolved only their mutual conflict, regardless of their conflict with the subject aircraft. All pilots did realize after a short while that the markers did not offer a valid solution and successfully used the bands to come up with a better maneuver.

Hostile maneuver Scenario HE In this scenario one intruder KL001 was located at the right of the own aircraft and made a hostile maneuver towards the own aircraft. the intruder turned approximately 80 degrees, placing the own aircraft in a sudden and dangerous conflict situation. Two more aircraft, KL002 and KL003 were further limiting the maneuver options available, Figure 4.8(f). With both displays the pilots anticipated too late on the intruder's maneuver and made a resolution maneuver of more than 50 degrees. There was no noticeable difference between XATP and PASAS. With both displays pilots identified the maneuver by a sudden movement of the FBZ/bands. This scenario expressed the need for communication with the surrounding aircraft concerning their maneuver behavior or intended path.

4-8-2 Pilot insight

To confirm the stated differences in support of the displays, the pilots were questioned on their knowledge on the conflict situation, more precisely on the essential elements of the situation. The answers to these questions were validated either correct or incorrect. The percentage of correct answers per element is shown in Figures 4-14 and 4-15.

The shortcomings in one or both displays become visible and confirm the previous statements. All pilots determined the intruder's velocity more often correctly with XATP than with PASAS, and therefore the pilot's mental model of the conflict geometry was much better with XATP. PASAS lacked of support for the assigning of the bands, while XATP provides enough information to the pilot to correctly couple the FBZ's to an intruder. The influence of XATP and PASAS on these three variables was confirmed to be significant after performing an ANOVA analysis.

Determining the level of urgency during multi-conflicts and the time of passing

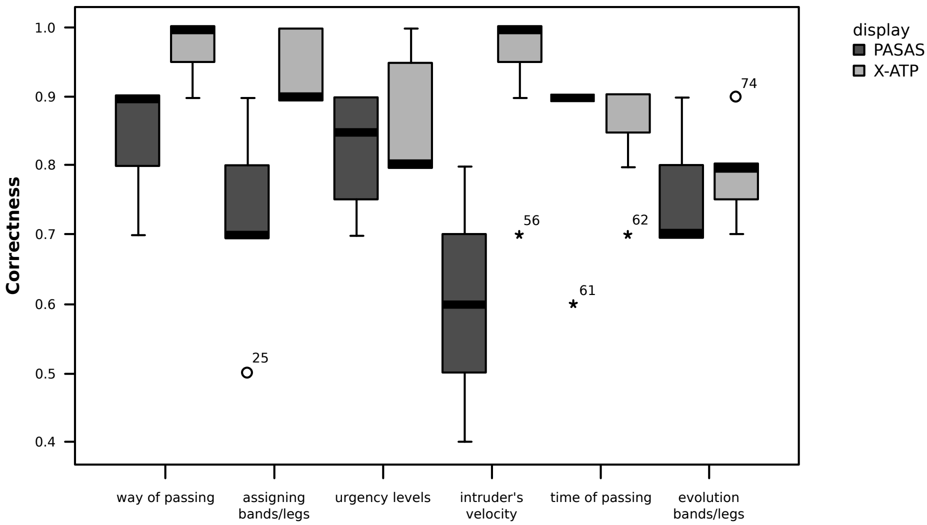


FIGURE 4-14: Boxplot: the elements of a conflict situation.

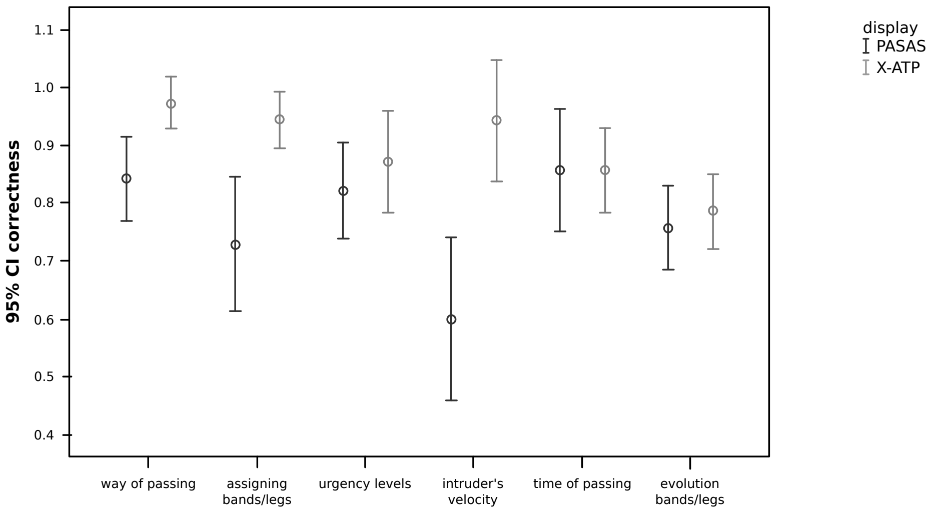


FIGURE 4-15: Error Graph of 95 % Confidence interval: the elements of a conflict situation.

the intruder, was a complex task independent of the display type. However, these tasks were slightly less difficult because the information of the intruder's velocity was available on XATP. Similarly, the availability of intruder's velocity information made it slightly easier to predict the evolution of the XATP legs as compared to the PASAS bands. In these cases an ANOVA analysis defined the influence of both displays on all three variables as insignificant.

Hypotheses From Figures 4-9 and 4-10 and from Figures 4-14 and 4-15 hypothesis ♯3 is confirmed: XATP provides more information sources to retrieve sufficient insight in the conflict situation. XATP also assists the pilot better during multi-conflicts, as predicted in hypothesis ♯4, but PASAS demands less effort from the pilot during single conflicts ♯3, since the markers do not require any cognitive processes to determine the best resolution.

4-8-3 General observations

After monitoring the pilots during the runs, some general observations could be derived. These observations were confirmed by the pilots themselves when they commented the chosen resolution, during the runs or after the runs:

- The majority of the subjects anticipated on the conflict in advance; they did not wait for orange bands or orange FBZ's. They claimed anticipating in advance would decrease the deviation from the path and that preventing a conflict situation is always better than resolving one.

- During multi-conflicts the pilots first addressed to the FBZ's and then to the surrounding aircraft to select a resolution in XATP. With PASAS pilots tended to address first to the surrounding aircraft to form a decision on the resolution and afterwards to the bands to confirm the feasibility of the chosen state.

- When approaching the intruder at less than 10 miles, 6 out of 7 pilots only focused on the Protected Zone of the intruder and neglected the bands or legs.

- 6 out of 7 subjects opted to minimize the path deviation (efficiency) over a safe buffer between the own state and the no-go zones (safety). With both displays the pilots knew sufficiently on the situation to limit the safety buffer, but a sudden state change of the intruder, could jeopardize the safe situation.

- None of the pilots had difficulties with the crossing of the legs or bands. They were capable of predicting the maneuver time and the time needed to cross the no-go zones. They were not repulsed by the idea of having to cross the bands or legs in order to minimize the flight path, nor did flying parallel with other intruders scare the subjects.

4-8-4 Pilots' opinion

In the questionnaire pilots were asked to rate the difficulty of retrieving information from the displays and their acceptance of these displays or of the components of the displays. The Likert-scale was used to help the pilot in his ratings. The retrieval of information was rated from 1 to 7; from effortless to impossible to do, Figure 4-16. The representation acceptability was rated from 1 being unacceptable to 7 being perfect, Figure 4-17. These tables served as a mean to compare the objective findings with the pilot's opinion. The overall conclusion from these tables is that XATP generally scores better on display acceptability and on information retrieval. Looking at Figure 4-16, it can be seen that the pilots indicated a preference for a two-dimensional resolution representation and for use of a state vector in combination with the FBZ's. All other components of the displays were equally accepted by the subjects. Figure 4-17 confirmed some previous statements: the intruder's velocity can be derived from XATP more easily than from PASAS and predicting the intruder's behavior was experienced as equally difficult for both displays. No general conclusions can be drawn on the pilot's scores on the urgency levels and the evolution of the legs or bands.

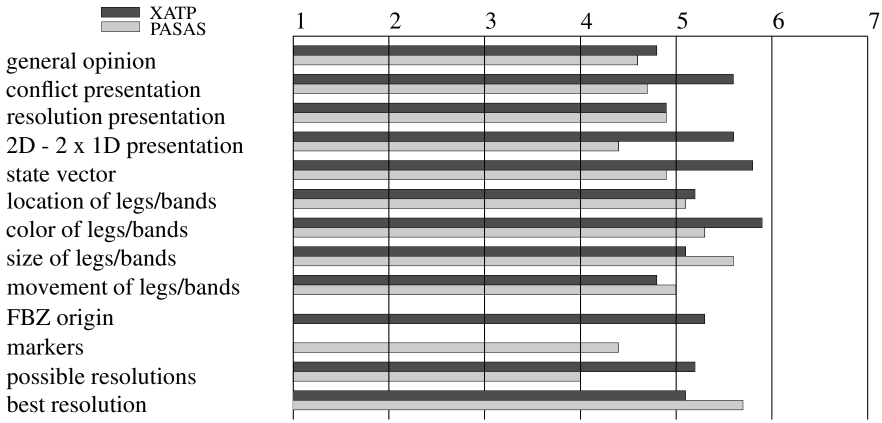


FIGURE 4-16: Mean scores for pilot acceptance of representation (ranging from '1'= unacceptable to '7'= perfect).

In the questionnaire pilots wrote down some general remarks or tendencies in their behavior. The results of the open questions are listed below.

- Five out of the seven pilots preferred a two-dimensional resolution instead of two times a one-dimensional representation, confirming the previous statement concluded from Table 4-16.
- Two pilots suggested an indication of the optimal resolution in XATP. Both pilots were the least experienced ones.
- All pilots found the State Vector Envelope (SVE) presentation on the ND too limited in shape: when the intruder flew at an angle of (-) 90 degrees or more

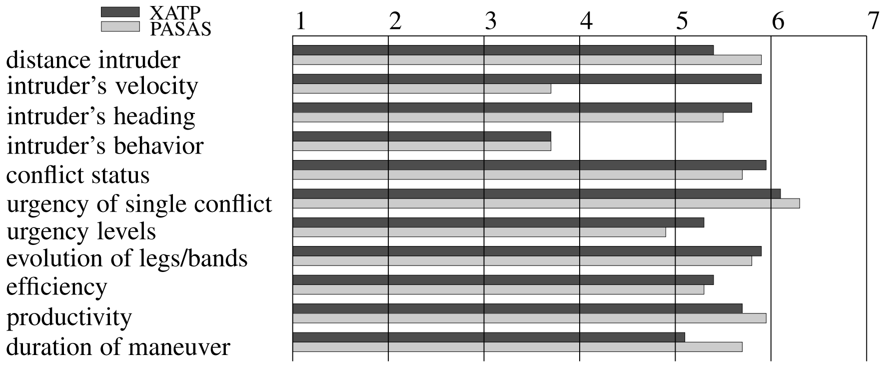


FIGURE 4-17: Mean scores for pilot opinion on information retrieval (ranging from '1'=impossible to '7'= perfect).

different from the own aircraft, the FBZ-origin was not visible on the SVE anymore. They suggested a rose-shaped SVE (entire donut instead of semi-donut) to keep the origin on the ND at all times.

- All subjects preferred a heading change over a speed change.
- Four out of seven subjects preferred increasing speed over decreasing speed, when performing a velocity maneuver
- All pilots pointed out that intent information or communication with the intruders is critical for the succeeding of airborne separation. They indicated that the sudden state change necessary to resolve a sudden, extreme conflict due to a hostile maneuver of the intruder, was unacceptable.
- It should be possible to filter the surrounding aircraft on the Navigation Display. The SVE projected on the ND was not experienced as the cause of clutter on the ND, but the pilots reported the presentation of all aircraft on all different flight levels as disturbing.
- The large velocity changes possible in the simulator were encountered as unrealistic.
- All subjects agreed that XATP provided a better insight in the situation. Three out of seven pilots stated that the better overview of the situation and the overall higher awareness of the situation is the largest advantage of XATP over PASAS.
- Five out of seven pilots ultimately preferred working with XATP, two preferred PASAS.

4-9 Discussion

During *single conflicts* the pilots experienced PASAS to be the superior interface. The markers showing the optimal resolution during a conflict, simplified the separation task for the pilot. During *multi-conflicts*, XATP scored better, assisting the pilot better during the trade-off for the best resolution and providing more information on the conflict situation. During multi-conflicts the markers did not take the surrounding aircraft and the next waypoint or destination into account. The markers did not prevent the triggering of a new conflict and therefore pilots also use the speed and heading band to see which maneuvers are safe.

The *intruder's velocity* was considered to be an important variable. All subjects indicated that this information was vital to form a mental image of the conflict situation, to predict the evolution of the legs and bands, the time to intrusion and therefore also the level of urgency of the conflicts. The theoretical analysis did not predict such a large impact of the knowledge on the intruder's velocity on the situation awareness, but both the objective and subjective results did.

Another critical insight when resolving a conflict, was the *assigning of the legs or bands*. Many pilots were not able to couple a speed or heading band in PASAS to an intruder during multi-conflicts. Not being able to assign the bands increases the probability of an incorrect or inefficient resolution maneuver and again decreasing the insight in the situation. The inability to assign an intruder to a heading or speed band in PASAS increased the level of complexity to determine the different urgency levels in multi-conflict situations. Again the importance of this task was underestimated during the theoretical analysis, but the online probing and the questionnaire revealed the complexity of this task when using PASAS.

The third difference between both displays is the *dimension of the action state space* where the no-go maneuver constraints are presented in. Most pilots indicated the advantage of a two-dimensional representation in XATP over the one-dimensional heading and speed bands in PASAS, as it provides a more complete overview of the conflict situation. The preference was not influenced by the resolution needed or the complexity of the conflict. This result is somehow remarkable since in the earlier comparison experiment, the pilots' preference for a display type depended on wether the conflict had to be resolved by a one-dimensional (PASAS) or two-dimensional (XATP) resolution maneuver.

Predicting the intruder's behavior was experienced as very difficult for both displays. All subjects accentuated the importance of communication with the surrounding aircraft. They found the sudden hostile maneuvers of the intruders unacceptable. For both displays a solution must be found to resolve this problem. The Dutch Aerospace Laboratory (NLR) has expanded PASAS into PASAS Intent, with intent info presented on the display [22], while the in-house XATP has also developed a FBZ representation that presents intent information during airborne self-separation [23].

The *markers in PASAS* decrease the cognitive processes needed to assess the better resolution, limiting the pilot's behavior to RBB, Figure 4-9. In the experiment it became clear that several situations forced the pilot to abandon the markers, when they indicate an inappropriate resolution. The markers do not account for the surrounding aircraft when presenting a resolution maneuver; they do not prevent triggering new conflicts. In multi-conflicts the markers based on superposition of individual solutions only function when the intruders follow their own markers. When they deviate from their indicated resolution, the subject's markers indicate a resolution that will not resolve the conflict and pilot switch to heading and speed bands for deciding about a maneuver.

It can be argued that a more complex calculation of the algorithms for the markers that effectively deals with the triggering of new conflicts and multi-conflict scenarios improves the reliability of the markers. However, a dangerous automation trap is to design complex algorithms that are not transparent to the human nor compatible with the way humans best deal with the problem. This might decrease the pilot's ability to understand the advised resolution. In the exceptional case where algorithms fails to come up with a proper conflict resolution, pilot might also fail to come up with one due to a lack of situation awareness.

Measuring techniques to establish the level of situation awareness of the subjects are only useful when the situation is properly defined. The measuring techniques used in this study were found to be productive and more useful than the safety, performance and workload measures used in an earlier experiment [8]. The on-line probing technique revealed the wanted information, since the questions could be asked at the exact moment and, depending on the situation, on the exact topic. Unusual maneuvers of the participants were anticipated for in the experiment by making the questions or the topic of the questions dependent on the pilot maneuver decisions during the runs. When online questions would be too suggestive or disturbing, the pilot was not disturbed and encouraged to think out loud. The pictures of the conflict situation shown to the pilot at the end of the run, gave ample time to ask extra questions and recapitulate the previous run. The questions posed in the questionnaire strongly depended on the memory and the self-confidence of the pilot, but served as a good backup for the on-line and post-run findings.

4-10 Conclusions

After the analysis of the results, one fundamental question still remains unanswered: are displays developed following the EID principles better in assisting the pilots?

Both theoretically and in the experiment, XATP supported pilots better at dealing with unforeseen situations and creating a correct image of the entire conflict situation. XATP requires more effort of the pilot in the search for the best resolution in single conflicts, but during this trade-off ample information sources were available to provide the pilot with information on the situation's boundaries and possibilities. These information sources helped the pilot resolving multi-conflicts as well. The supply of sufficient information caused an increase of the pilot's insight in the critical situation's components and therefore it is believed to better promote pilot situation awareness. Five out of seven pilots subjectively indicated a preference of the XATP display, confirming the objective results. However, as in previous research [8], we cannot conclude high situation awareness of the pilot results in a significantly improved safety and efficiency level of pilot decisions.

Post-hoc rectification *Throughout this paper an emphasis exists on pointing out that the location of FBZ-origin on the SVE reveals the heading and speed of the intruder aircraft. This relation exists and beyond any doubts allows pilots to couple the FBZ origin on the SVE with the heading of the intruder. Additionally, throughout this paper, the assumption is made that when pilots assign individual FBZ's to intruder aircraft on the ND, this assignment is done based on the same relation: the coupling between the FBZ-origin and the speed and heading of the intruder. However an additional and equally significant coupling exists: the direction of the FBZ-legs on the SVE point out where the intruder aircraft is located on the ND. Using both cues, origin 'and' direction of the FBZ, pilots can now correlate the intruder's position and magnitude and direction of the speed vector on the ND.*

A more correct way to do the analysis and evaluation in this paper, should therefore have used both the FBZ-origin *and* FBZ-direction *or a labeling that includes both. The authors expect, however, that this issue will not fundamentally change the analysis and experimental results as pilots where instructed clearly on both the features, i.e., they were explicitly instructed that the FBZ-origin represents the intruder velocity vector and that the FBZ legs point towards the intruder position. Thus, in terms of pilot behavior and insight, pilots were already using both information cues. After completion of a few runs however, pilots' attention might have been biased more consciously towards the relationship between the origin and the intruder speed and heading due to the use of term 'FBZ origin' during the probing and questionnaires.*

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5
Vertical design

The ecological approach to visualize separation is applied to the vertical plane. Using the Vertical Situation Display as a basis, novel ecological overlays are added, yielding the Vertical Situation Awareness Display (VSAD) which can be considered to be the vertical counterpart of the horizontal (X)ATP design. In addition to the existing work domain content for the horizontal plane, the vertical plane analysis also includes energy conservation laws. This chapter discusses the design in the vertical plane with its particular design issues, including an off-line pilot experiment that focuses on traffic situation awareness.

Paper title Design of an Ecological Vertical Separation Assistance Cockpit Display

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ABSTRACT

Many of the proposed airborne separation assistance tools provide pilots explicit resolution commands, similar to those used for short-term collision avoidance. Explicit commands do not support pilots in exploring solutions other than those presented, however, and may preclude the full exploitation of travel freedom offered by future airspace. Most of the tools also fail to show the reasoning of the automation that deals with the separation problem, resulting in low pilot traffic situation awareness. This paper describes a tactical navigation support tool, in the vertical plane, designed to effectively deal with conflict situations while reserving 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 own aircraft performance and limits imposed by surrounding traffic. A questionnaire-based evaluation, involving twelve glass-cockpit experienced pilots, shows that the ecological overlays considerably improved pilot traffic awareness in vertical conflict situations.

Nomenclature

C_D, C_L	drag and lift coefficients	S	wing surface, m^2
D, L	drag and lift forces, N	T	thrust force, N
df	degrees-of-freedom	W	weight, N
E	aerodynamic efficiency	γ	flight path angle, deg
F	ratio of sample variances	ρ	air density, kg/m^3
K	lift-dependent drag coefficient	σ	air density-difference
p	significance	Γ	aircraft-specific quantity, deg

Subscripts

FC, SC	fastest climb, steepest climb
$intruder$	intruder aircraft
own	own aircraft
rel	relative
SSL	standard sea level

5-1 Introduction

AIRSPACE congestion and delays force airspace authorities and governments to explore more effective ways to manage air transportation. Novel Air Traffic Management (ATM) concepts such as Free Flight [1–3] and, more recently, the Next-Generation Air Transportation System (NextGen) [4, 5] and Single European Sky ATM Research (SESAR) [6] 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’.

A more flexible use of airspace probably leads to more complex traffic situations and would increase workload on air traffic controllers who have the task of securing separation between aircraft. A possible way to reduce their workload would be to delegate the separation task to the flight deck. The problem then of how to assist pilots in performing this new task of self-separation has attracted great interest in the research community, and several solutions have been proposed in the past decade.

First of all, Cockpit Displays of Traffic Information (CDTI) were designed, including advanced route analysis tools that helped pilots in conflict detection and resolution [7–14]. Second, Airborne Separation Assurance Systems (ASAS), like Predictive ASAS (P-ASAS), and often including CDTI, have been developed [15–17]. Both solutions deal with conflict situations and form a strategic complement to currently-deployed Airborne Collision Avoidance Systems (ACAS) like the Traffic alert and Collision Avoidance System, TCAS II [18].

Many of these proposed airborne separation assistance tools provide pilots with *explicit* automated solutions, in the same way as for ACAS systems. That is, typically these tools tell the pilot how to resolve a conflict, by presenting a ‘ready-to-use’ avoidance maneuver. Support systems that apply explicit, automated solutions have proven to be effective as far as providing conflict resolution and reducing workload are concerned. A few observations can be made, however, with respect to the use and presentation of automated airborne self-separation support.

First, the use of explicit solutions holds pilots back from exploring solutions other than those presented, and therefore may preclude the full exploitation of travel freedom and airspace capacity offered by future airspace environments. Second, the explicit advice often fails to show the ‘cognition’ behind the automation that deals with the separation problem. That is, the interface does not show the underlying data or rationale of 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 and decide how to deal with it. Third, although not an inherent flaw of all automated systems, previous research shows that some separation assurance algorithms recommended maneuvers that triggered new conflicts [15].

In this paper an alternative airborne self-separation assistance tool for the vertical plane is described, extending the current standard navigation interface for presenting the vertical situation, the Vertical Situation Display (VSD) [19]. Adopting the principles of Ecological Interface Design (EID), [20] the VSD is extended with graphical overlays that present functional information regarding how the own aircraft vertical maneuvering possibilities are constrained. These constraints originate from, on the one hand, limits to the own aircraft vertical flight performance, and on the other hand limits on vertical maneuvering imposed by surrounding traffic. The resulting display, the Vertical Separation Assistance Display (VSAD) aims in particular at supporting pilots in maintaining a high level of traffic Situation Awareness (SA) [21].

The main goal of this paper is to show how EID can be used as a guideline to identify the constraints in aircraft vertical motion, and how these constraints can be visualized and integrated on an existing cockpit display. It complements our earlier work that focused on identifying and visualizing separation constraints in the aircraft horizontal motion [22–26]. Obviously, traffic is a three-dimensional problem, and the vertical and horizontal maneuvering constraints should be visualized in a more integrated fashion than presented here. This is the subject of ongoing research, [27] and beyond the scope of the current paper.

The paper is structured as follows. After a brief introduction to the basic principles of EID, first the main results of a Work Domain Analysis (WDA) are described. This analysis focused on the self-separation task and allowed us to identify the principal constraints regarding vertical maneuvering. Second, it is discussed how these constraints are represented in graphical overlays on the VSD, yielding the VSAD. Third, after an introduction to traffic situation awareness, the results of a questionnaire-based SA-oriented evaluation of the VSAD are discussed.

5-2 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 [20, 28]. 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. This approach is hypothesized to yield interfaces that better support worker adaptation, even in situations that were not anticipated by the interface designers.

A survey showed that in many cases EID indeed resulted in better operator problem-solving performance as compared to traditional designs [29]. Recently, EID principles have been applied to support pilots in various tasks including energy management and terrain awareness [30–34]. Amongst the designs, an interface for horizontal separation assistance support was conducted and evaluated experimentally [26, 35]. The VSAD presented in this paper can be considered the 'vertical' analog of this earlier design.

Along the lines of J.J. Gibson's work [36], EID advocates a visualization of all constraints relevant for goal-directed behavior on the display, in such a way that the operator can take effective action and understand more about how these actions will fulfill the objectives. Applying these principles to vehicle control and navigation, Gibson's direct coupling between perception and action is achieved by mapping the affordances* for vehicle locomotion on the interface [26, 33, 37].

In the context of airborne interfaces to help pilots in tasks of maintaining separation with terrain, weather and traffic, these affordances emerge by carefully analyzing the constraints to locomotion that limit the options for functional or goal-directed behavior. Earlier attempts to design ecological interfaces in these tasks have shown that a useful distinction can be made between 'internal' and 'external' constraints [26, 34]. The 'internal' constraints originate from the own vehicle performance characteristics, and condition the behavior of the pilot-aircraft system itself. "How fast can the aircraft fly?", or, "How much time does it take the aircraft to climb to a certain flight level?" are examples of questions that refer to these internal constraints. The 'external' or environmental constraints originate from the terrain and (the motion of) other aircraft, and further limit the opportunities for the own aircraft locomotion. Here, a question like "When the current flight-path angle is maintained, will a conflict occur with another aircraft flying ahead?" is relevant.

Within the context of supporting pilots in performing the vertical self-separation task, the internal aircraft constraints that reflect the boundaries of aircraft performance, could be presented using a performance overlay that would inform pilots of their aircraft climb, glide and/or turn capabilities. The external constraints, that reflect the aircraft kinematic 'motion boundaries' imposed by maintaining separation with surrounding traffic, could be presented using a second overlay. An appropriate mapping of *both* layers of constraints is hypothesized to much better allow pilots to identify which aircraft cause, or might potentially cause, conflicts and also *see directly* which maneuvers are possible and preferable to resolve these conflicts and prevent new conflicts to emerge. Vicente and Rasmussen typify this as "making visible the invisible" [20].

Summarizing, 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

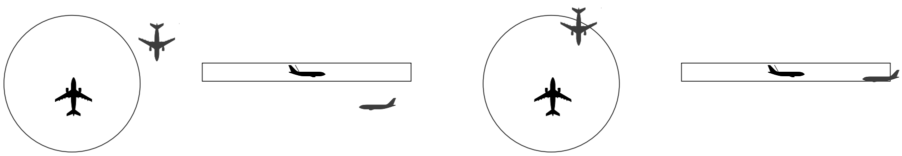
*An affordance is a goal-relevant property of the system that describes opportunities for action with respect to the capabilities of a particular actor. For example, a car affords transportation to the average man, but to a race-car driver it affords competition.

need to be addressed [20]. 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? These questions are dealt with extensively in Sections 5-3 and 5-4, respectively.

5-3 Work Domain Analysis

In this section a work domain analysis will be presented of the vertical separation assurance task. The main tool in conducting the Work Domain Analysis is the Abstraction Hierarchy (AH), discussed in Section 5-3-1. Using the AH, the principal work domain functions and constraints have been identified, which are discussed in more detail in Sections 5-3-2 and 5-3-3.

Before the domain analysis is conducted, however, the work domain and its boundaries have to be further specified. The work being analyzed in this paper is tactical navigation 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. This work domain has similarities with the work domain analyzed for the design of a support system for "pilot terrain awareness" [32, 34]. Whereas in these terrain awareness support systems the environmental constraints are fixed in the world, in separation with other moving traffic the constraints are much more dynamic.



(a) Separation

(b) Separation is lost, intrusion of the protected zone

FIGURE 5-1: Geometrical definition of the separation criteria [38].

Minimal separation can be defined using a Protected Zone (PZ), a virtual coin-shaped area, around each aircraft, as shown in Figure 5-1. This area is to remain free of other aircraft. At the moment another aircraft enters this PZ, separation is lost. Generally, the current separation minima are used; 5 NM horizontally, and 1000 ft vertically [38]. 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 [39].

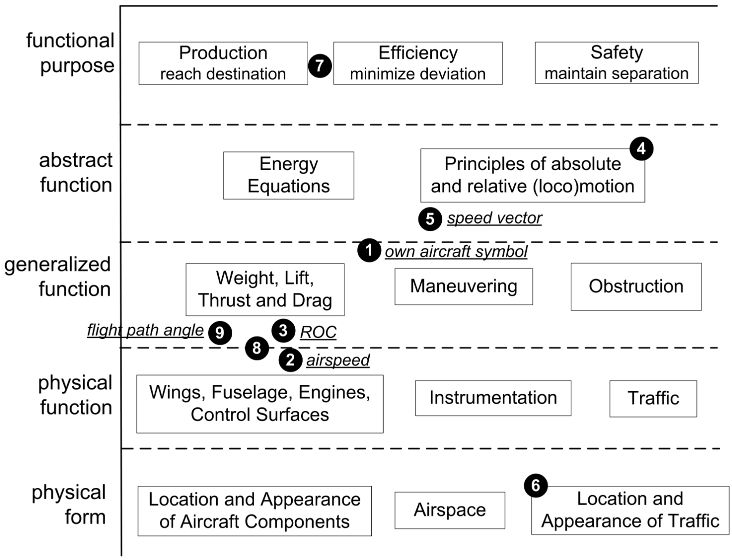


FIGURE 5-2: Abstraction Hierarchy for tactical navigation in the vertical plane.

5-3-1 Abstraction Hierarchy

The AH is a tool to reveal content and structure of the work domain. It is a goal-oriented stratified hierarchy, as it shows the system from different perspectives going from a functional (top) to a physical description (bottom) [40]. Each level provides the means for the ends identified at the next higher level. A typical AH consists of five levels: Functional Purpose, Abstract Function, Generalized Function, Physical Function and Physical Form [41].

Figure 5-2 shows the Abstraction Hierarchy that has been developed for the tactical navigation in the vertical plane. Note that the numbers in this figure refer to display elements in the VSAD that will be discussed later in Section 5-4 (Figure 5-5). The numbers that are accompanied by underlined text refer to variables that characterize the functions to which they relate in the hierarchy. The five levels of the AH are described as follows.

Functional Purpose As for most transportation systems, three main purposes can be identified at this level, production, efficiency and safety. The safety purpose is twofold: (1) to stay in the air, i.e., remain within the performance envelope, and (2) to maintain separation. The efficiency purpose is to resolve and prevent conflict situations by minor deviations of the planned flight path.†

†Here it is assumed that the planned flight path represents 'optimal flight' (in terms of fuel-use,

The production goal is to fly towards the destination of the programmed flight path.

Abstract Function This level describes the underlying principles that are necessary to meet the purpose of the system. For the transport domain, this level is often best described by physical laws. The aircraft vertical motion is governed by energy laws that describe the aircraft kinetic and potential energy. These can be considered a higher-level representation of the own aircraft locomotion that is usually described in terms of speed and altitude. The second set of physical laws is given by the kinematic principles of 'absolute motion' and 'relative motion', with the latter the motion relative to other aircraft [26].

Generalized Function This level describes how the laws at Abstract Function level can be achieved independent of the physical implementation of the system. Here, weight, lift, thrust and drag functions, and the maneuvering functions (aircraft dynamics and performance) impose internal constraints on aircraft behavior. 'Obstruction' describes the function of other traffic with respect to the own maneuvering, and govern the external constraints that have to be coped with to comply with the safety purpose of separating the own aircraft from other aircraft.

Physical Function The states of systems and their capabilities are described. The states and configuration of the wings, fuselage, engines and control surfaces as part of the aircraft components that realize the internal functions on the Generalized Function level. The states of the other aircraft in the environment are described by 'traffic'. A particular function is 'avionics' which receives and measures state information related to both the external traffic-related[‡] and internal own aircraft-related constraints, respectively.

Physical Form This level contains the appearance, location, shape, condition of the components of the own aircraft as well as the location and appearance of other aircraft (the latter from a complete aircraft perspective). The 'airspace' contains several physical properties such as its position and volume, air density and wind conditions.

Two different groups of constraints can be found from the domain analysis. Up until the Abstract Function level, the content of the AH can be clearly separated

time, or both). Whether a 'small deviation' from this planned flight path is indeed an 'optimal' solution to resolve a particular conflict, remains to be seen. This question is, however, beyond the scope of this paper.

[‡]Navigation data of intruder aircraft is assumed to be communicated via Automatic Dependent Surveillance Broadcast (ADS-B).

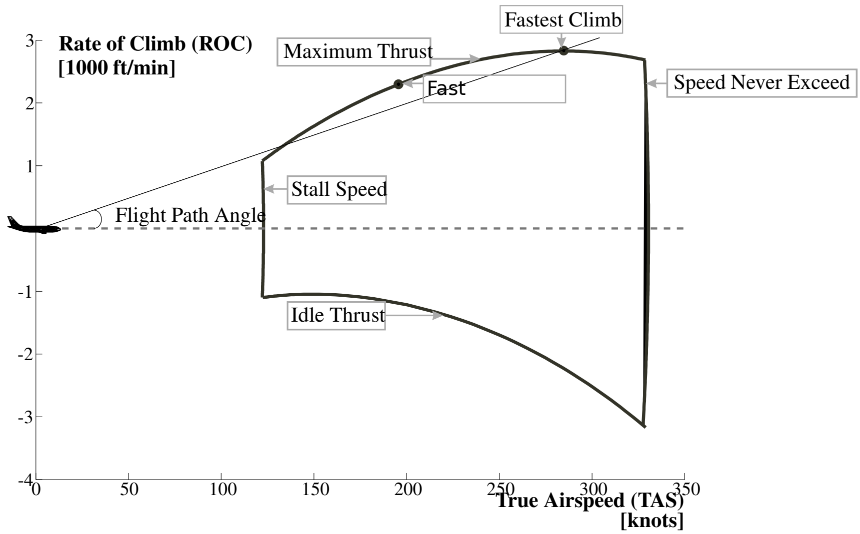


FIGURE 5-3: Performance envelope of the Cessna Citation I, in TAS/ROC state space.

into internal, own aircraft-related domain functions and relations (left-hand side of Figure 5-2), and external, environment-related functions and relations (right-hand side of Figure 5-2).

5-3-2 Internal Aircraft Constraints

Within the Physical Function and Physical Form levels of the abstraction hierarchy, the physical boundaries of the work domain are defined. Within the aircraft itself, the engines relate to the throttle settings which result in boundaries for maximum and minimum thrust. The wings and fuselage determine the aerodynamic forces and aerodynamic efficiency. Coupled to the generalized functions of lift, drag and thrust, boundaries can be defined in terms of speed, altitude, flight path angle and rate-of-climb (ROC). This leads to maneuver boundary capabilities for aircraft performance such as 'fastest climb' or 'idle thrust'. These boundaries can be visually presented by plotting the performance envelope in a polar graph within a true airspeed/rate-of-climb state space, see Figure 5-3. Note that in this paper, all figures are plotted for the Cessna Citation I, trimmed at 16,405 ft and 292 kts True Airspeed (TAS), in clean configuration [42, 43].

Figure 5-3 shows that the aircraft internal performance-related constraints are determined by on the one hand, minimum and maximum speed, and on the other hand, minimum and maximum thrust characteristics that limit the aircraft flight-path. These will be discussed below.

Velocity constraints. The minimum velocity is the stall speed, the lowest indicated airspeed an aircraft can fly. The velocity is the never-exceed speed, also called the 'red line airspeed'.

Maximum thrust constraints. Maximum throttle settings at a certain speed yield a flight-path angle γ, obtained from the equilibrium of forces by dividing the amount of excess thrust by the weight of the aircraft:

$$\sin\gamma \;=\; \frac{T-D}{W}. \tag{5-1}$$

More excess thrust yields a larger climb angle γ, and vice versa. If we include the aircraft aerodynamic efficiency E or lift-to-drag ratio L/D, flight-path is related to the lift-coefficient C_L:

$$E = \frac{C_L}{C_{D_0} + KC_L^2} \;=\; \frac{1}{(T/W)-\gamma}, \tag{5-2}$$

with K the lift-dependent drag coefficient. The velocity that corresponds with a certain flight-path angle and aerodynamic efficiency can be calculated with:

$$L = 1/2\, C_L\, \rho\, V^2\, S \;=\; W\ \cos\gamma \qquad \Leftrightarrow \qquad V \;=\; \sqrt{2\frac{(W/S)\ \cos\gamma}{C_L\ \rho_{SSL}\ \sigma}}, \tag{5-3}$$

with σ the air-density difference, dependent on altitude [43].

Two particular figures of merit of the aircraft are the steepest and fastest climb. The steepest climb (SC) flight establishes the upper limit of the flight-path angle γ that an aircraft can achieve in stationary flight with maximum thrust T_{max}, see Figure 5-3:

$$\gamma_{SC} \;=\; \frac{T_{max}}{W} - \frac{1}{E_{max}}, \tag{5-4}$$

where $E_{max} = 1/(2\sqrt{C_{D_0}K})$.

The fastest climb (FC) indicates the minimum time to climb to a specified altitude and occurs when the rate of climb is maximal, see Figure 5-3:

$$\gamma_{FC} \;=\; (T_{max}/W)(1-\Gamma/6) - \frac{3}{2\,E_{max}^2\,\Gamma\,(T_{max}/W)}, \tag{5-5}$$

where Γ is a non-dimensional aircraft-related quantity dependent of E_{max}, T_{max} and W [43]. Note that this is also the situation where energy-efficiency is maximum.

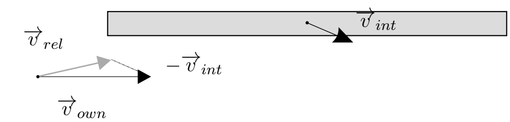
Minimum thrust constraints. Aircraft can fly on idle or minimum thrust, in so-called 'unpowered' or 'gliding' flight, where T equals 0. This yields the following quadratic polynomial in V^2 to determine the speed at every possible flight path angle:

$$0 = \frac{\rho_{SSL}\,\sigma\,C_{D_0}}{2\,(W/S)}\,V^4 + \gamma\,V^2 + \frac{2\,K\,(W/S)}{\rho_{SSL}\,\sigma} \tag{5-6}$$

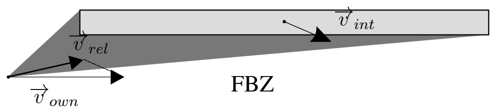
The minimum and maximum thrust settings yield non-linear contour lines for flight-path γ at various airspeeds, Figure 5-3. These contours depend on the aircraft type, its configuration, and altitude. Hence, they represent performance constraints that are dynamic in their own right.

5-3-3 External Traffic Constraints

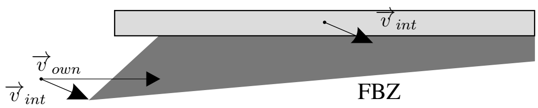
On the Physical Form and Physical Function levels, the position and motion of 'traffic' in the vicinity of the own aircraft determine if an aircraft 'obstructs' (Generalized Function level) the maneuvering of the own aircraft. The way pilots are supposed to deal with this external constraint determines if one of the safety goals, 'to maintain separation', is achieved or not. Separation is conceptualized by defining a protected zone around each aircraft, Figure 5-1.



(a) Relative velocity



(b) FBZ in the Relative Plane



(c) FBZ in the Absolute Plane

FIGURE 5-4: Definition of the Forbidden Beam Zone (FBZ), in the relative and absolute velocity planes.

On the Abstract Function level, the physical laws concerning vehicle separation are based on kinematic principles using relative and absolute aircraft motion. These represent the (conflict) geometry *in motion*. When the relative velocity of the own aircraft with respect to the intruder aircraft is defined, a conflict will occur if this relative speed vector points in the direction of the intruder aircraft protected zone, as illustrated in Figure 5.4(a).

This can also be visualized by drawing a beam-shaped area (in the sense of a flashlight beam, or conic section), originating from the own aircraft position and tangent to the outer sides of the rectangular shape of the protected zone, Figure 5.4(b). Throughout this paper, this zone will be referred to as the 'Forbidden Beam Zone' (FBZ). Note that this nomenclature follows the definitions of earlier work on separation assistance systems conducted in the horizontal plane [26]. If the tip of the relative velocity vector $\overrightarrow{v}_{rel}$ lies within or moves into this 'forbidden area', separation will eventually be lost. The pilot's task with respect to conflict resolution is therefore to keep the relative speed vector out of the FBZ.

Now, the constraints of the aircraft are constraints in aerodynamic velocity space, i.e., in an aerodynamic reference frame. Somehow the external constraints, originating from relative motion, must be *combined* with the internal constraints. To this end, 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, $\overrightarrow{v}_{intruder}$, see Figure 5.4(c). Then, the pilot should simply move the own aircraft speed vector, $\overrightarrow{v}_{own}$, 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. The result is a layered geometrical shape including several FBZ shapes, together showing the 'total' collection of constraints imposed by other aircraft in the vicinity on the own aircraft locomotion. This allows pilots to choose a 'global' solution that avoids all FBZ's at once, and this way pilots avoid resolution maneuvers that might lead to new short-term conflicts with other aircraft.

In line with our previous work on horizontal separation assistance interfaces, [26] the combination of the performance overlay and the conflict geometry overlay is called the State Vector Envelope (SVE). In the SVE the internal and external constraints imposed on the own aircraft locomotion are mapped on one display.

5-3-4 Conclusions from the WDA

From the work domain analysis it can be concluded that the possibilities for aircraft locomotion in the vertical plane are shaped by the internal aircraft performance-related constraints, Section 5-3-2, and external traffic-related constraints, Section 5-3-3.

The performance envelope, Figure 5-3, shows the aircraft performance constraints regarding flight-path and speed in a TAS/ROC state space. The constraints imposed by other traffic are captured by the combined FBZ's of each individual intruder aircraft, shown in terms of the own aircraft velocity vector in the vertical plane, Figure 5.4(c).

Given the compatibility of the state variables in which both types of constraints can be expressed, the constraints can be mapped onto each other, yielding the SVE. As will become clear below, this mapping is the fundamental feature of the Vertical Separation Assistance Display (VSAD), as it enables pilots to directly perceive what maneuvers are 'feasible' to resolve an existing conflict situation and also to prevent steering into new conflicts.

5-4 Interface design

In the development of the VSAD, our aim was to comply with an existing cockpit interface, the Vertical Situation Display (VSD). [19]. The VSD is a situation display that contains visual aids that provide feedback for the vertical flight management tasks of navigation. It is located underneath the Navigation Display (ND) in a co-planar view. The VSD allows the crew to better manage the vertical flight path for climb and descent phases inside busy Terminal Areas [19]. Currently, the presentation of terrain on the VSD, to avoid controlled flight into terrain incidents, is investigated [32].

5-4-1 Mapping the constraints on the VSD

The VSAD has been implemented using an existing VSD standard, adding layers of functional information identified in Section 5-3. 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 [15, 39].

Figure 5-5 shows the VSAD. It integrates the performance envelope of Figure 5-3 and the conflict geometry visualization of Figure 5.4(c) in a conventional VSD. In Figure 5-5, 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 the aircraft identification, its 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.

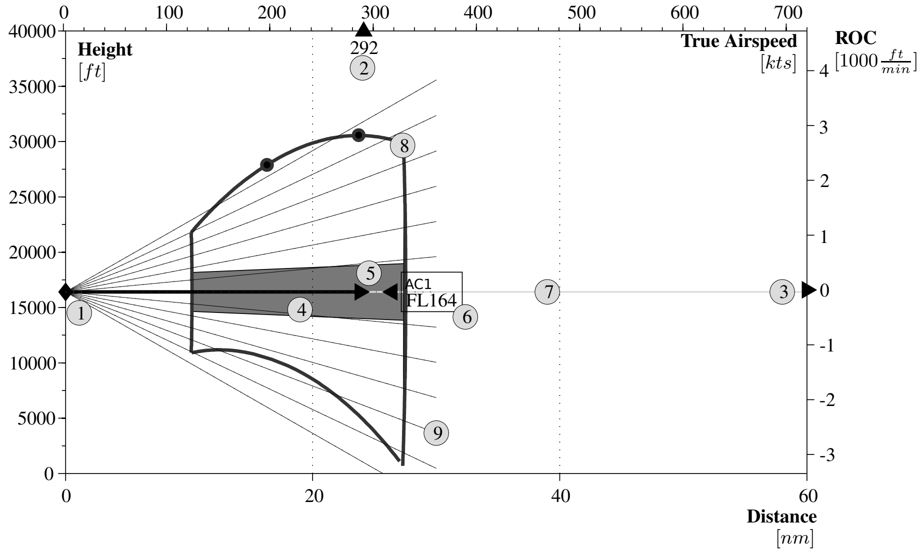


FIGURE 5-5: The Vertical Separation Assistance Display (VSAD).

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.

Only surrounding aircraft that are located within the prediction interval of 5 minutes, that either already cause a conflict or could cause a conflict when the pilot would maneuver anywhere within the boundaries of the own aircraft performance, are considered for calculation and presentation of their FBZ. These aircraft are labeled ‘intruder aircraft’, and are assumed to not change their flight-path or velocity. Of each intruder aircraft, only the part of the FBZ within the performance envelope is shown on the display. The algorithm that is used to create the FBZ is based on the relative velocity, Section 5-3-3.

If the aircraft flies in the same direction as the own aircraft, with parallel speed, the relative velocity will be small and the distance between potential intruder aircraft and the own aircraft is small. If the intruder aircraft flies with opposite speed, the intruder aircraft can only be located in front of the own aircraft, but with a far greater distance. Figure 5-6 shows the potential intruder aircraft for a Cessna Citation I, where areas **A** and **B** represent potential intruder aircraft with parallel speeds and opposite speeds, respectively. Note that in drawing these areas it is assumed that potential intruder aircraft have the same capabilities as the Cessna Citation I, and do

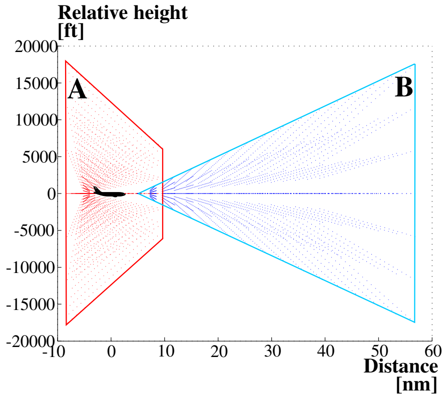


FIGURE 5-6: Positions of possible intruder aircraft for a prediction time of 5 minutes.

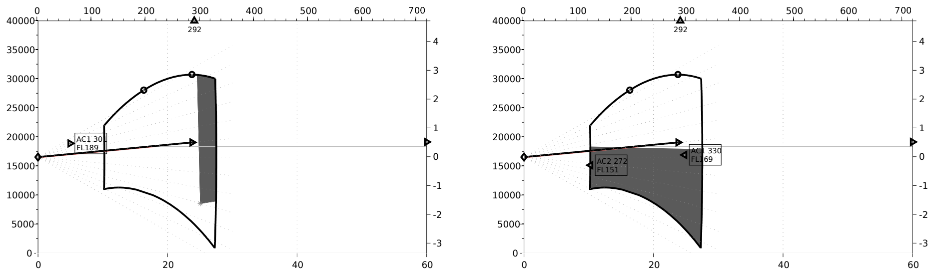
not change their flight-path or velocity.

5-4-2 VSAD and Work Domain Content and Structure

Figure 5-5 illustrates how information about the various constraints identified in the work domain analysis are presented on the display. The numbers in the abstraction hierarchy, Figure 5-2, correspond with the numbers in the display, to clarify what part of the VSAD relates to what part in the abstraction hierarchy. This is also achieved by visualizing some of the most important means-end relationships [28]. Note that the numbers with an underlined text label in Figure 5-2 do not refer to the functions and relations themselves, but to the variables that characterize them.

Figure 5-5 shows that the safety goal is realized by keeping the velocity vector tip ❺ inside the performance envelope ❽ and outside the FBZs ❹ of all intruder aircraft. In this example only one intruder exists, flying in opposite direction and positioned in front of the aircraft. For the traffic constraint, the FBZ represents the principles of absolute and relative motion on the Abstract Function level of the AH. The FBZ is mapped onto boundaries of the performance envelope, yielding the SVE, revealing the connections between functions related to aircraft constraints defined on the left-hand side of the AH, and functions related to traffic constraints, defined on the right.

The characteristics of the FBZ also play an important role in revealing vertical means-ends relationships from the safety goal at the Functional Purpose level to the Physical Form at the lowest level in the AH. An example is the visualization of the intruder aircraft ‘state’ that corresponds with the shape of its particular FBZ. A large angle between the legs of the FBZ indicates that the distance between the own and intruder aircraft is small. Also, the intruder aircraft is located somewhere between the two directions indicated by the FBZ legs, considered from the own aircraft perspective.



(a) Parallel Speed (b) Opposite Speed

FIGURE 5-7: Conflict situation with intruder aircraft flying at an opposite and a parallel speed.

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. The tip of the FBZ is represented in the design by a star (*), see Figure 5-7. 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 ❻. Note that, as far as separation assistance is concerned, it would be preferable to also show part of the airspace ‘behind’ the own aircraft, as illustrated in Figure 5-6, 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 production goal is achieved by following the flight path as well as possible, while the efficiency goal is to avoid any conflicts by conducting minor deviations from the programmed flight path. The yellow line, ❼ in Figure 5-5, in the VSAD represents the flight path as programmed in the Flight Management System (FMS). The speed vector ❺, besides serving the performance purpose, also relates to the navigation purpose as it is a predictor of where the aircraft will be located in 5 minutes time. Now, if the tip of the speed vector is located on the edge of the FBZ ❹, the own aircraft will just avoid the conflict, and so the efficiency of the escape maneuver in terms of achieving a minimal deviation from the planned trajectory can be high. But to prevent very time-inefficient resolution maneuvers, the tip of the FBZ is to be avoided; then the conflict will never be resolved since the own aircraft will fly parallel with the intruder aircraft. The resolution strategies efficiency is discussed in detail by Van Dam et al. [26].

5-4-3 VSAD information processing: Skills, Rules, Knowledge

Rasmussen's Skills, Rules and Knowledge taxonomy (SRK) is a tool for describing the mechanisms that humans have for cognitively processing information [44] Three levels of cognitive control, i.e., skill-based, rule-based and knowledge-based behavior, are distinguished when describing human behavior in reaction to available information [20, 44]. These levels cover a range of behavior going from direct actions with little cognitive effort up to complex problem solving. EID aims: (1) to support the operator at 'all' levels of control, and (2) to not force control to a higher level than necessary, saving cognitive resources of the human operator when desired [20, 29].

Skill-Based Behavior is supported by the VSAD through enabling pilots to act on directly perceivable constraints. The speed vector should be kept inside the performance envelope and outside the SVE. Through appropriate path control, i.e., by adjusting speed and ROC settings on the autopilot mode control panel, the pilot can directly manipulate the goal state without the need for higher-level cognitive control.

Ruled-Based Behavior involves associating familiar perceptual cues in the world with an action or intent. There should be a consistent one-to-one mapping between the work domain constraints and the perceptual information on the interface. Indeed, the VSAD incorporates a clear one-to-one mapping between the conflict situation and the FBZ geometry. Over time, different maneuver strategies can be tested, selected or discarded, depending on their efficiency. The tip of the FBZ represents the vector state of the intruder aircraft and is to be avoided, while no other FBZ zones can be entered when resolving a conflict. The same one-to-one mapping exists between the shape of the performance envelope and the actual configuration and flight conditions of the aircraft. As these conditions change, so does the envelope's shape.

Knowledge-Based Behavior involves analytical problem solving based on a symbolic mental model. The interface should present the content and relations identified by the abstraction hierarchy model of the workspace. The relation between the generalized functions (aircraft performance, obstruction) and the abstract functions lies in the formulation of the constraints in the speed vector space which is layered upon the 'absolute' position space of the VSD, using the 5 minutes prediction time. As explained before, the FBZ and related intruder aircraft are correlated with each other on the display through various relations between the appearance of the FBZ and the own and intruder aircraft position and speed. Pilots can easily see how their aircraft will pass the intruder aircraft. Mapping the performance envelope on ‘absolute space’, using the five-minute prediction, in combination with the FBZ geometry and the positions of intruder aircraft, pilots can immediately see how urgent and dangerous a conflict situation is, and also what the opportunities are for actions needed to resolve it.

5-4-4 VSAD and Traffic Situation Awareness

A high level of Situation Awareness (SA) is needed for effective decision-making and performance in any complex and dynamic environment [45]. However, there is no generally-accepted definition of situation awareness. An academic definition would be: “*SA is the experience of fully understanding what is going on in a given situation, seeing each element within the context of the overall goal and being able to fit all the pieces together into a coherent picture*” [46]. In the words of a pilot, SA is “*knowing what’s going on so you can figure out what to do*” [47]. Although the term SA is the subject of considerable debate, we considered it to be useful to evaluate our designs, as far as it allowed us to find out how much our subjects understood their ‘situation’ [48].

A frequently-used approach, also adopted here, is to divide SA in four cognitive levels: perception (level 1), comprehension (level 2), projection (level 3) [21] and meta-cognition (level 4) [49]. In the context of pilot traffic awareness, these levels can be described as:

Level 1: Perception Perception of situational elements, such as the speed of the own aircraft, the relative position of intruder aircraft.

Level 2: Comprehension Understanding the meaning of the perceived elements with respect to the pilot’s goals. Is the other aircraft causing a conflict, how risky is the situation and how much time is available to initiate an escape maneuver?

Level 3: Projection The ability of pilots to plan and apply strategies based on the current state of the process and activities. It involves the selection of preferred escape maneuvers, insight in the feasibility and difficulty to perform these maneuvers

Level 4: Meta-cognition The self-assessment of a pilot’s own traffic awareness. That is, how sure are pilots in perceiving, comprehending, and projecting a particular situation?

These four SA levels will be the main measurements that were conducted in a first preliminary evaluation of the VSAD, described in the following sections. The primary goal of this evaluation was to see whether the functional information layers in the VSAD indeed improved pilot traffic awareness. Based on the discussions above, it is expected that especially at the 'comprehension' and 'projection'-levels, situation awareness will increase.

5-5 Evaluation

To check whether the Vertical Separation Assistance Display is set to meet its main goal of supporting pilot traffic SA, and to elicit pilot comments regarding the novel VSAD functional overlays, an evaluation with pilots was conducted. Pilots were shown movies of 20 to 30 seconds, illustrating dynamically a certain conflict situation in the vertical plane. Using a set of questionnaires pilot situation awareness was measured in a systematic fashion.

5-5-1 Method

Subjects. Twelve professional airline pilots participated (average age 40.3 years (σ=11.4) and average experience of 5,850 (σ=2,600) flight hours), with extensive experience with glass cockpits.

Independent variables. Two independent variables were varied, the display configuration, and the experimental scenarios. Regarding the former, two displays were investigated: (1) the Vertical Situation Display (VSD) [19]; and (2) the Vertical Separation Assistance Display (VSAD). Screenshots of both displays are shown in Figure 5-8.

Because the number of possible scenarios that could be tested was limited, ten scenarios were designed that were considered to best represent six 'typical' conflict situations.

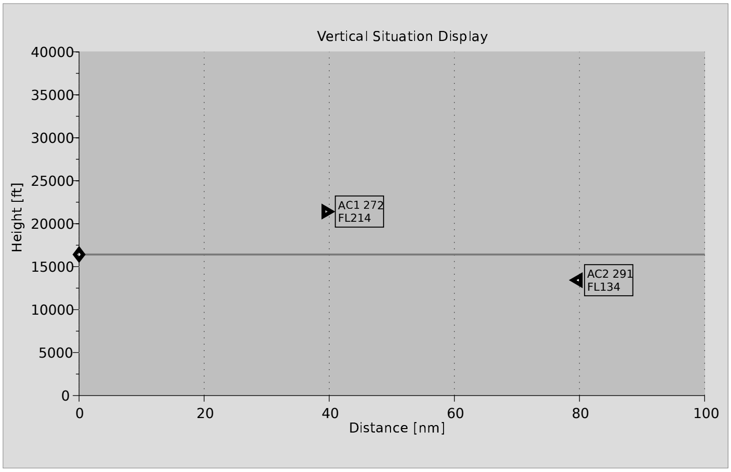
Scenario design. The typical conflict situations were defined as follows:

1. **Opposite maneuvers** The intruder aircraft is located ahead of the own aircraft and flies head-on towards the own aircraft.

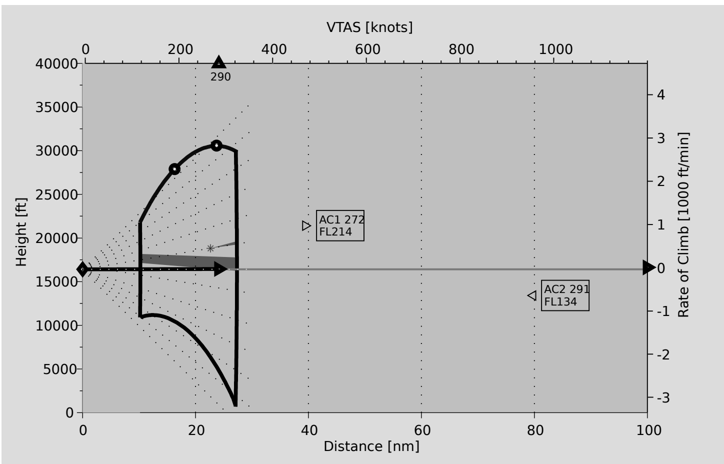
2. **Parallel maneuvers** The intruder aircraft is located above or under the own aircraft and, respectively, descends or climbs into the own aircraft flight path.

3. **Overtake maneuvers** The intruder aircraft is located *behind* the own aircraft and flies at a higher speed than the own aircraft.[§]

[§]Note that the situation where the own aircraft is overtaking other traffic is not considered.



(a) Vertical Situation Display



(b) Vertical Separation Assistance Display

FIGURE 5-8: Screenshots of the two display formats used in the evaluation.

4. **Multiple intruders** Three to five aircraft are within the five minute range of the own aircraft; one is causing a conflict.

5. **No conflict** Two to five aircraft are within the five minute range of the own aircraft; none of them, however, is causing a conflict.

6. **Resolution maneuver** The own aircraft is flying an escape maneuver, and in doing so resolves a possible conflict with an intruder aircraft.

Scenarios differed in the position and flight-path of intruder aircraft relative to the own aircraft. Table 5-1 lists the characteristics of the ten scenarios. The last screen shot (before the display went blank) of the VSAD for every scenario is given in Figure 5-9.

The first five conflict situations each have 2 scenarios, the sixth conflict situation is combined with another conflict situation. Between 1 to 5 intruder aircraft were simulated. For each scenario in Table 5-1, a frame around the intruder aircraft indicates what aircraft was responsible for the conflict situation (hence, no frames in scenarios 5 and 10).

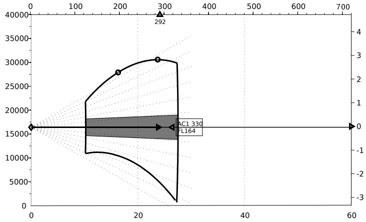
The initial relative location of each intruder aircraft is indicated by a quadrant number, see Figure 5-10. The definition of the initial aircraft location had an important effect on the evaluation. With the VSD, all intruder aircraft located in quadrants 5, 6 and 7 were not visible (rows with an asterisk in Table 5-1), as these are all located *behind* the own aircraft. Although for aircraft located in quadrants 4 and 8, this might happen as well, in the scenarios designed for this evaluation all aircraft in these quadrants were located in front of the own aircraft during the whole run. 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, i.e., the functional SVE conflict geometry overlay which shows the meaning of *all traffic around* the own aircraft.

This means that in the scenarios involving overtake maneuvers (conflict situation 3), i.e., scenarios 3 and 8, any comparison between the VSD and VSAD would be unfair, as with the VSD the aircraft causing conflicts were simply not visible for the pilots. Note, however, that in scenario 3 the own aircraft was performing a resolution maneuver, and since no other aircraft was presented on the VSD, most pilots did actually understand that they were in conflict with an aircraft located behind them. A comparable situation occurred in scenario 10, a 'no conflict' situation, where AC2 was not visible with the VSD, and pilots could only base their judgment of the situation from the presentation of AC1.

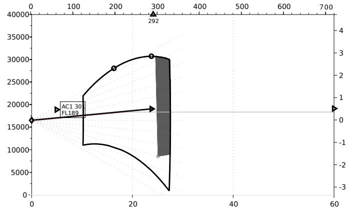
Therefore, although in the results section the experimental data will sometimes be shown for all scenarios, the data belonging to scenarios 3, 8 and 10 (gray columns

TABLE 5-1: The characteristics of all scenarios.

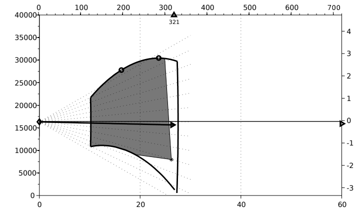
		scenario									
		1	2	3	4	5	6	7	8	9	10
conflict situation		1	2	3&6	4	5	1&6	2	3	4	5
# of intruder aircraft		1	1	1	3	5	2	2	2	5	2
intruder location (quadrant)	1		[AC1]			AC1,AC4		AC1	AC2	AC1,AC5	
	2	[AC1]					AC1				
	3				[AC1],AC3	AC3	[AC2]			AC3,[AC4]	
	4					AC5		[AC2]			
	5*										AC2
	6*								[AC1]		
	7*			[AC1]	AC2	AC2				AC2	
	8										AC1
intruder velocity	parallel		AC1	AC1	AC2	AC2,4,5		AC1,2	AC1	AC2	AC1,2
	opposite	AC1			AC1,3	AC1,3	AC1,2		AC2	AC1,AC3-5	
own aircraft flight-path	climb		x							x	
	straight	x						x	x		x
	descent				x	x					
	resolution			x			x				



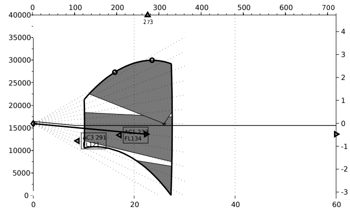
(a) Scenario 1 (conflict situation 1)



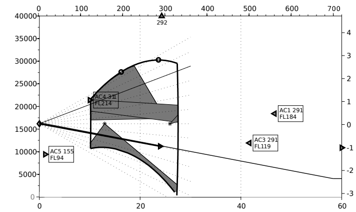
(b) Scenario 2 (conflict situation 2)



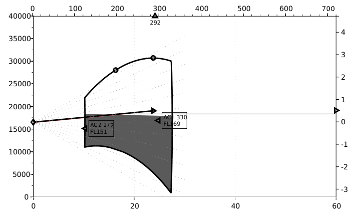
(c) Scenario 3 (conflict situations 3 & 6)



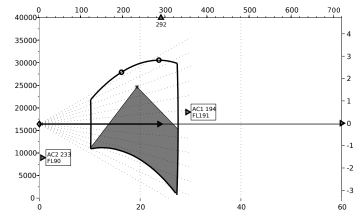
(d) Scenario 4 (conflict situation 4)



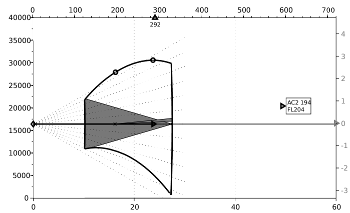
(e) Scenario 5 (conflict situation 5)



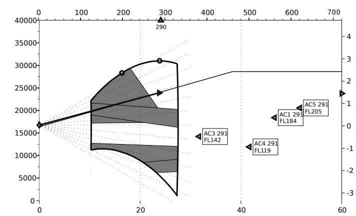
(f) Scenario 6 (conflict situations 1 & 6)



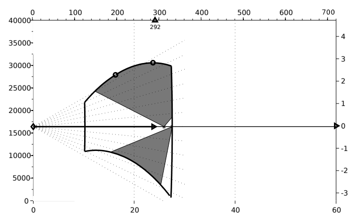
(g) Scenario 7 (conflict situation 2)



(h) Scenario 8 (conflict situation 3)



(i) Scenario 9 (conflict situation 4)



(j) Scenario 10 (conflict situation 5)

FIGURE 5-9: Final VSAD screenshot of the experimental scenarios.

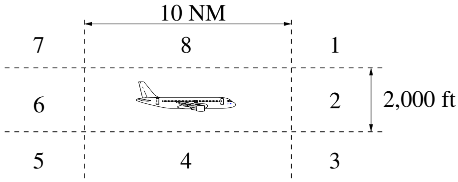


FIGURE 5-10: Quadrants of intruder aircraft positions.

TABLE 5-2: Overview of the evaluation.

Briefing & examples		30 min.
Pre-questionnaire	acceptance & symbology evaluation	10 min.
Dynamic questionnaire	SA validation	50 min.
Post-questionnaire	acceptance & symbology evaluation	10 min.

in Table 5-1) *were not used* in any statistical analyses regarding comparisons between VSD and VSAD. As far as investigating potential SA-dependencies with the VSAD are concerned, however, all data were used. In particular, the 'number of intruder aircraft' and 'conflict situation' will be considered as individual factors influencing pilot awareness.

Procedure. The experimental procedure is summarized in Table 5-2. Pilots first received a 30-minute briefing, that started with a presentation about conflict geometry principles, the performance envelope presentation and an introduction to the VSD and VSAD. Six static examples (i.e., pictures) were given and one dynamic example (i.e., a movie) where a resolution maneuver was performed. After the briefing the experiment was conducted. It consisted of two parts: the 'acceptance and symbology evaluation' and the 'situation awareness validation'.

Acceptance and symbology evaluation. The 'acceptance and symbology evaluation' consisted of a pre- and post-questionnaire, both lasting approximately 10 minutes. In the pre-questionnaire, pilots were asked to reveal their thoughts about various strategies to use the VSAD, and also to give their first opinion of the information shown. These were based solely on the briefing. The same questions were asked at the end of the experiment, when the 'SA validation' stage was finished, using the post-questionnaire.

The post-questionnaire also contained five statements requiring a final subjective self-assessment of pilots on their traffic situation awareness, addressing especially the levels of 'comprehension' and 'projection'. All statements are listed in Table 5-3. Using an 11-point Likert-scale (0 = Not True, 10 = True) pilots indicated, for each statement, how much they agreed with that statement.

TABLE 5-3: Post-questionnaire pilot SA self-assessment statements.

S1	“I knew exactly how much time was left before the conflict would occur”
S2	“I knew exactly which maneuver would be the best to escape safely”
S3	“I knew the capabilities of my aircraft relative to the intruder’s position”
S4	“I knew exactly when to perform a maneuver”
S5	“I knew exactly which intruder aircraft was related to which part of the envelope”

SA validation measurements. The ‘SA validation’, also referred to as the ‘dynamic questionnaire’ in the following, was conducted using movies that showed the different scenarios with either the VSD or the VSAD. Scenarios were randomized to mitigate any learning effects.

Each scenario started from a fixed trim situation and showed a particular conflict situation for 20 to 30 seconds. Pilots were instructed to watch these movies, and prepare themselves for the SA questions; no pilot actions were needed. Then the screen turned black and the pilot was asked to complete the SA validation questionnaire before moving on to the next scenario.

The questionnaire consisted of nine questions, three for each level of SA. Table 5-4 lists nine example questions asked after completion of one particular scenario. The answers to each individual question were evaluated by attaching a score of 0, 3, 6 or 9 that depended on the error margin that belonged to that particular question. The thresholds between the scores for each individual question were determined with expert pilots. Total SA was defined as the average over all nine questions. This procedure was used successfully in Borst et al. [32, 34].

In this experiment, the fourth SA level, meta-cognition, was considered a measure for a pilot’s own assessment of his or her answer to each individual SA question asked. That is, through the use of an 11-point Likert-scale, ranging between 0 (unsure) and 10 (very sure), pilots could indicate, for each question, how certain they were in answering that particular question. After taking a z-score of the indicated value, for each answer a score of meta-cognition was given in relation with the grade given on the SA score. This was done using a point system summarized in Table 5-5. Total meta-cognition was defined as the averaged score over all nine questions.

Apparatus. The movies in the dynamic questionnaire were made using Matlab^{TM}. Either the VSD or the VSAD was shown, together with a Primary Flight Display (PFD). Pilots were seated in front of a 17inch monitor and perceived the movies passively, i.e., no actions were required.

TABLE 5-4: Example questions of the SA validation questionnaire.

1 Perception	
	"What is your speed, in knots?"
	"What is the conflicting aircraft flight path angle, in degrees?"
	"What is the distance between you and the conflicting aircraft, in NM?"
2 Comprehension	
	"What is the level of risk? (1= too risky, 5= not risky at all)"
	"How much time do you have to initiate a resolution maneuver? [0-300 seconds]"
	"How many intruder aircraft create potential conflicts?"
3 Projection	
	"Which maneuver would you prefer to perform in the current situation?"
	"Is it possible to resolve the conflict by climbing 500 ft?"
	"Do you expect the escape maneuver to be difficult?"

TABLE 5-5: Grade determination of meta-cognition SA level.

	nominal measure	incorrect grades 0 or 3	correct grades 6 or 9
very sure	$z > 0.33$	0	9
fairly sure	$0.33 > z > -0.33$	1	6
unsure	$z < -0.33$	2	3

Aircraft dynamics. All aircraft were driven by a 6-DOF non-linear model of the Cessna Citation I, a small business jet [50, 51]. The model was trimmed at a total mass of 5,000 kg, at an airspeed of 292 knots and an altitude of 16,405 ft. It used an integrated altitude and auto-throttle autopilot. Intruder aircraft maintained a constant speed and flight path angle, i.e., only the own aircraft maneuvered (in scenarios 3 and 6). Wind or turbulence effects were neglected.

Dependent measures. There were three groups of dependent measures. First of all, the pilot scores for answering questions at the first three levels of situation awareness (perception, comprehension and projection), and the averaged or 'total' SA scores. Second, the pilot meta-cognition scores at these three levels, and the averaged or 'total' meta-cognition scores. These two groups of data were obtained through the dynamic questionnaire and allowed for a quantitative analysis.

The third group of data consisted of the subjective pilot acceptance and symbology ratings and additional pilot comments obtained in the pre- and post-questionnaires.

Since the evaluation involved a passive task, no workload measurements were taken.

5-5-2 Hypotheses

First, the VSAD was hypothesized to significantly improve pilot traffic SA. When regarding the different levels of SA, it was hypothesized that whereas differences between the VSD and VSAD would be small at the perception level, the VSAD would perform significantly better at the comprehension and projection levels. Metacognition was expected to show similar trends, i.e., considerably higher scores with the VSAD, especially at the projection level.

Second, with the VSAD, it was hypothesized that the traffic SA scores depend neither on the number of intruder aircraft, nor on the conflict situation.

5-6 Results and Discussion

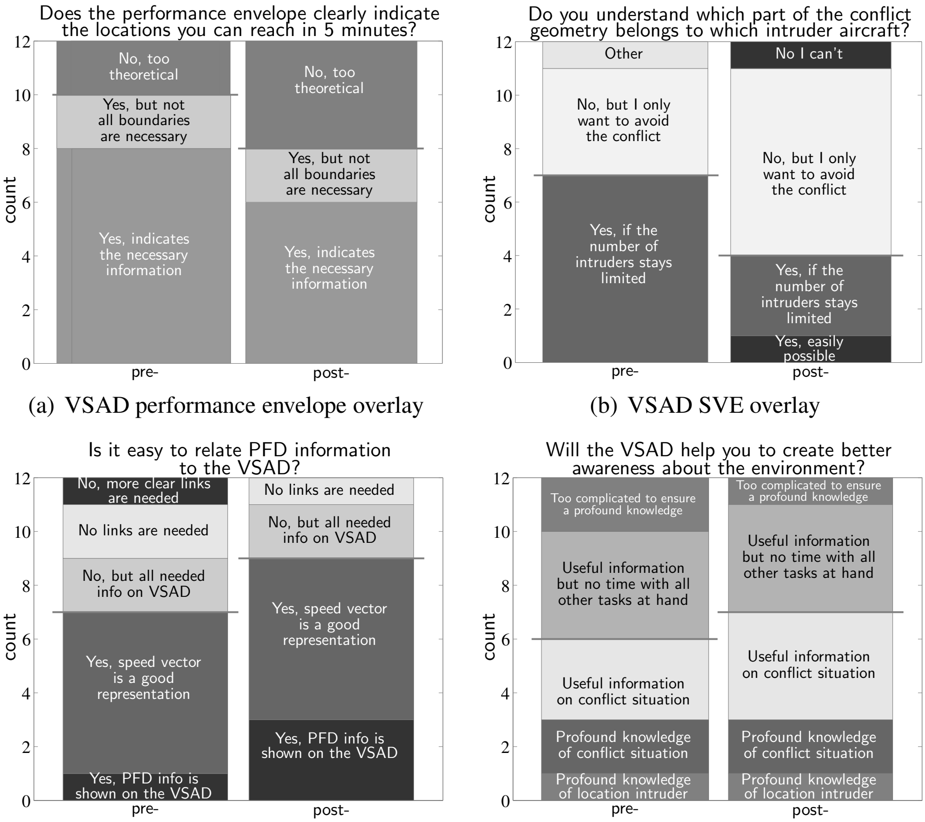
5-6-1 Acceptance and Symbology Evaluation

Pre- and post questionnaire results. 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 height. This is contrary to pilots' preferred strategies in the horizontal plane, collected in previous work on the horizontal separation assistance display, [26] 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.

Figure 5-11 shows the answers to four questions asked to the pilot in the pre- and post-questionnaires. In this figure, the black horizontal lines separates the 'favorable' responses (below) from the 'unfavorable' ones (top). Rather surprisingly, Figure 5.11(a) indicates 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, Figure 5.11(b). After the



(a) VSAD performance envelope overlay

(b) VSAD SVE overlay

(c) relation VSAD and PFD

(d) VSAD situation awareness check

FIGURE 5-11: Pilot answers related to the symbology and use of the VSAD.

dynamic questionnaire, however, 8 out of 12 pilots found it hard to detect which conflict geometry belongs to which intruder aircraft. From Figure 5.11(c) 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, Figure 5.11(d) illustrates the mixed response that was 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.

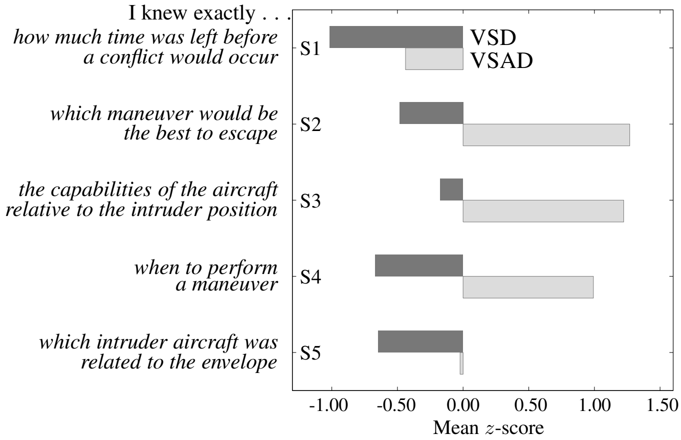


FIGURE 5-12: Mean z-scores, subjective SA statements.

SA self-assessment statements. The pilot ratings of the five SA statements, see Table 5-3, were transformed to z-scores to average the subjective measures. The results are shown in Figure 5-12; positive scores indicate a high level of pilot agreement with the statement, and vice versa.

As was expected, the VSAD ratings are all significantly higher for statements 2, 3 and 4 (t-test, $p < 0.001$). These reflect the level to which pilots are aware of what escape maneuver would be the best suitable (statements 2 and 3), and when it should be initiated (4). Pilots find themselves less aware of the time-before-conflict (statement 1), for the VSD, as was expected, but also for the VSAD which only showed slightly higher scores (not significant). Furthermore, the 'average' rating of the VSAD regarding statement 5 confirms the earlier finding that pilots had difficulty in understanding what intruder belonged to what FBZ on the VSAD conflict geometry overlay.

Pilot comments. Pilots were asked whether the VSAD needed changes or clarifications. First and foremost, pilots reported to have difficulties in linking intruder aircraft to the correct FBZ, and recommended that new ways should be thought of to make this more clear. 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.

5-6-2 Situation Awareness Validation

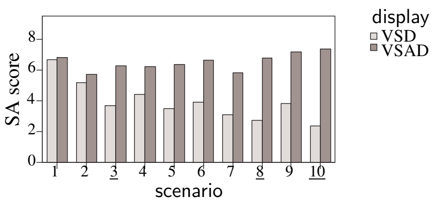
Comparison of VSD and VSAD. Figure 5-13 shows the SA and meta-cognition scores, averaged over all pilots, for all scenarios. Here, and in the following, the VSD and VSAD data are shown with the light-gray and gray bars, respectively. No confidence intervals are shown, any significant effect will be described in the text. The statistical significance of any trend is determined using Analysis of Variance (ANOVA), unless other specified. For the meta-cognition scores, horizontal lines at score levels 3 and 6 are shown. If the pilot answer to a particular SA query is incorrect, the meta-cognition score will always be lower than 3. If the pilot answer is correct, the score will range between 3 (pilot was 'unsure') to 9 (pilot was 'very sure'), see Table 5-5.

From Figure 5-13 it is clear that, generally, the SA and meta-cognition scores are (much) higher with the VSAD, as was hypothesized. Notable exceptions are scenarios 1, 2 and 6 at the 'perception' level, where the VSD scores are slightly higher. The same holds for the meta-cognition scores at the 'projection' level for scenarios 2, 3 and 5. With an exception of scenario 5, all these exceptions occurred in scenarios involving only one other aircraft.

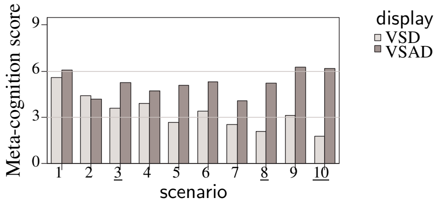
Because of the fact that any comparison between the VSD and VSAD would be unfair in scenarios 3, 8 and 10 (as here some of the intruder aircraft were invisible on the VSD), these data are excluded. Figure 5-14 shows the averaged (all scenarios except 3, 8 and 10) SA and meta-cognition scores at all three levels of SA, including the 'total' scores.

Figure 5-14 indicates that pilot SA is higher with the VSAD as compared to the VSD, at all levels of SA and meta-cognition. These effects were indeed 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.

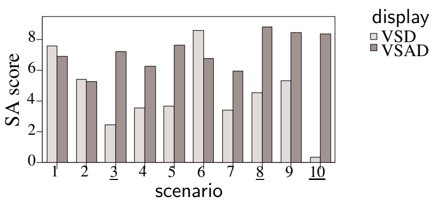
The benefits of the VSAD appear in particular at the levels of comprehension and projection, as was hypothesized. The fact that the meta-cognition scores are rather low with the VSD at these levels indicate that pilots often gave the wrong answer to SA queries that regarded a potential conflict's risk 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 6 ('fairly sure', see Table 5-5). This illustrates that, although the pilots' answers to the SA queries were generally correct



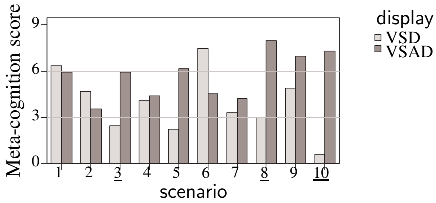
(a) SA total



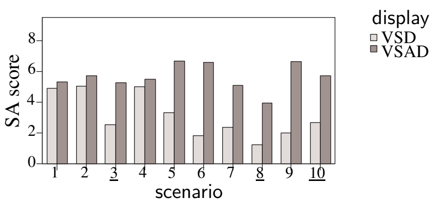
(b) Meta-cognition total



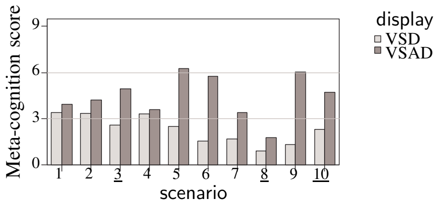
(c) SA perception



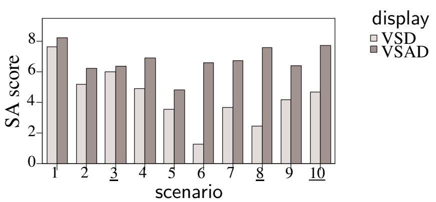
(d) Meta-cognition perception



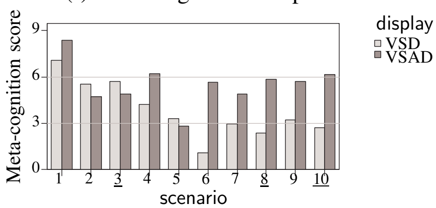
(e) SA comprehension



(f) Meta-cognition comprehension

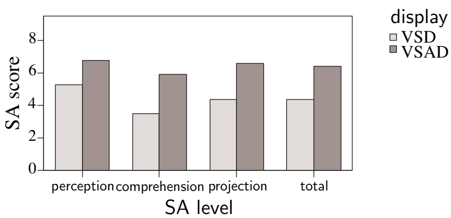


(g) SA projection

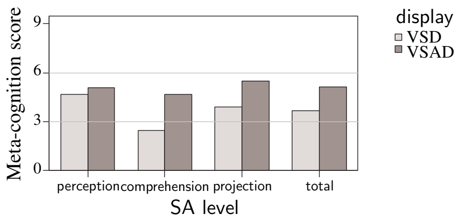


(h) Meta-cognition projection

FIGURE 5-13: SA and meta-cognition scores (all pilots, all scenarios).

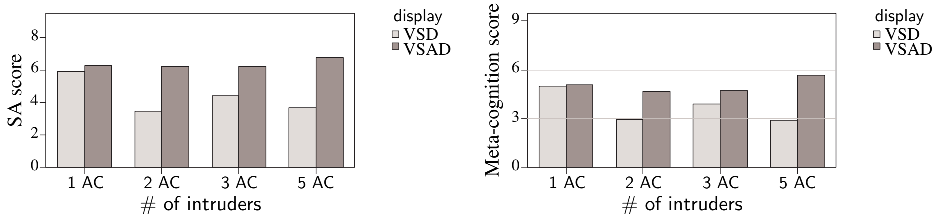


(a) Averaged SA



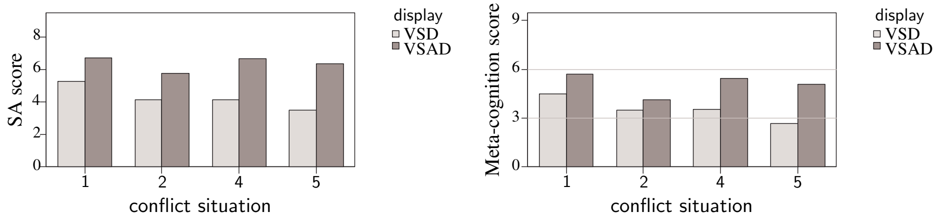
(b) Averaged meta-cognition

FIGURE 5-14: SA/meta-cognition scores, for all three SA levels (w/o scenarios 3, 8, 10).



(a) Averaged total SA (b) Averaged total meta-cognition

FIGURE 5-15: Total SA/meta-cognition scores, as a function of number of intruders (w/o scenarios 3, 8, 10).



(a) Averaged total SA (b) Averaged total meta-cognition

FIGURE 5-16: Total SA/meta-cognition scores, as a function of conflict situation (w/o scenarios 3, 8, 10).

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.

Figures 5-15 and 5-16 show the averaged total SA and meta-cognition scores as a function of the number of intruders (1, 2, 3 and 5 aircraft) and conflict situation (all except 3, the overtake maneuver), respectively. Note that when showing the data as a function of 'conflict situation', the scenarios with conflict situation 6 (resolution) are not analyzed separately; rather, the other occuring conflict situation (3 in scenario 3, and 1 in scenario 6) is taken as the reference.

Regarding the effects of number of intruders, a two-way ANOVA with 'display' and 'intruders' as fixed variables was conducted. For the display effect, Figure 5-15 shows that the total SA and meta-cognition scores are higher with the VSAD, a significant effect ($p < 0.001$ and $p = 0.011$ for SA and meta-cognition, respectively). What is also clear from Figure 5-15 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.

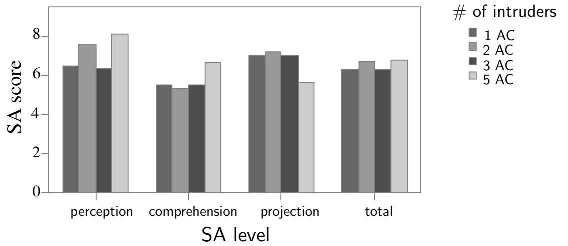
When considering the effects of the conflict situation, again a two-way ANOVA was done, now with 'display' and 'conflict' as fixed variables. Regarding 'display', Figure 5-16 shows that the SA and meta-cognition scores are higher with the VSAD, a significant effect (p <0.001 and p=0.002 for SA and meta-cognition, respectively). The largest differences occur in conflict situations 4 (multiple intruders) and 5 (no conflict).

Regarding 'conflict', the effects are less clear. Whereas for the VSD the scores tend to decrease when moving from conflict situation 1 to 5, with the VSAD the scores remain more or less the same, except for conflict situation 2 where all scores are slightly lower. The ANOVA showed that 'conflict' induced a significant effect for the meta-cognition scores (p=0.010), and no significant effect for the SA scores (p=0.057). The 'display $\times$ conflict' interactions were not significant for neither measure. Post-hoc analyses (SNK, α=0.05) indicated that none of the conflict situations yielded significantly different ratings. For the SA scores, only situations 1 (highest score) and 5 (low) differed significantly. For the meta-cognition scores, only situations 1 (highest) and 2 (low) were significantly different.

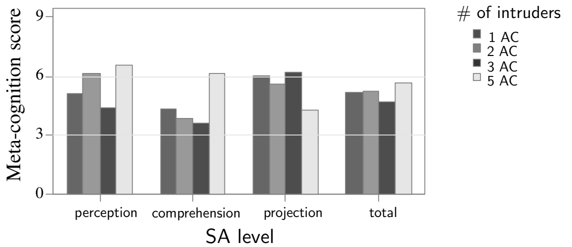
Additional VSAD analyses. Some additional analyses were performed for the VSAD display, using *all* scenarios. Figures 5-17 and 5-18 show the SA and meta-cognition scores, at all three levels and including the total values, as a function of number of intruders and conflict situation, respectively.

When considering the effects of number of intruder aircraft, a one-way ANOVA showed that the only significant effect occurs for the meta-cognition scores at the comprehension level (p=0.029), where, surprisingly, the scores are best for the situations with 5 intruder aircraft. Overall, Figure 5-17 shows that pilot SA scores were lowest at the comprehension level (average 5.6) and about the same at the perception (7.2) and projection (6.9) levels. Meta-cognition scores ranged between 4 and 7, indicating that pilots were on average unsure or only fairly sure of their answers to the SA queries.

The findings regarding the conflict situation, Figure 5-18, are similar. Although there are clearly lower scores for conflict situation 2 ('parallel maneuvers'), none of the visible effects were significant. The overtake conflict situations (3) resulted in the lowest scores at the comprehension level. These scores are partly caused by the fact that in scenario 3 (conflict situations 3 and 6 combined), most pilots did not appreciate the way in which the conflict was resolved. This is also a clear indication of the fact that with the VSAD, pilots can better judge the way in which a given

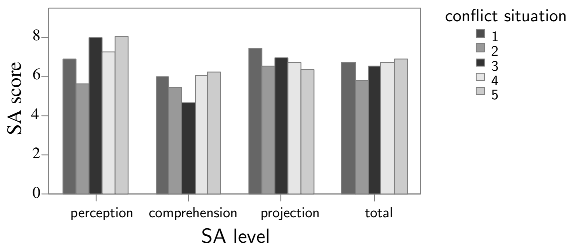


(a) Averaged SA

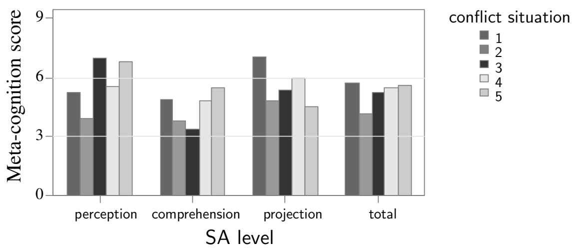


(b) Averaged meta-cognition

FIGURE 5-17: SA/meta-cognition scores, as a function of number of intruders (VSAD-only, all scenarios).



(a) Averaged SA



(b) Averaged meta-cognition

FIGURE 5-18: SA/meta-cognition scores, as a function of conflict situation (VSAD-only, all scenarios).

resolution maneuver satisfies their goals.

5-7 Discussion and Recommendations

5-7-1 Discussion

The VSAD display improved pilots' traffic situation awareness scores considerably. At all levels of perception, comprehension and projection, situation awareness scores increased. Pilots indicated that they better understand when they are in conflict, can better locate the intruder aircraft, and are better able to determine an appropriate resolution maneuver, not only to avoid the conflict but also to prevent other conflicts from occurring.

The highest influence of the VSAD is seen within the projection level, where it is determined what resolution maneuver would be preferred in the current situation. This is primarily due to the state vector envelope (SVE) representation, that shows the constraints imposed by the conflict geometries *in relation to* the own aircraft capabilities, the performance envelope. It is further shown that a larger number of intruder aircraft does not lower pilot subjective traffic SA with the VSAD. The effects of conflict situations on awareness scores are small with the VSAD, only during parallel maneuvers the scores slightly decrease.

Although the confidence level with the VSAD is still low, as judged by the meta-cognition scores, more training and hands-on experience is expected to increase this level considerably. The evaluation lasted less than two hours, and the large number of novelties in the VSAD overlays might have overwhelmed pilots.

5-7-2 Recommendations

First of all, the most important next step is to conduct flight simulator experiments where pilots are more actively involved in solving separation conflicts. Ultimately, the higher situation awareness demonstrated here should yield better pilot performance, in terms of efficiently maintaining safe separation with other traffic. Also more complex scenarios should be included in the experiment, involving more than one aircraft causing a conflict.[¶]

Second, despite its limited scope the current evaluation resulted in three useful recommendations by pilots for future designs. First and foremost, better ways must be found to attach more clearly the intruder aircraft to the belonging SVE. Second,

[¶]Note that in this respect, the horizontal complement of the current display allowed pilots to deal with these multi-aircraft conflicts very efficiently, [24, 26]. As Figure 5-9 illustrates, when more aircraft are near the own aircraft, either causing a conflict or not, at all times the SVE shows the set of maneuvering possibilities of the own aircraft that allows it to deal with *all* constraints imposed by all other aircraft.

implementing a color coding scheme is suggested to better indicate the difference between real conflicts and potential conflicts. Third, the short-term (ACAS-like) and long-term (ASAS-like) conflict support tools should be integrated together in one display, using similar symbology for clarification purposes of time and risk.

Another recommendation would be that, in the design of vertical situation displays, part of the display 'space' should be used to show 'what is behind' the own aircraft. The current standard, also adopted here, of having the own aircraft located at the left-most part of the display, prevents the presentation of traffic located *behind* the own aircraft, traffic that could impose constraints on the own aircraft locomotion. Although the VSAD conflict geometry overlay partly compensates for this missing information, as it presents the FBZs of aircraft located behind the own aircraft within the 5 minute conflict range, there is no possibility for pilots to check *what* aircraft are causing these FBZs. Figure 5-6 illustrates that, at least with the aircraft studied in this investigation, dedicating only a small part of the VSD to present 'over-taking' aircraft would already be sufficient. In this respect, the effects of other aircraft types, with different performance envelopes, on the required space should be analyzed.

Third, the SVE and FBZ calculations are currently based on several assumptions. For instance, the dynamic behaviour of both the own aircraft as well as intruder aircraft have not been included. Essentially this means that the SVE is not a completely accurate predictor of what maneuvers would yield a safe, productive and efficient conflict resolution. Simple kinematic models of aircraft climb/descent capabilities and acceleration and deceleration profiles should be included [52]. Note, however, that since the 5 minute prediction times frequently-used in separation assistance systems is very large, the effects of these dynamics are very small.

Fourth, it is recommended to better analyze the efficiency of resolving conflicts. That is, what exactly would be an 'optimal' maneuver, and how can the VSAD (in particular the SVE) help pilots in finding the optimal solution? Not all points on the legs of the forbidden beam zone are equally efficient, as was discussed by Van Dam et al. in their analysis of the horizontal complement of the current display [26]. But whereas the optimality of a resolution maneuver is relatively straightforward in horizontal flight, it is less simple in the vertical plane as it involves many more performance constraints. And obviously, ultimately the most optimal maneuver would be a truly three-dimensional resolution, involving simultaneous changes in heading, speed, and altitude.

Fifth, then, now that the vertical and horizontal constraints have been analyzed, what remains is the challenge to integrated them into a three-dimensional separation assistance display. The currently triangular shape of the FBZ then becomes a cone, and the conflict can be represented *both* on the ND and the VSD [27]. Attempts to integrate (parts of) these constraints in aircraft collision avoidance [53] and separation assistence [54] have already been reported.

Finally, note that our research did not address the question whether an ASAS interface design requires an explicit compelling advisory or not. In any case, an appropriate ecologically-inspired design alleviates the dependency on such an advisory. Besides increasing traffic awareness, providing pilots with a more profound layer of information is expected to better support them in dealing with a given problem, especially in cases where automated advices would unexpectedly fail.

5-8 Conclusions

Pilot traffic situation awareness scores improve significantly with the 'performance' and 'conflict geometry' overlays presented on the Vertical Separation Assistance Display. These ecological 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. However, 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 and more pilot experience 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. It is recommended to conduct an extensive flight simulator evaluation, where pilots are more actively involved in maintaining safe separation.

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6

Intent-based horizontal display design

In the previous chapters the 'state-based' XATP and VSAD interfaces all used trajectory and conflict prediction based on current *speed and heading of the own aircraft and the surrounding traffic. This assumption limits the applicability of the system as it does not use autopilot information such as the current speed or heading settings, neither FMS flight plan information. In this chapter, information on autopilot settings is used to enhance the presentation of ongoing intruder maneuvers, while the FMS Trajectory Change Points (TCP) are communicated over ADS-B to provide a better tactical image of the traffic situation according to each flight plan. We will analyse how* intent *information could enhance the state-based design and proposes an intent-based XATP design, and related maneuver strategies capable of supporting pilots in different aircraft control modes.*

Paper title The Use of Intent Information in an Airborne Self-Separation Assistance Display Design

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ABSTRACT

In the context of future airspace organization, an ecological pilot support tool for state-based airborne self-separation in cruise flight in the horizontal plane was developed and evaluated. The design visualizes tactical maneuvering constraints in a speed-heading vector 'action space'. This paper describes how Target State (TS) and Trajectory Change Point (TCP) intent information of the own aircraft and the surrounding traffic reshapes the typical conflict geometry used to present tactical maneuver constraints of the own aircraft. The 'time-circle' technique is used to determine whether own aircraft maneuvers will make both aircraft pass each other 'before' or 'after' the TS or TCP maneuver occurs. The 'ghost image' technique is used to correctly visualize the conflict geometry for the situation after the TS or TCP maneuver. Furthermore, it is also discussed how these maneuver constraints should be mapped on the Navigation Display so that pilots can be aware of the effect of aircraft mode control changes on the constraints. As a result an intent display concept is presented that helps pilots to effectively deal with both state-based and intent-based 'FMS-enabled' conflict situations across different aircraft control modes.

Nomenclature

$ASAS$	Airborne Separation Assurance System
$(X)ATP$	(eXtended) Airborne Trajectory Planning
CPA	Closest Point of Approach
EID	Ecological Interface Design
FBZ	Forbidden Beam Zone
FCU	Flight Control Unit
FMS	Flight Management System
MCP	Mode Control Panel
ND	Navigation Display
$POST$	trajectory after TCP
PRE	trajectory before TCP
PZ	Protected Zone
TCP	Trajectory Change Point
TCR	Trajectory Change Report
TSR	Trajectory State Report
SVE	State Vector Envelope
Subscripts	
int	intruder aircraft
own	own aircraft
rel	relative
on	FMS on, MCP-FCU mode
off	FMS off, FMS-RNAV mode

6-1 Introduction

In future airspace environments [1, 2], aircraft will fly more autonomously and would be allowed to fly a 4D trajectory of their choice. In certain parts of the airspace unmanaged by Air Traffic Controllers, pilots will be responsible for separating their own aircraft from others. Under these conditions, pilots need support for airborne self-separation. At Delft University of Technology an interface was designed, the eXtended Airborne Trajectory Planning interface, XATP for short, to support airborne self-separation embedded into tactical trajectory (re)planning support. The design is inspired by the Ecological Interface Design framework [3]. The interface visualizes which maneuvers will prevent a Loss of Separation while not causing new conflict situations. The design assumes general definitions for conflicts and airborne self-separation [1, 2, 4, 5] including a 5NM horizontal *separation* and a 5 minute look-ahead horizon for conflict detection.

The resulting interface distinguishes itself from more traditional designs in two ways. First, it shows maneuver constraints rather than an explicit conflict resolution. Hereby it preserves the 4D planning freedom and allows integration with other planning constraints. Second, the constraints are presented in an aircraft speed vector space. This presentation integrates velocity and heading constraints, enabling the pilots to efficiently resolve and prevent conflict situations in a coordinated fashion. Details about the EID aspects and pilot experiments can be found in previous publications [6–10]. A display design for the vertical design and a general overview of how the EID framework is applied to vehicle motion problems is presented in the following publications [11, 12].

In the state-based XATP system, only *state* information of the surrounding aircraft is retrieved through use of ADS-B technology [13]. This means that the display presentation is based only on current velocity and heading of the own ship and of surrounding traffic. However, ADS-B technology can also be used to exchange *intent* information with nearby traffic. In this design study, intent information is taken into account in the form of the ADS-B Target State (TS) report, informing about ongoing aircraft maneuvers, and Trajectory Change (TC) reports, informing about planned maneuvers in the future according to the FMS information [14]. Using the state-based XATP display as a basis, intent information will be used to enhance the already existing speed-heading vector overlay of tactical maneuver constraints [6]. As will be discussed in Section 6-4, the vector 'time circle' and 'ghost image' techniques are used in order to account for the effect of including information on the intruder TS (TS_{int}) and Trajectory Change Point (TCP) (TCP_{int}), and the own aircraft TCP TCP_{own}, on the calculation and presentation of maneuver constraints.

Along the lines of the ecological approach and Gibson's direct perception-action coupling [15], the main purpose of enhancing the maneuver constraints is to present them in such a way that pilots can directly perceive whether the trajectories of the own aircraft and the surrounding traffic will cause a conflict, and if so, perceive which pilot maneuver actions can be done to resolve the situation effectively. Introducing FMS enabled flight in the tactical navigation work domain introduces a new dimension to the pilots action space in the sense that the pilot makes aircraft control mode changes, e.g., going from trajectory control to target state control, Figure 6-1. When the FMS of any aircraft is disconnected, this 'mode change' action discretely and instantly changes the predictions on aircraft motion. Special attention will be given to make pilots aware of the effect of FMS mode changes on the conflict situation 'before' the control action is done, i.e., before the FMS is (de)activated. Given the tactical, and therefore time-critical nature of the navigation support tool, the manipulation of the flight plan Trajectory Change Points (TCP) points using the

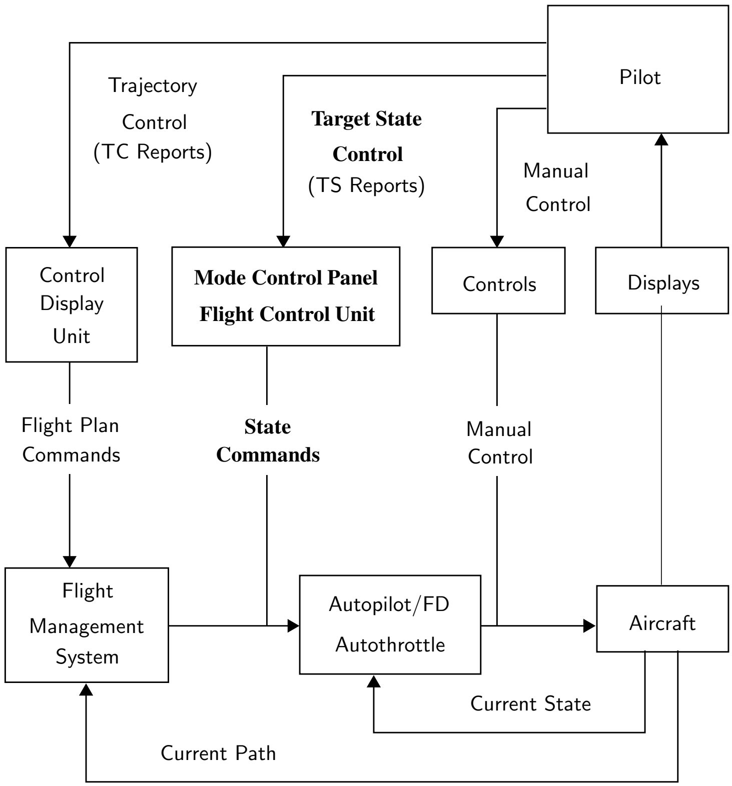


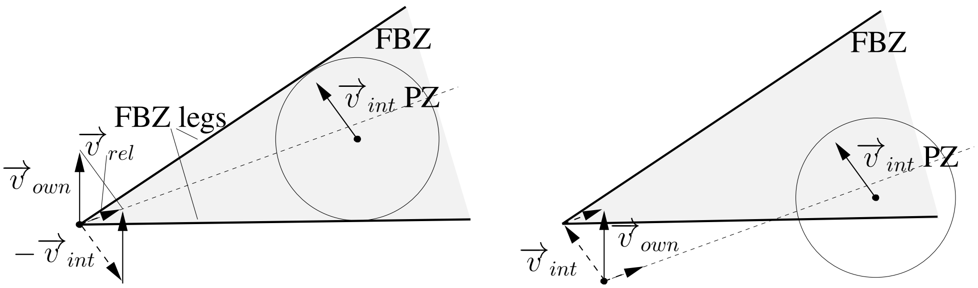
FIGURE 6-1: The three aircraft control states: (1) Manual Control; (2) Target State Control, and (3) Trajectory Control [14].

Control Display Unit is not considered in this work. For the same reason and also to avoid excessive complexity at this stage of research, only the first TCP of each FMS path is considered.

In the next section the basic no-intent design is discussed. Then the ADS-B Trajectory Change (TC) and Trajectory State (TS) reports are detailed and the terminology for intent is given. In the work domain analysis, details are given on the work domain boundaries, the conflict resolution task, the effect of TS and TCP information and aircraft control mode changes on the maneuver constraint geometry, the Forbidden Beam Zone (FBZ). The findings of the analysis are used to come up with an enhanced mapping symbology of the FBZ maneuver constraints on the XATP-intent interface design. An adapted pilot action strategy allows pilots to effectively work with the display in both Trajectory control mode, FMS_{on}, and TS control mode, FMS_{off}.

6-2 The state-based XATP system

The current version of the no-intent design is called the eXtended Airborne Trajectory Planning (XATP) [7] and only works in the horizontal plane. A complementary design has been made for the vertical plane in order to integrate both dimensions [11]. The basic concept of ATP is to display which combinations of heading and speed will result in an intrusion into the intruder's Protected Zone (PZ) and at what time such an intrusion would happen. If a conflict situation is triggered, pilots should choose a proper speed-heading combination that resolves the conflict situation without creating new ones. In this context a conflict is defined as a predicted *loss of separation* within the next five minutes.



(a) Calculating FBZ in relative plane.

(b) Translation of the FBZ to the absolute plane.

FIGURE 6-2: Calculation and translation of the Forbidden Beam Zone (FBZ).

6-2-1 Conflict representation

The conflict constraint calculations of (X)ATP are primarily done in the relative plane, Figure 6.2(a). By subtracting the speed vector of the intruder aircraft $\vec{v}_{int}$ from the own speed vector $\vec{v}_{own}$ the relative speed $\vec{v}_{rel}$ is calculated. If this vector lays within the 'legs' of the Forbidden Beam Zone (FBZ), at some point in the future an intrusion will happen, unless action is taken that moves this vector outside the FBZ. Because it is not intuitively clear for pilots how to change the relative speed, the FBZ is translated by the speed vector of the intruder aircraft, thereby mapping it onto the absolute velocity plane, Figure 6.2(b). This translates the relative speed vector changes $\vec{v}_{rel}$ into absolute speed vector changes $\vec{v}_{own}$ and pilots can see which absolute vector changes result in avoidance of the FBZ. The point where the two FBZ legs meet is called the 'origin' of the FBZ. The location of the origin is determined by the intruder aircraft speed vector and therefore the intruder aircraft speed and heading are implicitly presented through the location of the FBZ origin.

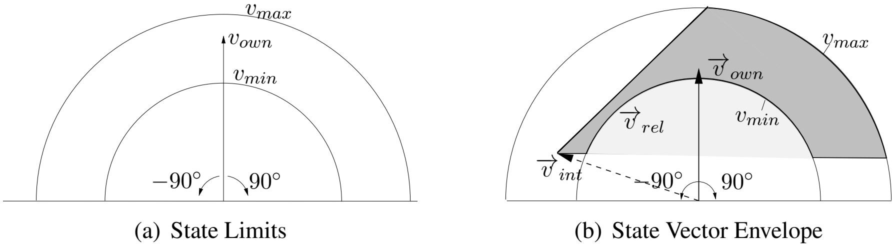


FIGURE 6-3: Adding performance boundaries to the state vector space (left) yields the State Vector Envelope (SVE) (right).

A maneuver of the intruder can be deduced from the translation of this origin. The direction of the FBZ legs indicates where the intruder aircraft that creates the FBZ is located relative to the own aircaft position.

In Figure 6.3(a), the options to change the own speed vector are further constrained. The speed of the own aircraft is limited by the constraints introduced by the flight envelope. These are shown as circular boundaries. The need to fly "towards" the destination of the aircraft excludes heading changes of more than 90 degrees away from the heading towards the destination. If the FBZ is clipped using these limits, the State Vector Envelope (SVE) is created.

At this point it is important to distinguish the FBZ from the SVE. The SVE is an 'action state space' or maneuver space upon which work domain constraints are mapped. In this case a predicted loss of separation is mapped on the SVE by means of the FBZ shape. Looking at the constraints mapped in the action state space, a desired conflict-free 'state' can be chosen and realized by manipulating the own speed vector $\vec{v}_{own}$ out of the FBZ.

In practice such a manipulation is a heading and/or speed change, and accomplishing this change will take time due to aircraft dynamics. During this time both aircraft move and the shape of the FBZ becomes wider as the aircraft approach each other. To account for turn maneuvers, XATP includes the turn dynamics into the calculation of the FBZ legs assuming turns implemented by an autopilot [7].

6-2-2 Interface mapping

In Figure 6-4 the state-based XATP system is shown. The SVE is mapped onto the ND at the own aircraft position. In other words, a speed vector overlay is layered on the ND plan view position space. Around the intruder aircraft symbol an outer circle is plotted representing the PZ. This circle scales when the display is zoomed in or out. The PZ is colored according the predicted time to loss of separation for the current speed $\vec{v}_{own}$ (orange and red, representing cases of less than 5 or 3 minutes

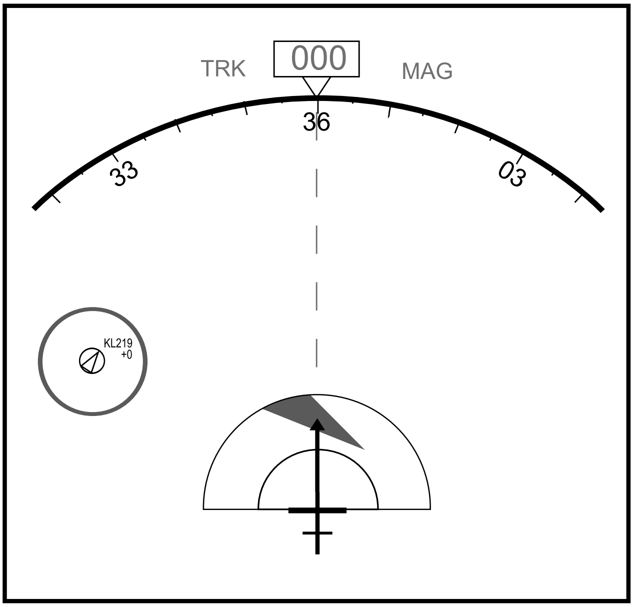


FIGURE 6-4: The state-based XATP display with State Vector Envelope (SVE) mapped onto the ND at the own aircraft position.

to intrusion, respectively). If no conflict exists, i.e., $\vec{v}_{own}$ is located outside the FBZ, the FBZ area is filled in gray and the intruder PZ is outlined in gray too. The inner icon indicates aircraft heading, and points in the direction where one can find the origin of the related FBZ on the SVE. Multiple conflicts result in multiple FBZs, mapped onto each other allowing the pilot to resolve all conflicts with one maneuver (moving out of FBZs), and prevent the creation of new conflicts [6].

6-2-3 Intent information to communicate a maneuver strategy

In order to resolve and prevent conflicts in a safe and efficient way, i.e., to minimize total path deviation from the original trajectory while safely resolving the conflict, a maneuver strategy can be specified. When a conflict is detected, pilots move the speed vector $\vec{v}_{own}$ out of the FBZ. The following maneuver strategy rules apply: [6]

- Minimize the state change (maneuver), i.e., "shortest-way-out"-principle,
- Stay away from FBZ origins,
- Avoid entering other FBZs (do not trigger new conflicts).

Since the "shortest-way-out"-principle also assures implicit coordination in one-to-one conflicts, single conflicts are always geometrically symmetrical. By staying away from the FBZ origin, the relative approach speed towards the intruder, $\vec{v}_{rel}$, is kept away from zero. This strategy rule encourages the selection of a fast 'crossing' maneuver over a slow 'parallel' maneuver, hereby promoting a low time to Closest Point of Approach (CPA), a fast return to the desired path.

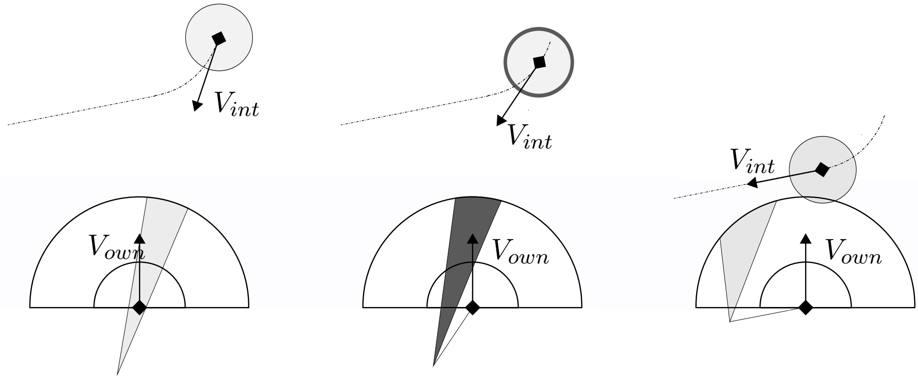
Because the XATP motion model uses the AP turn characteristics for motion prediction, the exact edges of the FBZ are shown. This means pilots are sure to enter and leave the FBZ without losing separation if, (1), the FBZ edge lies within the SVE envelope boundaries at the moment the crossing maneuver is initiated, and (2), the intruder aircraft will not make any counteractive "hostile" maneuver. However, the maneuver strategy, as used in the no-intent interface, does not allow to temporarily trigger a conflict situation in order to cross the FBZ, since a state-based system can not inform the maneuver intent to other aircraft in the surrounding, i.e., pilots are unable to identify safe maneuvers that temporarily trigger a conflict from dangerous or hostile maneuvers that trigger real conflict situation.

6-2-4 The need for intent information

A similar problem is described for the traffic situation sketched in Figure 6-5. According to the FMS planned trajectory, the intruder will make a Fly-By turn at the TCP waypoint. A typical situation were this kind of aircraft behavior can be expected is at the transition to/from controlled airspace nearby entry/exit points. Moreover, the intruder aircraft reaches its TCP point before both aircraft pass by each other, i.e., before the Closest Point of Approach (CPA)* is reached. Looking at the FBZ constraint before, during and after the TCP turn, there is no conflict situation before or after the turn maneuver of the intruder, Figures 6.5(a) and 6.5(c). During the turn maneuver however, the speed vector enters the FBZ, Figure 6.5(b). When this happens, the pilot of the own aircraft could consider this intruder action as hostile, and could counter-act by steering the speed vector away from the FBZ, i.e., initiate a turn to the left. This would cause the SVE to remain similar to Figure 6.5(b) as long as the intruder is turning. If the pilot would be aware of the intent of the intruder turn maneuver, he or she would not react.

It is clear that the present state-based system should be enhanced with information that enable pilots to deal properly with initiated or ongoing maneuvers as well as with future trajectory changes of both the own aircraft and the surrounding traffic. This calls for the inclusion of TC and TS report information into the representation of maneuver constraints used in the XATP system. The following section

*The Closest Point of Approach is defined as the position of a trajectory where the subject aircraft is closest to the intruder aircraft. If the distance between the intruder aircraft and the CPA is smaller than the separation minima, separation will be lost. A more informal way to address this point is the point where both aircraft 'pass each other'



(a) before TCP turn (b) during TCP turn (c) after TCP turn

FIGURE 6-5: SVE images before, during and after the TCP turn as shown on the state-based XATP display: (a) intruder starts a turn, (b) due to the ongoing turn, the FBZ translates so that a conflict exists, (c) by the end of the turn the FBZ has already moved far away from the own vector and the conflict is resolved.

describes the available ADS-B technology and explains some intent terminology used throughout the paper.

6-3 ADS-B and Intent Terminology

ADS-B transponders are used to enable airborne data communication between aircraft in the same vicinity. In addition to current state information, the messages can also contain intent information. The transmitting aircraft must support ‘FCU-MCP’ TS mode to acquire information for TS commands and ‘FMS-RNAV’ trajectory control mode to get the flight plan information. The requirements regarding the message contents are laid down in an RTCA report [14] and are used as a general guideline here. Based on the technical specifications, it is assumed plausible that the capacity and update rates of the system are sufficient to properly support an intent-based separation assistance tool. There are multiple types of data messages that are sent through ADS-B. Aircraft state reports include actual position and speed information that is used by the state-based XATP system. For intent messages, two message types exist. First, the Trajectory Change (TC) report gives information on the aircraft FMS flight plan. The Target State (TS) report provides information about the aircraft target state commands, for example, target heading entered by the pilot in order to make an autopilot controlled turn. Figure 6-1 presents an overview of aircraft control states [14].

6-3-1 Trajectory Change (TC) and Target State (TS) reports

The FMS system maintains a detailed flight plan and has a navigation aid database that contains intent information in the form of trajectory waypoints. A part of the flight plan can be transmitted using ADS-B in a 'TC report' The information of a waypoint is detailed in a so-called 'Trajectory Change Point'(TCP), and TC reports can contain up to four TCPs. TC report cycle numbers make it possible to distinguish between TCPs and they define the sequence order of the waypoints for reconstructing the flight trajectory. Table 6-1 lists the elements provided in a TC report. Included are waypoint elements such as Time-To-Go, position, turn radius, track to TCP, track from TCP, and the command/planned flag for different TC types, e.g., a Fly-By turn or a Direct-to-Fix transition. TC reports can only be sent when the FMS is enabled and the aircraft is flying in accordance with the flight path depicted by the FMS. In case the pilot uses the the FCU-MCP to command a autopilot maneuver, the FMS flight plan is automatically disabled. From this moment on, all TC reports are still sent out but have the flag type set on 'Planned' instead of the 'Command' indicating that the FMS has been disengaged and the listed TCP points are not 'active' anymore. With the FMS disabled, additional TS reports are sent out, containing the MCP target heading. When the pilot updates and activates the FMS again, the TS reports are suspended. The elements of a TS Report are also given in Table 6-1.

6-3-2 Intent terminology

Throughout the paper the trajectory parts of the own and intruder aircraft will be labeled as shown in Figure 6-6. Aircraft control modes are described as follows: FMS$_{int}$(on) refers to the intruder aircraft flying FMS enabled. Alternatively, this is called FMS-RNAV mode or trajectory control mode. FMS$_{own}$(off) refers to the own aircraft flying FMS disabled, also referred to as MCP-FCU mode or TS control mode.

The acronym PRE refers to the trajectory part before the TCP is reached. PRE$_{int}$ refers to the intruder trajectory before the TCP point is reached according the FMS plan, FMS$_{int}$(on). POST$_{own}$(off) refers to the own trajectory after the TCP that would be flown if the own FMS would be disabled, FMS$_{own}$(off). POST$_{int}$(on) refers to the intruder's trajectory after the TCP when the intruder would fly FMS enabled, FMS$_{int}$(on). Using the definition for trajectory parts, the own aircraft can theoretically lose separation with the intruder aircraft for nine different path encounter combinations, listed in Table 6-2. However, for a given traffic situation geometry, only a few encounter types can occur. For the traffic situation of figure 6-6, type 5, 6, or 8 can possibly occur. Throughout this paper FBZ areas are often labeled with these numbers.

TABLE 6-1: Selection of Trajectory Change (TC) and Target State (TS) Report elements (adapted from RTCA [14]).

	Element	TC Content	TS Content	Bits
ID	1	Participant Address	idem	24
	2	Address Qualifier	idem	
TOA	3	Time of Applicability	idem	6
TCR number	4	TCR sequence number		2
TCR version	5	TCR cycle number		6
TTG	6	Time To Go	idem	6
Horizontal	7a	Data available and TC Type	Target Source Indicator	2
information	7b	TC Latitude	Target Heading or Track Angle	16
	7c	TC Longitude	Target Heading or Track Indicator	16
	7d	Turn radius	Mode Indicator	8
	7e	Track to TCP	-	8
	7f	Track from TCP	-	8
	7g	Command/planned flag	-	1
Vertical	8a	Data available and TC Type	Target Source Indicator	2
information	8b	TC Altitude	Target Altitude	12
	8c	TC Altitude Type	Target Altitude Type	2
	8d	Vertical Command/Planned Flag	Mode Indicator	1

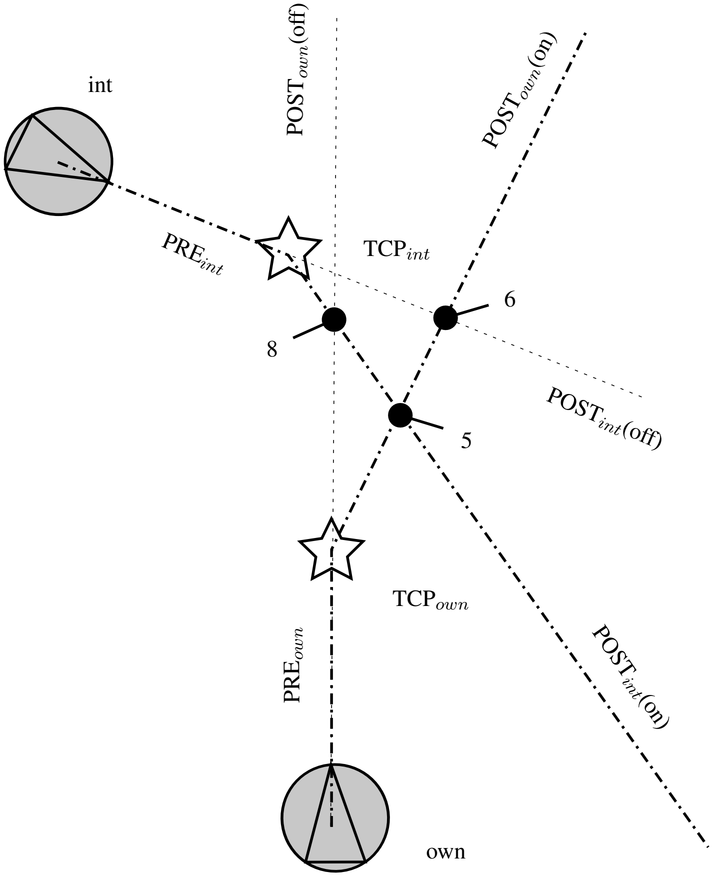


FIGURE 6-6: Conflict situation with intent for both aircraft. Geometry and definition of trajectory. PRE refers to the trajectory before the TCP is reached. POST(on) refers to the trajectory after the TCP point according the FMS plan, FMS(on). POST(off) refers to the trajectory after the TCP that would be flown if the FMS would be disabled, FMS(off).

TABLE 6-2: Matrix of flight path encounter types indexed by the trajectory parts of own and intruder aircraft, as given in Figure 6-6.

		OWN		
		PRE_{own}	POST_{own}(on)	POST_{own}(off)
	PRE_{int}	1	4	7
INT	POST_{int}(on)	2	5	8
	POST_{int}(off)	3	6	9

6-4 Work Domain Analysis (WDA)

For the state-based XATP design a work domain analysis has been made. The Abstraction Hierarchy (AH) was used as a tool to identify and relate functions and constraints of the work domain that shape the behavior of the worker. The reader is referred to previous publications for further details on the AH, see [6, 7]. In this paper the domain analysis will focus specifically on the effect of including intent information on the visualization of the FBZ maneuver constraints and the effect of using aircraft control mode changes.

Before the domain analysis is detailed, however, the pilot work and the work domain boundaries have to be specified. The work being analyzed in this paper is tactical navigation in the horizontal plane during cruise flight with initially all aircraft flying FMS enabled. As stated in the introduction because of the tactical time horizon and also to limit the complexity of the design challenge, only one future TCP waypoint for each aircraft will be taken into account in the analysis. It is assumed that pilots fly FMS(on) mode while they are confronted with a conflict situation. At all times all aircraft are allowed to disengage the FMS and can enter TS commands on the MCP.

The pilot task consists of the on-board path (re-)planning of speed and turn maneuvers, with the main goal of separating themselves from other traffic in the vicinity. After analysis of the situation, the pilot has three options to deal with the situation:

- the pilot does not act and continues to fly with the FMS enabled;
- the pilot disengages the FMS, but does not give any TS Commands on the MCP; and
- the pilot gives State Commands on the MCP and hereby the FMS is automatically disengaged.

When the conflict is resolved and both aircraft have passed each other, the pilot will initiate the path recovery maneuver by flying a Direct-to to the closest TCP waypoint on the FMS flight path. Updating and activating the FMS again are left out of the scope of this paper, but should be included in future research.

The interface should, regardless of which active control mode is present, always show ‘separation’ in direct relation with the pilot action space. The FBZ constraint areas should therefore show the separation problem, or conflict, in such a way that:

- In both FMS modes, the pilot are aware of the conflict status (perception);
- In both FMS modes, the pilots are aware of which actions can effectively solve the conflict situation without triggering a new one (action).

In the context of pilot action capabilities, the main difference with the state-based work domain is that pilot control actions are not limited to aircraft maneuvers in the form of continuous velocity vector state changes. Also aircraft control mode changes have an effect on the conflict situation as they change the motion path calculations for the aircraft. A mode change instantly causes a discrete ‘jump’ in the predicted trajectory as intent information that governs the FBZ constraints discretely changes. For example, the deactivation of the intruder’s FMS can instantly trigger or resolve conflicts, displace and/or (un)hide FBZ areas on the SVE. Direct perception-action coupling of separation is realized by showing how disengaging the FMS affects the appearance of the FBZ maneuver constraint areas. In other words, to allow for anticipation, the effect of the control change should be perceivable before the actual mode change is made.

In the following section, it is analyzed how a TCP_{int} affects the calculation of FBZ maneuver constraints. In continuation, the effect of introducing TCP_{own} is investigated. Using TCP_{int} or TCP_{own} trajectory information in the calculation of FBZ areas, it will become apparent that different types of FBZ constraint areas exist. The characteristics of the FBZ area depend on the trajectory part it refers to and the aircraft control mode that is currently active. The last section of the work domain analysis will therefore set up a typification of FBZ areas, which can be used as a basis for a new mapping symbology for the FBZ constraints on the interface.

6-4-1 The effect of intruder Trajectory Change Points (TCP)

The traffic situation as sketched in Figure 6-5 is used to explain the problem of FBZ constraint calculation when intent information is used. It shows how the intruder turn maneuver will translate the FBZ with respect to the current situation. Calculating the constraint area for the actual situation using the calculations and visualization of the state-based XATP system would normally result in the SVE given in Figure 6.5(a). However, within the SVE state space there are vector states of V_{own}

that will result in a situation where the intruder reaches the TCP before both aircraft pass each other, i.e., $t_{TCP} < t_{CPA}$. In that case the FBZ will translate during the turn maneuver, Figure 6.5(b), and after the turn will it will look like Figure 6.5(c).

If, on the contrary, a state vector V_{own} is chosen that results in a situation where both aircraft pass each other *before* the intruder changes heading, i.e., $t_{TCP} > t_{CPA}$, then the state-based constraint area can be used, Figure 6.5(a). ¿From the above, it becomes apparent that the speed-heading SVE vector space in which the maneuver constraint area (FBZ) is drawn should be split up in two types of areas. One area represents the speed-heading states that will result in both aircraft passing each other before the intruder turns. In this area the original FBZ of Figure 6.5(a) will be drawn. The other area represents the speed-heading states that make both aircraft pass each other after the intruder turns, and would contain an FBZ *similar* to the one presented in Figure 6.5(c).

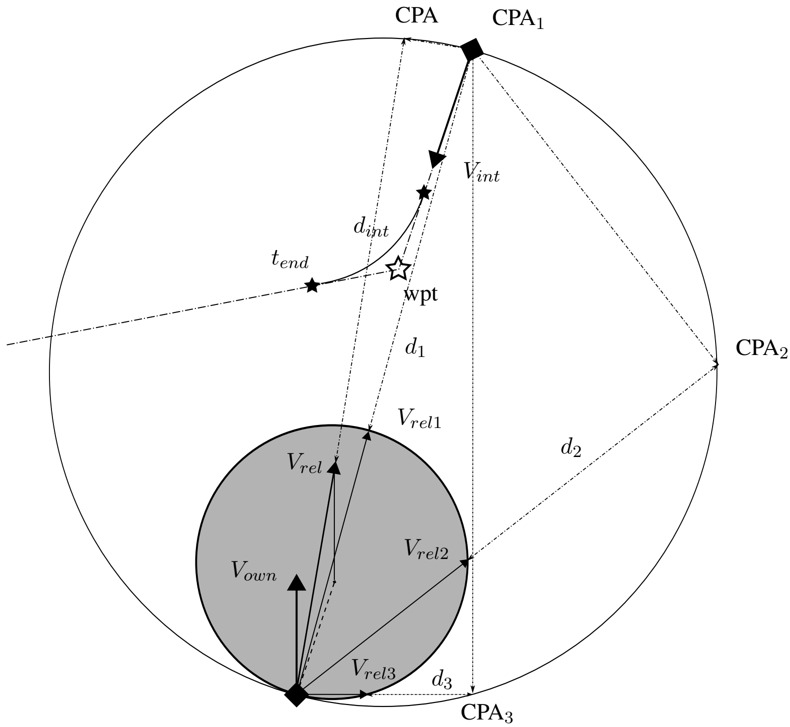


FIGURE 6-7: Calculation of the time-circle that represents the situation where t_{CPA} equals t_{TCP}, in relative velocity space, with the intruder position fixed.

The time circle technique. Figure 6-7 describes the same traffic situation as shown in 6-5. The geometrical relationships of the conflict are analyzed in order to find a useful description for the boundary where t_{CPA} equals t_{TCP}. Note that this situation is drawn in the relative plane, thus the position of the intruder is "frozen".

The large circle in Figure 6-7 is the collection of all CPA points that correspond to all directions of v_{rel} that go *towards* the intruder position. This collection of all CPA points contains both the positions of the intruder and the own aircraft, i.e., the diameter of the circles equals the distance between both aircraft. Each CPA point on that circle can be reached with any V_{rel} in the proper direction, however, only those V_{rel} that correspond with a situation where the CPA is reached at t_{CPA}. If for all possible directions, the related V_{rel} is drawn again a circle appears connecting the vector endpoints, the smaller circle in Figure 6-7 results. Note that the FBZ as shown in Figure 6.2(a) is also calculated in the relative velocity plane, and thus this small circle can be applied to break up the SVE in two zones. The small circle is defined as the 'time circle' throughout this paper.

Equation 6-1 expresses the geometrical relation between V_{rel} and the location of the TCA:

$$\frac{V_{int}}{d_{int}} = \frac{V_{rel,i}}{d_i}, \qquad (i = 1, 2, 3) \tag{6-1}$$

V_{int} is the intruder velocity, d_{int} is the distance from the intruder to the TCP along the flight-path, $V_{rel,i}$ is the relative velocity for $t_{TCP} = t_{CPA}$, and d_i is the distance to the CPA point. The vector $V_{rel,1}$ in Figure 6-7 is the vector that defines the time-circle. $V_{rel,1}$ has a CPA point, CPA_1 that lies exactly on the position of the intruder aircraft, leading to a course with a CPA distance of 0, i.e., a direct hit. If $V_{rel,1}$ is taken, this collision will occur exactly on the TCP. $V_{rel,1}$ can easily be obtained from equation 6-2. From the geometrical relations in Equation 3-1 it follows that:

$$\frac{V_{int}}{d_{int}} = t_{TCP} \equiv t_{CPA} = \frac{V_{rel,1}}{d_1} \tag{6-2}$$

The intruder time to TCP is known from the TC reports (TCR). Since the distance between both aircraft is the sum of d_1 and $V_{rel,1}$, the only unknown in the equation is $V_{rel,1}$. $V_{rel,1}$ defines the diameter of the time-circle and therefore the boundary geometry by means of the time circle is known.

Pre-TCP calculation using the 'time circle'. The time-circle can now be translated to the absolute velocity plane to fit in the SVE. The intersection with the "original" FBZ, i.e., the FBZ valid for the trajectory until TCP_{int}, indicates which part of the FBZ applies to the current situation. When the tip of the own speed vector is inside the circle, the own aircraft will reach the CPA after the intruder has made the turn at TCP_{int}. The area outside the circle represents all possible velocity vector solutions where CPA is reached before the intruder reaches TCP_{int}. Figure 6.8(a) shows how the constraint area is presented in the SVE.

Post-TCP calculation using the 'time circle' and the 'ghost image' technique. To come up with the FBZ constraint shape related to the situation after the intruder has turned over the TCP, a ghost image position needs to be calculated, Figure 6.8(b). The time-circle can now be calculated using the ghost position instead of the current position of the intruder.

In the example situation, the own speed vector is inside the circle. In this case the TCP will be reached before the CPA and the velocity state of the intruder at the end of the transition must be taken into account to be able to predict, calculate and visualize the constraint area with that velocity state. To calculate the constraint area in the SVE that belongs to this velocity state in current time, calculate the position back in time using the velocity state at the transition end-point. In other words, create an image at present time as if the intruder would have always flown on the flight-path it will fly after the transition end-point. Figure 6-9 shows the geometry and the resulting constraint areas in the SVE. The SVE shows that neither before nor after the intruder's TCP turn there will be a conflict. Figure 6.5(b) shows that the system without intent information reports a conflict during the turn maneuver.

6-4-2 The effect of intruder Target State (TS) information

The ghost image technique can be equally used during ongoing intruder turn maneuvers. Using the target state heading value, the related turn can be calculated. From the turn end point a ghost image can be made. The FBZ of the ghost image can be used to show the own pilot how the maneuver constraints are affected by the TS maneuver of the intruder aircraft. Figure 6-10 shows a sketch of the SVE during a turn maneuver. Such a maneuver could be expected when the intruder aircraft needs to handle a conflict with a third aircraft. The blue FBZ represents the FBZ of the ghost image where as the red FBZ is layered below it to show the location of the original state-based FBZ. Using the state-based FBZ, a conflict will be temporarily triggered between the actual time and the end of the turn maneuver.

6-4-3 The effect of the own TCP-point

In the same way as in the above sections, calculations for the time-circle and FBZ-areas can be made to visualize the effect of own intent information. Figure 6-11 shows screenshots of a traffic situation where the own aircraft will turn to the left. In Figure 6.11(a) information and drawings were added to show how the 'ghost image' of the 'own' aircraft is constructed in the same way as it was showcased for the 'intruder' aircraft in Section 6-4-1. A ghost-SVE is shown located at the

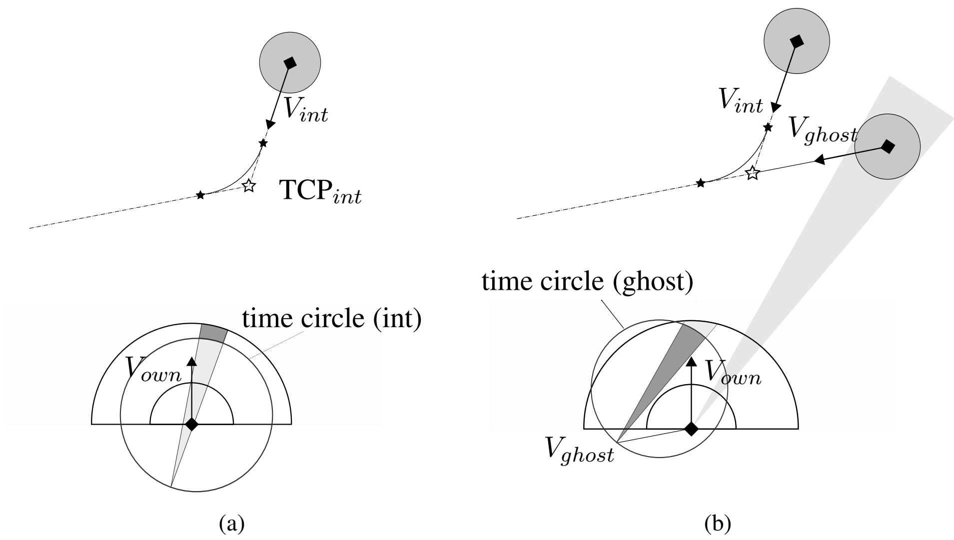


FIGURE 6-8: TCP_{int}: Calculation of FBZ areas for (a) PRE_{int} and (b) POST_{int}(on) trajectory parts using time-circle and ghost image technique.

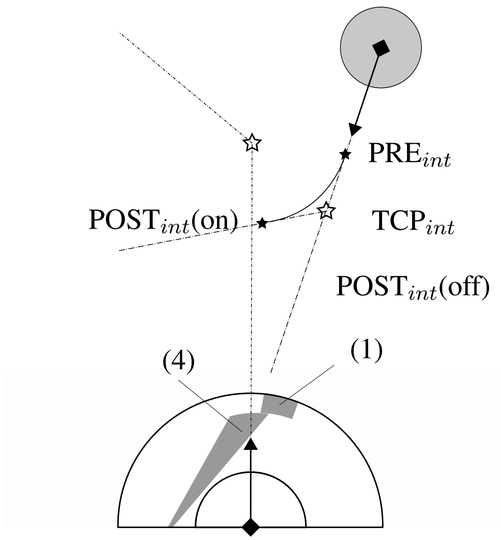
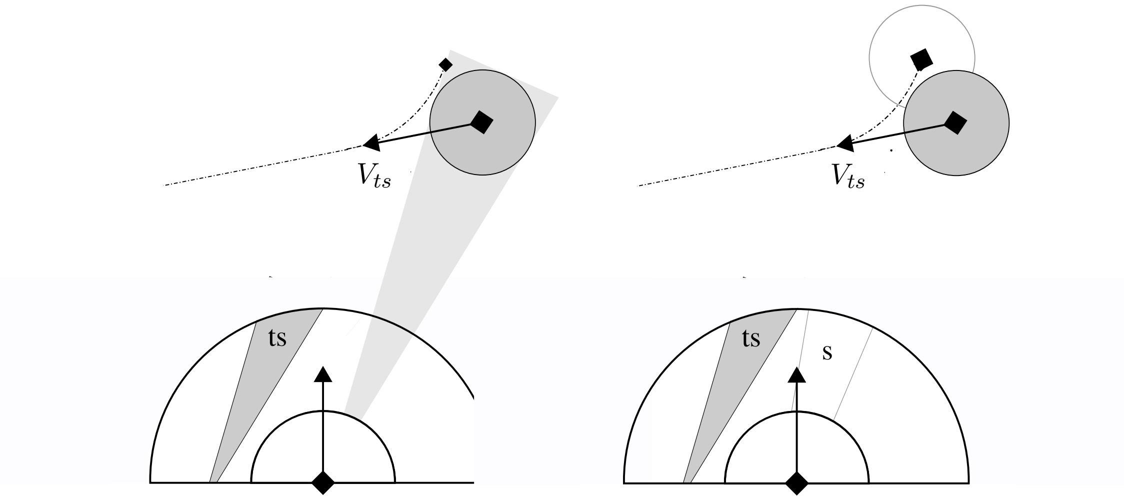


FIGURE 6-9: TCP_{int}: Both FBZ constraint areas are mapped on the SVE. FBZ area types (1), (4) are shown , area type (7) remains invisible in the state-based XATP interface mapping, see Table 6-2 for area type definitions. (1) refers to the intruder trajectory before turn, PRE_{int}, (4) refers to the intruder trajectory after the turn when following the FMS trajectory, POST_{int}(on).



(a) Calculation of FBZ based on Target State ghost image

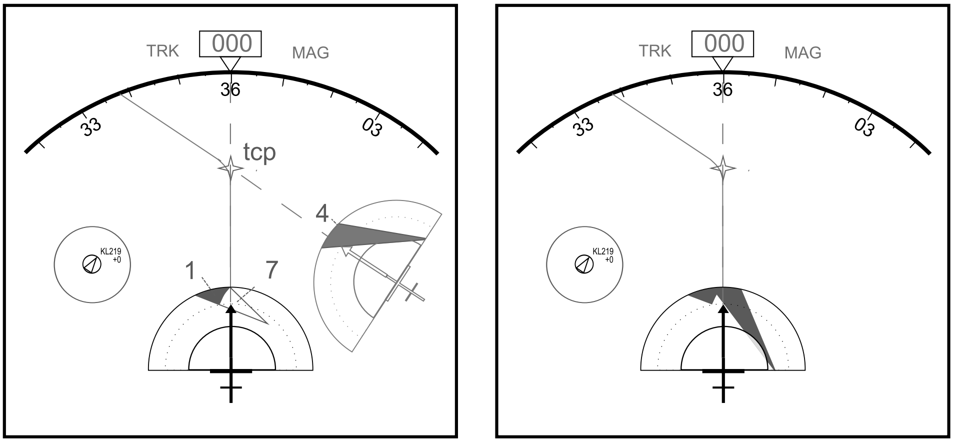
(b) SVE with Target State FBZ and state-based FBZ

FIGURE 6-10: Calculation of ghost image of intruder TS state image; the FBZ is based on the 'ghost' technique (note that in this figure 'ts' refers to target state, and 's' refers to current state).

hypothetical position of the own aircraft at current time as 'if it would already fly according the 'post-TCP' trajectory. In an early design version of the intent display, both SVEs were mapped on the actual aircraft position, i.e., the ghost-SVE was translated to the actual position and rotated so that the ghost state vector was exactly on the actual state vector V_{own}. Note that for the plotting of the FBZ areas the state-based XATP symbology is used.

Two important issues came to surface when testing this display in a simulation environment. First, it became apparent that, when using own intent, FBZ area (4) related to the intent part of the trajectory, POST_{own}(on), can only be used to detect a conflict situation but not to resolve it. Pilots would know a conflict situation exists when the state vector V_{own} is inside this area, but entering a TS command that would put the state vector out of this area would not assure the conflict is resolved, i.e., it can not be used as an *instant* maneuver constraint area. The term 'instant' is chosen because of the idea that these constraints remain present and usable on the display when the pilot would 'instantly' maneuver the aircraft. When considering TS maneuver options only to resolve the conflict, only for areas (1) and (7) are instant maneuver constraints to be considered, Figure 6-11.

Supposing the pilot needs to maneuver with the MCP, a second issue comes to surface. Once the pilot gives a State Command on the MCP, the FMS deactivates



(a) Using the ghost image technique for own intent

(b) Early version of the intent display using the FBZ symbology of the state-based XATP

FIGURE 6-11: Intent-based XATP display for the example conflict situation with own intent.

and the SVE would switch from the early intent design screenshot in Figure 6.11(b) to the no-intent state-based display screenshot, Figure 6-4. Post hoc, the pilot realizes that FMS deactivation triggers a conflict, i.e., V_{own} is now located inside the FBZ area (7), Moreover, area (2) has disappeared. Note that for this traffic situation, areas (1) and (7) together result in the original FBZ geometry as used in the state-based XATP display, Figure 6-4.

6-4-4 Categorization of FBZ constraint areas

Given the different nature of the FBZ constraint areas a categorization is set up. FBZ types can be related to the part of the trajectory they apply, both for the own aircraft and the intruder aircraft. As defined in Figure 6-6, each aircraft has three trajectory paths, one before its TCP, and two alternatives after the TCP. This means that theoretically nine combinations exist where loss of separation is possible. To distinguish between these cases, the FBZ constraint types are labeled according the flight path encounter types labeled in Table 6-2, resulting in nine types labeled (1) to (9).

According the work domain boundaries specified earlier, it is assumed that pilots would start out with a situation where both aircraft are flying with the FMS enabled, ‘ON-ON’. In the course of a conflict, either crew may decide to disable the guidance from the FMS, leading to the four cases summarized in Table 6-3. The nine types of FBZ areas never apply at the same time, but depend on the currently active FMS combination and the specific geometry of both FMS trajectories. Table 6-4 specifies for each FMS mode combination which FBZ types apply.

Using thes table one can clearly see how certain FBZ areas appear or disappear when the intruder or own aircraft disengages or engages the FMS guidance. For example disengaging the own FMS means going from the ON-ON table to the OFF-ON table. One can see that types (4), (5) would disappear and types (7) and (8) appear.

TABLE 6-3: Quadrant of possible FMS mode combinations for a single conflict.

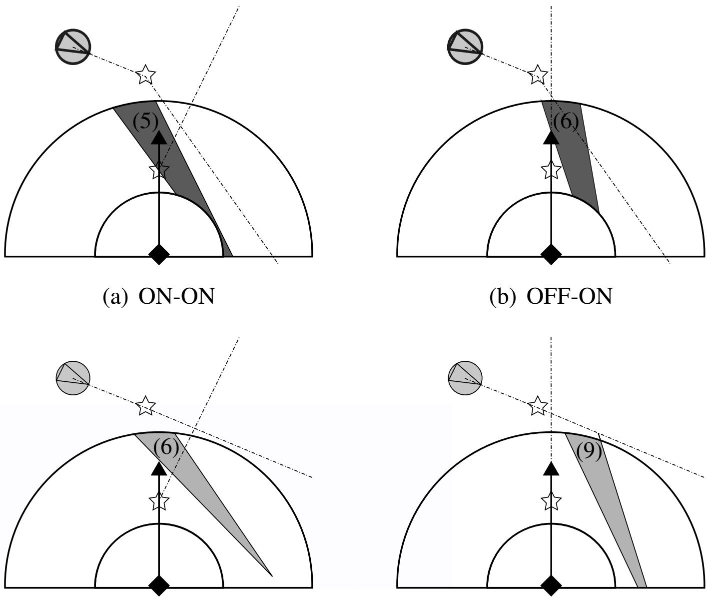
	FMSown(on)	FMS$_{own}$(off)
FMS$_{int}$(on)	ON-ON	OFF-ON
FMS$_{int}$(off)	ON-OFF	OFF-OFF

TABLE 6-4: Active FBZ constraint types for the four FMS mode combinations. Disengaging the own FMS, FMS$_{own}$(on) to FMS$_{own}$(off), results in areas (4) and (5/6) to be replaced by areas (7) and (8/9) respectively. Disengaging the intruder's FMS, FMS$_{int}$(on) to FMS$_{int}$(off), results in areas (2) and (5/8) to be replaced by areas (3) and (6/9) respectively. Areas (1), (3), (7) and (9) together define the FBZ as calculated in the state-based display, Figure 6-2. Section. Table 6-2 (top) is added to enhance the interpretation of the main table (bottom).

		OWN		
		PRE	POST(on)	POST(off)
	PRE	1	4	7
INT	POST(on)	2	5	8
	POST(off)	3	6	9

ON-ON			OFF-ON			ON-OFF			OFF-OFF		
1	4	-	1	-	7	1	4	-	1	-	7
2	5	-	2	-	8	-	-	-	-	-	-
-	-	-	-	-	-	3	6	-	3	-	9

Figure 6-12 presents the SVE maneuver space for the four FMS mode combinations as it would look like in the state-based XATP design for the traffic situation as described in Figure 6-6 when both fly FMS engaged. Note that both aircraft have their own TCP point much closer than the other ones TCP point. This implies that within the maneuver capabilities of the own aircraft it is not possible to lose separation in the pre-TCP trajectory path of the other aircraft, and therefore no time-circles exist within the SVE boundaries. In total four constraint types exist for this example: (5), (6), (8), and (9). In Figure 6-12, the constraint types appear and disappear due to mode control changes according to Table 6-4. Areas (8) and (9) are instant maneuver constraints whereas (5) and (6) are not because they are based on the POST_{own}(on) trajectory part.



(a) ON-ON (b) OFF-ON (c) ON-OFF (d) OFF-OFF

FIGURE 6-12: Presentation of the same conflict situation for the four possible FMS-mode combinations as they would appear using the state-based XATP symbology.

6-4-5 Discussion on the WDA

In the line of the ecological approach, the research challenge is to present separation affordances in a visual format so that pilots can directly perceive a conflict situation, in such a manner that it would enable them to solve it on either a skill-based level (using a strategy of avoiding zones), rule-based level (recognizing conflicts and using a learned reaction) or knowledge-based level (understanding and predicting the conflict geometry).

From the WDA analysis, it is clear that it is possible to account for the effects of intruder and own intent information in the geometry of the FBZ. However, a few complexities are introduced by the use of own intent information and FMS mode changes.

The own intent TCP divides the own trajectory in three parts PRE_{own},

POST_{own}(on), and POST_{own}(off). The conflict situation used in Section 6-4-3, Figure 6-11, showed that the FBZ-area related to the POST_{own}(on) trajectory part can inform if there is a conflict or not on that trajectory part in the current FMS-engaged mode, it can not be used as an instant maneuver constraint. After the categorization of FBZ constraints we can generalize this by stating that FBZ area types (4),(5) and (6) are not instant maneuver constraints and should be given a symbology that differentiates them from the other constraint types.

Figure 6-12 clearly shows that FMS mode changes displace the FBZ, and can trigger or resolve conflict situations. Since pilots should be made aware of the impact of their own FMS mode change, this should be made visible on the interface. From Table 6-4 one can see that switching from 'ON-ON' to 'OFF-ON' mode, type (4) will switch to (7), and (5) to (8). While switching from 'ON-OFF' to 'OFF-OFF' mode, type (4) will switch to (7) again, and (6) will switch to (9). The important thing to realize is that these pairs, i.e., (4)-(7), (5)-(8), (6)-(9), should be visible in both FMS modes, FMS_{own}(on) and FMS_{own}(off), moreover, within each pair it should be clear which one is 'active' and which one is not.

6-5 Interface mapping

Figure 6.11(b) represents an earlier attempt to make a suitable intent display based on the knowledge of the FBZ time-circles [16]. This design failed to meet the requirements to clearly show 'instant' maneuver areas and failed to present the active-inactive FBZ area pairs that show the FMS mode change affordances. Therefore the old symbology as used in the state-based XATP display is abandoned [7], and a new one is created to explicitly show the distinct types of FBZ constraints.

The following symbology rules are suggested for the new design:

1. 'Instant' maneuver constraints are presented in color, the others (4), (5) and (6) in gray.

2. 'Active' maneuver constraints are filled, 'inactive' areas are empty but outlined.

Applying these two symbology rules, Figure 6-13 shows how the SVE envelope is created. The total SVE is the result of mapping three overlays. Overlay 1 shows the FBZ areas (1), (2) and (3) related to the PRE_{own} trajectory. These FBZ areas in this layer are always colored and filled and are the top layer on the interface. Overlay 2 shows FBZ areas (7),(8) and (9) related to the POST_{own}(off) trajectory parts. These outlines of areas are always colored. Disengaging the own FMS will change them from empty to filled. Overlay 3 shows FBZ areas (4),(5) and (6) related to the POST_{own}(on) trajectory parts. These areas are always gray. Gray is chose to

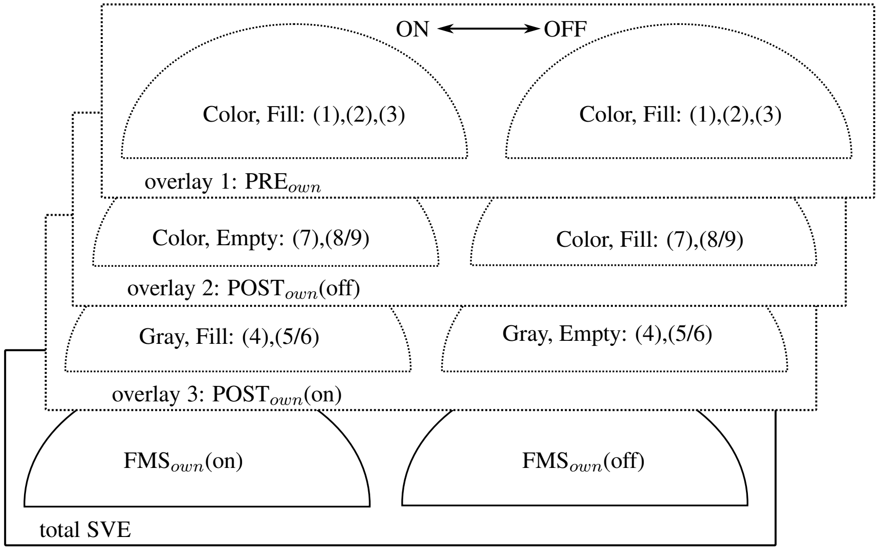


FIGURE 6-13: FBZ mapping order and symbology for the intent SVE. Layers 1 (top), 2 and 3 (bottom) are layered on top of each other to create the total SVE.

indicate less priority to these constraints in comparison with instant constraints that represent more urgent situations. It also reflects the idea that ultimately an intent-based system should still keep pilots very aware of the more physical 'instant' state-based constraints in addition to social 'intent-based constraints. This allows pilots to anticipate on situations such as 'what if finally the intruder aircraft does not turn according the FMS plan'. A disadvantage of using the gray color however becomes apparent when an aircraft is very close to its next TCP: misleadingly, gray areas represent conflict situations that could quickly lead to loss of separation.

Figure 6-14 shows the construction of SVE for the intent display for FMS enabled and disabled, respectively left and right. The situation is drawn for **FMS$_{int}$(on)**. The SVEs in Figures 6.14(e) and 6.14(f) can be compared with state-based XATP symbology, Figure 6.12(a) and 6.12(b). Equally, the SVEs in Figures 6.15(a) and 6.15(b) can be compared with Figures 6.12(c) and 6.12(d) for the case that **FMS$_{int}$(off)**. Figure 6.16(a) and 6.16(b) depict the new SVE design for the situation depicted in Figure 6-11.

6-5-1 Conflict resolution strategy

The conflict status can always be perceived by looking at all filled FBZ areas. If the vector lies inside any of the filled areas the aircraft is in conflict in the current control mode. The instant maneuver constraints are always visible as areas that are colored. Depending on the related time to loss of separation the zones can be colored differently, e.g., using orange and red as is done in the state-based XATP design.

The pilot flies FMS enabled unless the SVE speed vector lies inside a filled FBZ area. It is assumed that when the speed vector enters a filled FBZ area, the pilot remains in FMS_{own}(on) and analyzes the SVE envelope and decides about the resolution action needed. The following rules can be applied *in sequence* to come up with the most effective action:

1. If the state vector lies outside all *colored* filled or outlined areas, disengage the FMS without further maneuvering, otherwise follow step 2.

2. Disengage the FMS by choosing a target state that moves the vector out of the colored areas and use the state-based maneuver strategy as specified in Section 6-2-3.

When the FMS is disengaged the empty colored areas will fill up, showing all instant maneuver constraints filled. All gray areas representing the own intent are then outlined and no longer filled. Keeping these areas visible in FMS_{own}(off) allows pilots to see if the own updated FMS trajectory would trigger a conflict when the pilot would choose to activate the FMS mode again.

6-5-2 Observing intruder behavior

Intruder TS commands are implicitly visible by replacing the PRE_{int} and POST_{int}(off) trajectory parts by the trajectory flown as a result of the TS input in the calculation of the FBZ constraint areas. In the TS example, The FBZ based on the TS ghost image will be shown, labeled ‘ts’, instead of the state-based FBZ, labeled ‘s’, Figure 6.10(b).

The effect of intruder mode change affordances are not visualized, i.e., the own pilot can not anticipate that FBZ area (5) would be replaced by (6), and (8) by (9), when the intruder disengages the FMS. When the intruder performs this action, the own pilot can of course observe the change. In Figures 6-14 and 6-15, the effect of disengaging the intruder FMS, FMS_{int}(on) to FMS_{int}(off), will discretely change the SVE from Figure 6.14(e) to the SVE in Figure 6.15(a) when FMS_{own}(on). The SVE in Figure 6.14(f) will change in the one in Figure 6.15(b) when FMS_{own}(off).

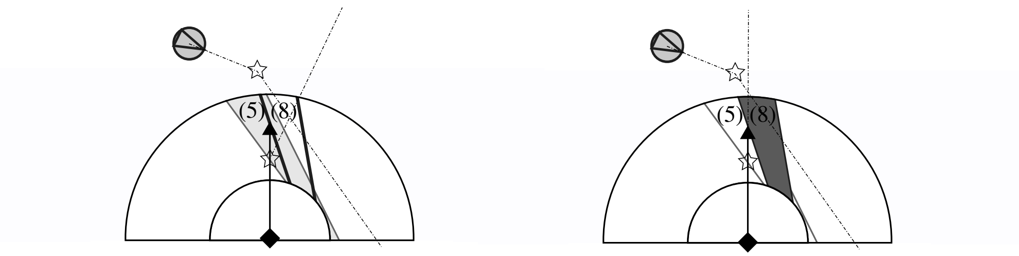
The main reason to not show the intruder mode change affordances on the own pilot’s SVE is to prevent information overload, or clutter on the SVE. The one scenario in which the own pilot would really benefit from knowing the intruder’s mode change action capabilities, would the situation in which the own pilot can see that the intruder could solve the conflict by simply disconnecting the FMS while for the

(a) overlay 2: FMS_{own}(on)

(b) overlay 2: FMS_{own}(off)

(c) overlay 3: FMS_{own}(on)

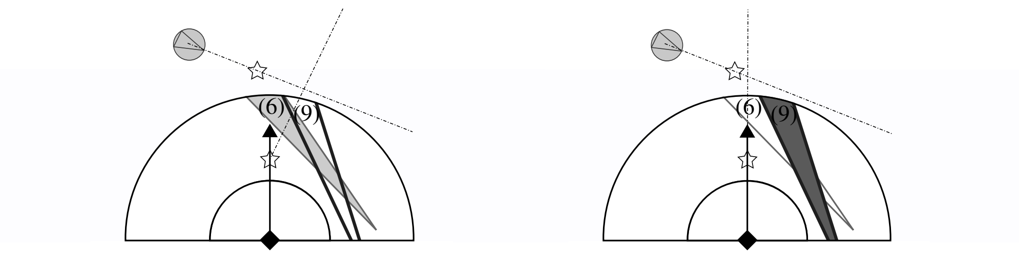
(d) overlay 3: FMS_{own}(off)



(e) total SVE for FMS_{own}(on)

(f) total SVE for FMS_{own}(off)

FIGURE 6-14: construction of SVE for the intent display for FMS enabled and disabled, respectively. The situation is drawn for **FMS_{int}(on)**. Compare with state-based XATP symbology, Figures 6.12(a) and 6.12(b).



(a) Total SVE for FMS_{own}(on)

(b) Total SVE for FMS_{own}(off)

FIGURE 6-15: SVE of the final intent display for, left side, FMS_{own}(on), and right side, FMS_{own}(off). The situation is drawn for **FMS_{int}(off)**. Compare with state-based XATP symbology, Figures 6.12(c) and 6.12(d).

(a) FMS_{own}(on) (b) FMS_{own}(off)

FIGURE 6-16: SVE of the intent display for FMS enabled and disabled, respectively. Compare with state-based XATP symbology, Figure 6-9.

own pilot the only possible way to resolve the situation would be a TS maneuver. This information would help the own pilot to do nothing, and wait for the intruder to disengage the FMS as this would be the most effective way to solve the conflict.

6-6 Discussion

The effect of own intent, TCP_{own}, intruder intent, TCP_{int} and TS_{int} on the appearance of the FBZ maneuver constraints are calculated using the 'ghost image' and 'time-circle' techniques.

Ghost Image: The ghost image technique is used to calculate the own FBZ maneuver constraints 'at present' of trajectory parts and states that are reached after completion of a TS (intruder only) or TCP maneuver (own or intruder aircraft). The ghost is created assuming the intruder would already be flying with the future state vector and aligned with the future trajectory part. The technique can be applied to intruder TS and intruder and own aircraft TCP maneuvers.

Vector time circle: For each TCP point affecting the maneuver constraints, a vector time circle is used to divide the speed-heading action space into two zones. In the case of an intruder TCP, a PRE_{TCP} zone, outside the circle, represents all the own aircraft maneuvers that will result in a motion path that passes by the intruder aircraft 'before' it makes the TCP maneuver. A POST_{TCP} zone, inside the circle, represents all the maneuvers that will result in a motion path where both aircraft will pass each other 'after' the intruder makes the TCP maneuver.

The effect of the time circle is only visible on the SVE if within the own maneuver space boundaries it is possible to perform a maneuver that would make both aircraft pass each other before the TCP point is reached. In many conflict situations this is not possible, and therefore the effect of the time circle on the FBZ constraint area is not visible as the circle is completely located outside of the SVE.

For calculation purposes, the ghost image and time circle techniques can be enhanced by dividing the maneuver trajectory path in several sequential sub paths and applying both techniques individually for each path. This would realize a smooth transition area connection the PRE_{TCP} and POST_{TCP}(on) maneuver areas.

FBZ types: Assuming 1 TCP point for both intruder and own aircraft and assuming two aircraft control modes, FMS_{on} and FMS_{off}, nine trajectory part combinations can be identified where both aircraft could potentially lose separation. These are represented in nine FBZ areas, see Figure 6-2.

Instant maneuver constraints: Maneuver areas (4), (5) and (6) are related to the own trajectory after the TCP turn when FMS enabled, POST_{own}(on). These constraints can be used for FMS-enabled conflict detection, but they can not be used as instant maneuver constraints used to find conflict-free speed-heading states to move own state vector $\vec{V}_{own}$. In the interface mapping, instant maneuver constraints are colored whereas 'POST_{own}(on)' areas (4), (5) and (6) are in gray.

Active maneuver constraints: Aircraft control mode changes discretely change the appearance of FBZ areas on the SVE. Mode change pilot support is given by showing both the active FBZ, (filled), and the inactive (empty). This way the additional 'action space' variable 'FMS mode change' is mapped on the SVE, and is added to the speed-heading variables already visualized in the state-based design.

When considering to show the mode change effect of the intruder aircraft on the own maneuver constraints, this would mean 3 areas, 1 active and 2 inactive should be shown across the 3 possible Mode combination (e.g., ON-ON, ON-OFF, and OFF-ON), and also an additional symbology should be used. In this case a trade-off appears between pilot Situation Awareness and cognitive workload.

The final design visualizes "conflict detection" by means of filled areas (keep vector outside), and "conflict resolution/prevention" by means of colored zones. The effect of own mode changes on the constraint areas is also supported by always showing the FBZ constraints for both modes independently from the active mode.

Future work More research should be done on defining what exactly is considered the most effective solution to a conflict problem, and how to cooperatively solve it, considering both the action space of the own pilot and intruder aircraft. If an FMS-based (ON-ON) conflict can be resolved by one aircraft through only disengaging the FMS, i.e., without further maneuvering, this solution seems more effective than the other aircraft disengaging AND having to maneuver. However, if this maneuver directs the aircraft towards its future TCP, this solution might well be considered more effective, as it keeps the aircraft position close to the FMS-planned position. Especially in the case of multiple aircraft conflict situations, the question should be raised whether explicit automated decision support is needed to determine what aircraft would need to act first. It remains then the challenge of ecological designs to visualize the constraints on conflict resolution actions, also (or perhaps, in particular) when the decision is automated.

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7

Conclusions

In this chapter the main results of the thesis will be discussed at the hand of the four research challenges stated in the Introduction. Final conclusions of the thesis are stated, followed by recommendations for future work.

7-1 Recapitulating the thesis goal and approach

Future air traffic concepts foresee that in unmanaged airspace, to reduce workload of air traffic controllers and the resulting constraints on capacity, the separation task will be delegated to the flight deck [1, 2]. Technology-driven pilot self-separation support systems have been developed that present *explicit* automated solutions to deal with conflicts. These systems do not offer a transparent window on the reasoning of the automation, making it difficult for pilots to judge the validity of the proposed automated solution. In addition, they do not allow pilots to engage safe 'good-enough' alternatives that satisfy travel goals that may not be fully incorporated in the automation design, such as weather.

Ultimately, pilots bear the responsibility in safeguarding the safety of flight, and to support pilots in this role this thesis engaged to solve the fundamental problem of determining 'what information', and 'what visual form' would *best promote pilot traffic awareness*, to safely and effectively deal with traffic. In the introduction chapter this problem statement lead us to state the following thesis goal:

Thesis goal

Determine the meaningful information in the work domain of air traffic conflict avoidance. Design and evaluate suitable interface mappings that enhance pilot traffic situation awareness and decision making as compared to state-of-the-art CDTI and ASAS displays.

In this thesis several prototypes for an airborne trajectory planning tool were designed and evaluated, aimed at improving pilot SA and decision making. A formative constraint-based design approach was adopted, Ecological Interface Design (EID), to create an 'ecological' airborne separation assistance system. Graphical information overlays on the Navigation Display and Vertical Situation Display were developed to support pilots in their trajectory (re-)planning in case of traffic conflicts in unmanaged airspace.

The ecological approach gives priority to the worker's environment, or 'ecology', focusing on how the environment imposes constraints on the worker [3, 4]. Ecological interfaces are designed to present these constraints graphically on the interface in a meaningful and also functional way, exploiting the unique human capabilities to directly perceive and act on the work domain affordances. EID is hypothesized to improve operator SA and overall system safety when compared to normative task-oriented user-centered design approaches, especially in situations that were unanticipated by designers.

The ecological approach to traffic awareness, developed in this thesis, consists of the traditional two steps in EID. First, a Work Domain Analysis (WDA) is performed to identify the functions, constraints and means-end relationships of the work domain. Second, several display mappings have been developed that aim to map the work domain constraints on the display in a visual form that supports the Skills, Rules, Knowlegde (SRK)-based cognitive processing capabilities of human operators. Both steps are clearly defined in the thesis goal formulated above.

In the following the main results of the thesis will be discussed, at the hand of how we dealt with the four research challenges identified in Chapter 1. The chapter ends with conclusions and recommendations for future research.

7-2 The four research challenges

Recall the four major research challenges stated at the start of the project:

Research challenges

1. Gain insight into the laws of physics that govern the **work domain** of tactical self-separation and express them in a format meaningful to pilots.

2. Gain insight into **interface mappings** by addressing the *creative gap* between work domain analysis and interface design.

3. Gain insight into *how* and *to what extent* **automation** should be involved in tactical self-separation, such that a high level of pilot situation awareness is maintained.

4. Gain insight into how conflict avoidance displays could be objectively **evaluated** and compared, such that the EID benefits or pitfalls become apparent.

In the following it will be discussed how these challenges were engaged and – perhaps only partly – solved.

7-2-1 Work Domain Analysis for airborne separation

The Abstraction Hierarchy. EID starts with an analysis of the operator's work domain or environment by means of a Work Domain Analysis. The WDA is an activity-independent analysis, aimed at identifying and mapping-out the environment's goal-relevant constraints (and their relationships) that shape human, or automation, actions [3]. The results are summarized in an Abstraction-Decomposition Space (ADS) called the Abstraction Hierarchy (AH). The AH typically describes the work domain on five levels of functional abstraction: Functional Purpose, Abstract Function, Generalized Function, Physical Function, and Physical Form [5]. EID was originally applied to process control with DURESS as the main example [6]. The application of WDA to the domain of vehicle control brought about changes in the constraints encountered at the various levels of abstraction.

At the Functional Purpose level, the goals for trajectory planning were defined as flying safely, productively and efficiently through unmanaged airspace. Each goal can be further decomposed, e.g., safety involves maintaining sufficient separation from other objects such as aircraft and terrain, and keeping the aircraft within its flight envelope. With respect to dealing with conflict situations, the descriptions of goals were narrowed down to maintaining separation with other aircraft adhering separation minima (safety) [7] while decreasing distance to the destination (productivity) and minimizing deviation from the planned path (efficiency).

The most significant challenge was found at the Abstract Function (AF) level. At this level Vicente and Rasmussen discuss *holonomic* constraints [3], constraints imposed upon us by physics: inescapable, unless our understanding of the physical world proves to be wrong. In the example of DURESS, the Abstract Function level describes the system in terms of mass and energy flows, storage, sources and sinks [6]. For the vehicle control domain in general and for airborne self-separation in particular, the mass and energy flow based descriptions were substituted in this thesis by descriptions of the general physical laws that dictate flight, absolute and relative locomotion and the geometrical properties of the separation problem [8].

The results of the WDA as condensed in the AH can be seen as a 'snapshot' of the designer's perspective on and understanding of the functionalities, constraints and means-end relationships of the work domain, and is above all a systematic roadmap to gain further understanding of it. Imperfections in the AH, nevertheless, do not necessarily slow down the designer's progress in understanding the work domain, and finding constraint descriptions suitable for visualization. Hence, the sequence in which the various Abstraction Hierarchies are presented in this thesis provide snapshots of how they evolved in time.

Most noticeable, sub-components of the main travel goals such as spatial separation, destination approximation and path deviation minimization were first placed as 'key-functions' on the Abstract Function level, see Figure 2-1. Currently, we understand that the Abstract Function does not exactly describe the physical laws of each key function, e.g., path deviation minimization, but rather describes how the physical laws for flight, locomotion and separation 'shape' the boundaries to realize those goal-functions at the highest level [9]. Nonetheless, analyzing these key functions on the Abstract Function level helped us not only to identify the physical laws involved to describe those functions, but also, or even more so, to describe their goal-directed means-end relationships with respect to the travel goals.

The work domain in this thesis has similarities with the work domain analyzed for the design of a support system for pilot "terrain awareness" [10, 11]. Whereas for terrain awareness the environmental constraints are fixed and well-defined in the world, constraints related to surrounding traffic are more dynamic and poorly-defined. The behavior and intention of traffic can not be as accurately modeled and predicted as constraints imposed by the own flight performance and the (more or less fixed) surrounding terrain or airspace boundaries. In this thesis the approach was taken to first come to a complete understanding of the physics that govern conflict avoidance, and then investigate how the intentional aspects of traffic awareness could be taken into account in the display design and use, Chapter 6.

Meaningful physics. In EID literature a creative gap exists between the WDA (and other stages of cognitive work analysis) and the actual design of the interface. Also in this thesis research this gap was experienced. Traditional engineering descriptions for aircraft motion, motion paths and separation provide accurate system descriptions and hence, create understanding of the work domain constraints. Nevertheless, these descriptions do not readily lead to a proper representation that is instantly suitable for mapping on the interface.

The essential step is to consider alternative descriptions of the constraints at the AF level of the AH, to create a 'practical' match between user controls and the representation, and a 'functional' match between system purpose and the representation [12]. The alternative description of work domain physics, *meaningful to interface design* is referred to as finding the 'meaningful physics' of a work domain.

To become practical, the high-dimensional descriptions of possible aircraft behavior had to be replaced by lower-dimensional descriptions that match current flight practices, and that also match the current cockpit interface designs which are not likely to change dramatically in the next decades. It was assumed that the pilot controls the own aircraft motion through manipulating its speed, heading and vertical speed settings on the Mode Control Panel (in 'Target State Control'-mode as referred to throughout this thesis). Therefore the (loco)motion model (travel function) that describes possible aircraft behavior (travel options), is based on these variables as control inputs.

All dynamics and kinematics describing the relationship between the pilot controls and the aircraft motion were neglected due to the short time-scale of these dynamics relative to the much slower dynamics of the aircraft separation problem. To become more meaningful, however, descriptions of aircraft motion needed to become useful or 'functional' to goal achievement. This involved mapping the internal constraints to flight, imposed by aircraft performance, within the context of the external constraints to flight, imposed by the surrounding traffic. The capabilities for action in terms of (loco)motion had to be related with constraints imposed by the need to maintain separation from other moving aircraft.

In Chapter 2 the analysis of single conflicts in the horizontal plane showed that simplified locomotion models that consider one-dimensional state changes only (e.g., turning without speed change, speed change without heading change) are not always functional to goal-achievement: in some conflict situations these models fail to provide an efficient conflict resolution. This lead to a more profound analysis of the two-dimensional locomotion or travel model called the 'speed-heading travel function', the fundamental speed-heading action space.

The relationship between locomotion and separation can not be visually described in the absolute motion plane as the dynamic behavior of geometrical conflict properties are too dynamic and complex, and not suitable to visualize conflict avoidance. When describing motion *relative* to the intruder aircraft, however, the behavior of geometrical conflict properties become significantly less complex and more 'static'. In the first WDA iteration in the horizontal plane this lead to the concept of the Forbidden Zone Beam (FBZ) defined in the relative motion plane.

To reinforce the coupling with flight practice, the FBZ was translated from the relative motion space to the absolute motion space hereby mapping (the affordance of) separation into the natural (speed-vector) action-space of the pilot controlling his own aircraft [13]. This is what ecological psychologists refer to as "perception-action coupling". As a result, the FBZ was sufficiently static and much more suitable to separating the own aircraft from other aircraft as it visualizes how the conflict geometry imposes constraints on the own aircraft travel possibilities.

7-2-2 Interface mapping

Traditional mappings. The PASAS-bands were chosen as the viable technology-driven design alternative to the ecological interface. From a evolutionary perspective, these no-go bands in the heading and speed tapers where designed during the PASAS project out of the need to prevent the creation of new conflicts when pilots agreed to implement automated ASAS solutions [14]. These bands are in fact also a constraint-based visualization that may have narrowed the gap between SA shared between automation and pilot.

A theoretical and experimental comparison between XATP and PASAS in the horizontal plane in Chapter 3 showed that pilot actions based by representation of separation on speed and heading bands indeed sometimes lead to inefficient maneuvers and large path deviations [15]. Experimental results indicate that pilots have a preference for heading changes over speed changes, and hence, may have an incomplete mental model about the conflict dynamics. Even more so, these results provide evidence that a gap exists between the awareness shared between automation and pilot: whereas the explicit ASAS markers (=automation) successfully present the most efficient solution, pilots can not always come up with an efficient solution themselves, when these markers are not shown.

The traditional mapping of constraints on one-dimensional speed and heading tapers on the PFD and ND, as done in the PASAS design, provides a good practical match between the control actions and representation. The one-dimensional 'cross-sectional' representation, however, impoverishes or even destroys the functional match with some of the domain constraints, and does not allow for exploring 'optimal' settings that may involve small changes in *both* speed and heading dimensions. Experimental results of this thesis provide clear evidence that, in absence of a valid *explicit* resolution advisory, this may sometimes lead to less efficient maneuvers (Chapter 3) and lower scores for conflict Situation Awereness measures (Chapter 4). Hence, reducing the dimension of the solution space may have benefits in terms of cognitive workload related to selecting and executing automated resolutions, however it disintegrates conflict information and requires in fact *more* cognitive effort from pilots to build a correct and complete mental picture of the conflict situation; the latter to the benefit of pilot SA, and air traffic safety.

Ecological designs. To facilitate integration with current-day interfaces, ecological overlays were integrated with existing navigation displays in the horizontal and vertical plane, respectively, the ND and VSD. This was achieved by mapping the two-dimensional action-space made up by speed and heading (horizontal) or speed and rate-of-climb (vertical) integrally *on top* of the own aircraft position space to safeguard its meaningful qualities. A best match with the 'current ecology' of flying was achieved by mapping the origin of the action space on the own aircraft position on the ND (or VSD). This way a direct visual mapping resulted between constraint zones in the action space (the FBZs) and the location of the other traffic causing these constraint zones.

With each iteration of work domain analysis, interface design and experimental evaluation, the relations between different parts in the AH became more apparent. The iteration was most particularly done in the horizontal plane and its value was recognized when the first implementations of the first prototype showed the *dynamic* behavior of the FBZ in relation to simulated traffic behavior. Not only did the ecological overlay make efficient conflict avoidance directly perceivable from the display, it also provided an extensive set of meaningful contextual information, significantly enhancing conflict situation awareness. Some examples of this context can be characterized best as simple questions that may pop-up in the pilot's mind when dealing with other traffic: "Where do I find the aircraft causing the FBZ-constraint?", "Will I pass the other aircraft in front or behind?", "Which other aircraft may cause conflict problems?", "Which aircraft needs the most attention?" and "What is the effect of the other aircraft maneuvering on the FBZ-constraints?". These crucial pieces of information were considered to be strongly integrated and meaningful to pilots with respect to conflict and traffic awareness. Eventually, this also gave us key insights on how to approach situation awareness and its measurement in pilot experiments, leading to the comparison study reported in Chapter 4.

Understanding the richness of information emerging from the static and dynamic properties of the FBZ, allowed us to better fill in parts of the Work Domain Analysis. Most noticeably: a 'decision-making' maneuver-strategy for safe and efficient conflict avoidance was set up in Chapter 2, [13]. For single conflicts, this strategy assures implicit coordination between two pilots using the same ecological display, unless they are on an exact collision course. In addition, the interface mapping allowed pilots to directly perceive the effect of intruder aircraft maneuvers on the FBZ, hence, the own motion capabilities. This also generated a deeper understanding into how to deal with the 'intent' of others in conflict situations, reflected in the analysis of Chapter 6.

These examples show that the analysis of the work domain and the design of the ecological interface are indeed *iterative* rather than consecutive steps. In that sense, it proved to be more helpful to first perform a basic work domain analysis, and then to develop and test a prototype interface reflecting that analysis. Based on the insights gained from the dynamic behaviour of the initial ecological overlays during first simulations, the work domain analysis became more comprehensive, yielding better interfaces in consecutive prototyping evaluations. The more physical constraints on the work are understood and are properly represented on the interface, the more design activities can shift towards cognitive task-oriented display requirements to improve the initial design.

7-2-3 Role of automation

Transparency. This thesis showed that an ecological self-separation interface can be used by pilots to assure separation with other traffic without any help of automation. In several instances, however, it was noticed that presenting the basic FBZ could be insufficient. For instance, when the CPA distance equals zero and both aircraft are projected to exactly hit each other, a worst case scenario, *both* pilots will not know what to do as the own aircraft velocity vector is positioned exactly in the center of the FBZ, masking the otherwise implicit maneuver completely. Here automation, or perhaps basic 'rules of the air' could be mandatory to assure safety [9].

The same can be said about conflicts with multiple aircraft. Although XATP showed to be superior than traditional designs in resolving multi-aircraft conflicts (Chapter 4), the efficiency of the resolution maneuvers is not as obvious as in the single aircraft conflict. Here automation can play a role in computing the 'best way out' for all aircraft, and also indicate which aircraft should 'move first', in order to obtain the best global optimal solution.

Despite these comments on the ecological displays, it is believed that even when introducing automation in these situations, providing pilots with the ecological overlays will still be very valuable. The overlays, presenting work domain constraints that are true for both pilots *and* automation, are still valid and can act as a 'window' on the rationale behind the automated solution (or suggestion), increasing the transparency of the automation considerably, to the benefit of pilot situation awareness. This is also likely to result in increased pilot trust in the automation and also may lead to pilots accepting higher levels of automated solutions.

Trade-off: design for complexity, design for simplicity. The effect of instantaneous or planned intent information on the appearance of constraints can be modeled and visualized. In Chapter 6 the effect of target state changes, the effect of planned trajectory waypoints and the effect of switching between the 'FMS Target State' and 'Trajectory State control' modes, are accounted for in the horizontal design of XATP and its FBZ constraint shapes.

Incorporating traffic intent information into the work domain of conflict avoidance inevitably introduces more work domain constraints, in several dimensions, and with that adds significant complexity to the ecological interface. By taking into account intent-based information and 'enhancing' the state based design, it is shown that the FBZ constraints change shape, making it more difficult for pilots to perceive some of the formerly very intuitive features of the FBZ constraint geometry and dynamics. Even more, by taking into account the possibility of each pilot to switch between a state-based and intent-based mode (change FMS mode), the part of the constraint shape may discretely jump from one to another. A multi-conflict situation will very easily lead to a cluttered hard-to-use interface, even for experienced pilots.

Hence, the preliminary design of the intent-based XATP system in Chapter 6 poses a fundamental question: What level of automation is needed to ensure effective human-machine interaction? Amongst the options to reduce overwhelming complexity could be automating the decision who of all pilots involved should act first, automating the decision to (dis)-engage FMS mode, introducing some type of explicit advisory, etc. The challenging integration of state-based and intent-based conflict avoidance is one where design for complexity and design for simplicity must meet each other. But again we like to stress that the ecological overlays can act as a companion to automation, increasing its transparency to the user, as the work domain constraints are independent on the actor, human or machine.

7-2-4 Evaluation of EID displays

One of the core challenges of the application of EID in many domains remains how to objectively compare traditional task-oriented displays with ecological displays. To collect evidence for the possible benefits of the constraints-based design methodology, a number of comparison studies were conducted in this thesis.

Choice of display alternative. The work in the horizontal plane covered in Chapters 3 and 4 compared the ecological design against a viable design alternative. The work in Chapter 3 compared two displays that both use *constraint-based* representations in the horizontal plane, one the result of traditional engineering, PASAS, and one the result of the ecological approach, XATP. By the absence of an automated resolution advisory in the traditional display, differences in pilot behavior between both systems were expected to be directly related to the differences between both constraint-based collision avoidance displays. Both displays, however, performed equally well, and neither display was found to be superior in terms of task performance, workload or safety.

The later work in Chapter 4 compared the same displays, with the major difference that the PASAS heading and speed bands were enhanced with the *explicit automated resolution advisories* by the use of taper markers. As a result, pilot behavior is largely influenced by these advisories, and differences between both displays in terms of ecological properties were expected to emerge less explicitly from the pilot's performance but rather from the pilot's insight in the situation. It was found that indeed the ecological display better supported pilots to deal with unforeseen situations and create a better mental model of the conflict situation. Overall, situation awareness was higher, which did not result, however, in better performance.

In the vertical plane, Chapter 5, the ecological interface, VSAD, was compared against a baseline display 'standard', the VSD. As opposed to the comparison in the horizontal plane, proving the superior qualities of the VSAD in terms of SA and decision-making was more obvious as the ecological design provided an additional layer of information. Hence, the comparison with the baseline display in this study did not lead to new insights regarding this matter.

Situation awareness. When evaluating ecological designs, conventional metrics for flight safety, task performance and workload are all *indirect* measures of SA. Chapter 3 described a first in-depth comparison both theoretically and experimentally for the horizontal design. With the explicit automated resolution advisory removed from the traditional design, differences between both displays in terms of performance and workload were not identified, leading to the conclusion that no direct relation exists between pilot traffic awareness on the one hand, and task performance and workload on the other [15]. This lead to a shift in evaluation methodology from a cognitive task-oriented approach of measuring workload and task performance to one of measuring conflict Situation Awareness.

The situation-centered approach of Chapter 4 focused on obtaining *direct* measures of SA. Based on the experience of earlier design iterations and a profound knowledge on the work domain constraints, the focus shifted to revealing what situation awareness actually means with respect to self-separation, how can it be evaluated theoretically, and measured experimentally.

The first two questions lead to determining what pieces of conflict information are crucial to promote SA and yielded a summary of the main 'chunks' of information that define a conflict situation, Table 4-1, and some possible information bottlenecks and uncertainties, Table 4-2. The experimental results show that for more complex situations the one-dimensional bands provide less SA, require more cognitive effort to understand the situation than with XATP, leading a majority of the pilots to prefer the ecological display in those conditions. Experimental results also indicate, however, that the ecological display may require more cognitive effort as compared to a system that provides just an automated resolution advisory. See, e.g., Chapter 4 when facing simple single conflict situations that require a one-dimensional action (e.g., a turn maneuver).

The third question calls for the need of proper evaluation techniques. Several measuring techniques were used to target SA specifically and were found to be more useful than the performance metrics used in Chapter 3. Online probing was found to result the desired information regarding pilot SA in a more systematic and situation-adaptable manner, even more so than a post-experiment questionnaire the use of which depended on pilot memory and self-confidence.

Experimental scenario design. Apart from an initial evaluation of any conflict avoidance display, simple and standard conflict scenarios provide little or no challenges to pilots when supported by a viable conflict avoidance display. It may be able to provide proof that an ecological display is able to be as 'safe' and 'easy-to-use' in most frequent scenarios, but to evaluate its core ecological quality of providing support in events *unanticipated* by the (automation) design is more likely to come to surface in much more complex and rare situations.

As part of a focus on SA, conflict scenarios evolved from rather simple to more complex situations in the experimental iterations that took place for the horizontal design. One of the most interesting conflict scenarios performed was one where the automated resolution did not solve a multi-conflict situation. In this situation the benefits of XATP became more apparent, see Chapter 4, assisting the pilots better during trade-offs for the best resolution, by providing a more complete overview of the conflict situation geometry.

Despite the difficulty of these more advanced conflict situations, the question remains how the various (ecological, traditional) interface designs support the pilot in unanticipated events, with e.g., faulty sensors, broken communication links, etc.

These 'extreme' and 'unlikely' events will need to be evaluated, however, to obtain any differences between ecological and traditional designs. This thesis contains some examples of introducing unlikely events, such as the 'hostile maneuver' in Chapter 4, but this needs to be examined more thoroughly. It is clear that introducing unlikely events experimentally will remain to be a challenge, as obtaining sufficient data for these events requires more repetitions, affecting their 'likeliness'.

Safety. Tn this thesis, flight safety was measured in terms of the minimum distance between aircraft (CPA distance) and loss of separations (intrusion of the protected zone). Overall, the experiments showed that both the traditional as well as ecological interfaces resulted in only a few, and minor, intrusions, often less than a few hundred feet. These losses of separation occured due to either last-minute unanticated ('hostile') maneuvers of the intruder aircraft, or the pilot's actions to bring the own aircraft back to the original trajectory as soon as the conflict had passed. Similar to the ecological terrain displays developed by Borst [10], the visualization of the ultimate boundaries for action sometimes lead pilots to 'push the envelope', an inevitable 'risk migration' effect common to all human-machine systems.

It is recommended to study the existence and applicability of 'ecological' metrics for safety, such as metrics that can tell how much 'action space' is still currently available in dealing with separation constraints, or that reflect how difficult it may be to maneuver to or stay within a 'safe' zone (e.g., in terms of the FBZs). Properly modeling the geometric properties of FBZs may lead to more ecological descriptions for conflict 'severity' or 'urgency' in particular, and flight safety as a whole.

Training. In the evaluations conducted in this thesis, a recurring observation is that the pilot subjects needed (much) more time to get accustomed to the ecological overlays. Generally speaking, pilot appreciation for the ecological interfaces grew towards the end of the experiments, but still pilots needed (much) more practice and experience to better comprehend and use the information. In fact, throughout working on this subject also we as designers repeatedly discovered 'novel' attributes of the FBZ overlays, as the richness of the information is surprisingly large. Clearly, ecological interfaces need more elaborated instructions and much more user experience before users start to understand the behavior and dynamics of work domain constraints represented on the interface. The time scale of many pilot experiments in this thesis was too limited to notice this effect.

7-3 Conclusions and recommendations

7-3-1 Conclusions

In working on this thesis, interested colleagues and pilot participants often commented: "... but you have to automate this ... it's safer!". Undoubtedly, this work shows that an ecological display can be as safe and as effective as traditional display and automation solutions. Providing pilots a profound layer of information, as compared to displays that primarily present explicit automated advisories, has been shown to be at least as effective in supporting pilots to deal with particular situations, without any help of automation.

The basic geometrical characteristics of a 'constraint shape', the Forbidden Beam Zone (FBZ), forms the basis for an effective conflict detection and resolution interface. The FBZ dynamic geometry allows pilots to directly perceive the state of intruder aircraft relative to the own aircraft state, *see* which aircraft cause a separation problem, and *see* how they can effectively deal with the situation in terms of own aircraft control actions. In addition, the FBZ shape inherently visualizes efficient conflict resolution maneuvers, and its symmetry enables implicit coordination between two aircraft in all but one situation (CPA=0), a situation that requires an additional rule. But clearly we 'made visible the invisible' in this thesis.

During the design process the work domain analysis was iterated several times, often in combination with (testing) various visualization designs. This thesis showed that ecological displays for domains where the abstract functions are less obvious, can be designed in an incremental, evolutionary fashion, allowing interface form and work domain analysis to give input to each other. Indeed, EID is not a recipe for creating ecological interfaces, but rather benefits from an interative and incremental design approach.

Regarding the comparison between the ecological XATP display and the more traditional PASAS design, in the horizontal plane, it is clear that XATP promotes a higher level of situation awareness as compared to PASAS, and that the pilot decision making based on XATP's maneuver strategy matches with PASAS proposed automated solutions. In this regard it is worth repeating that although reducing the dimension of action or solution spaces can have benefits in terms of reducing a pilot cognitive load, in the end it may lead to *more* cognitive load for pilots to build a correct and complete mental model of the conflict situation.

Ecological interfaces are believed to better support pilots in dealing with rare and unanticipated situations, cases where automated advices could unexpectedly fail. Although this thesis provides some evidence for this hypothesis, in terms of superior pilot situatin awareness ratings for ecological displays, observable pilot decision making did not change. This remains an important avenue for future research, a challenging avenue however as unanticipated and unforeseen events are, well, difficult to predict and perhaps even more difficult to analyze experimentally.

In this thesis, we did not address the question whether a self-separation interface design requires an explicit compelling advisory or not. It has been shown that an appropriate ecologically-inspired interface can alleviate a pilot's dependency on such an advisory. However, when scaling-up the interface to include some of the other pilot control alternatives involving more and more automation has shown that the added dimensionality of the problem may in fact render the ecological display to become too complex, and can perhaps only be used in combination with automation. In this context, the ecological overlay could in fact be the 'missing link' to design a Joint Cognitive System, a combination of pilot and machine to conduct the task of self-separation. That is, the ecological overlays may be used to close the gap in the awareness of situations shared between automation and pilot, enabling pilots to better judge the fidelity of the proposed solution and, in case the automation fails, to come up with good-enough alternative resolutions shaped by task- and actor-independent domain constraints.

7-3-2 Recommendations

The basic ecological interface designed in this thesis can be improved in a number of ways. First of all, the horizontal and vertical designs should be better integrated, to show the full dimensionality of the three-dimensional separation problem. Several novel designs are being developed at the Control and Simulation section for this purpose [9]. Second, in many future airspace concepts four-dimensional (position and time) trajectory-based operations will be of paramount importance [2, 16], moving the pilot task towards one of monitoring separation, and selecting automated resolution advisories. The ecological displays developed here should be able to also facilitate this 4D trajectory management, as it all boils down to relative motion of vehicles in space and time.

It would be very interesting to also investigate whether the ecological interfaces will function in situations where multiple pilots (or pilot crews) share the same airspace. While in this thesis all intruder aircraft were programmed and behaved in a deterministic fashion, a multi-actor experiment would introduce (much) more (perhaps unexpected) variability and emerging behaviour that is hard to predict beforehand. Before conducting any new human-in-the-loop studies, however, this thesis clearly shows the need for extensive pilot training, to get experiment participants accustomed to the ecological designs and allowing them to comprehend and fully appreciate the richness of the information provided.

Task-oriented displays and ecological displays do not exclude each other's use in one system. As Chapter 6 clearly shows, ecological designs should compromise design for complexity with usability. Task-oriented support may provide lower cognitive workload in simple standard situations by use of easy-to-use automated instructions to the pilot of 'what to do'. Ecological support may show the 'total information' needed the most in exceptional situations. Key in this matter is to use automation as a tool to lower cognitive effort and improve decision making in such a way that it does not destroy the short and long-term benefits of ecological properties of the design. A common pitfall for engineers still remains to use too much automation, too fast, too easy. It is important to see how these 'hybrid' combinations of ecological overlays and automation functions can complement each other, at various levels of automation.

Finally, the above considerations also advocate the use of 'more ecological' designs as training tools, supporting pilots (or human operators in general) to develop a correct, complete and comprehensive mental model on the work domain physics/dynamics. This may very well require training sessions using displays without any task-oriented information, such as explicit resolution advisories, to promote long-term learning effects on the physics that govern the work domain, the possible use of ecological overlays as decision aids and also on understanding the underlying rationale of automation. This approach may also foster a successful introduction of 'hybrid' system designs in the future.

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Appendices

A

Simulation apparatus

In this chapter the experimental apparatus used for all experiments discussed in this thesis will be briefly discussed.

Fixed-base simulator

All pilot-in-the-loop experiments of this thesis have been performed in the fixed-base flight simulator at the Faculty of Aerospace Engineering at the Delft University of Technology. This simulator is placed in the Human-Machine Systems laboratory (HMSlab) and is operated by the Control and Simulation section.

The HMS laboratory consists of an experiment room, in which a fixed-base simulator is placed, and a simulation control area, see Figure A-1. The pilot is seated in an adjustable real co-pilot chair in the noise-free and darkened experiment cabin while the experimenter stays outside the experiment cabin in the simulation control area. The experimenter has access to a computer node that is used to control the experiment configurations, e.g., loading different scenarios, changing the display configurations, etcetera. An intercom allows for voice communication between the experimenter and the subjects seated in the flight simulator.

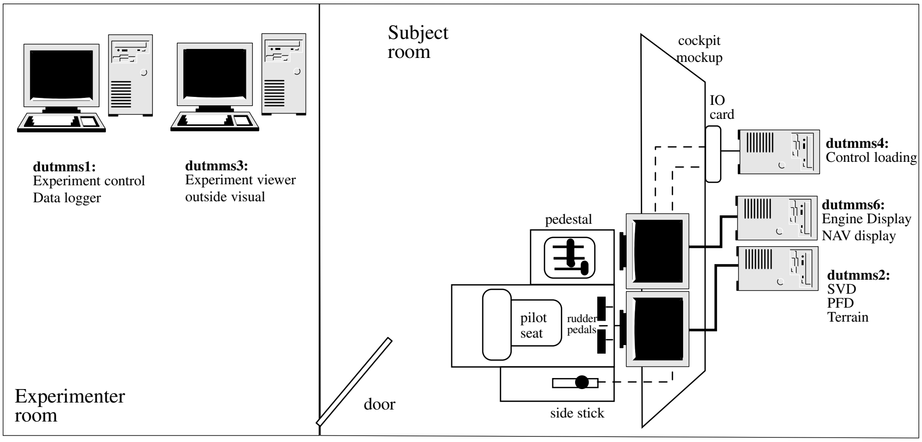


FIGURE A-1: Layout of the Human-Machine Systems laboratory fixed-base flight simulator.

In the experiment room an 18 inch LCD monitor mounted in a cockpit mockup is used to show the main cockpit interfaces, like a PFD, ND and a virtual MCP. No outside visual display was used in this thesis. The aircraft model is controlled by adjusting the virtual MCP settings, such as autopilot speed and heading, using a touchpad. In one experiment, workload was measured by a secondary task consisting of a critical tracking task that was shown on the same screen as the PFD. This tracking task was performed using an electro-hydraulic stick mounted to the right-hand side of the pilot.

Simulation software

Timing, communication, and actuation The implementation of the simulations was done in the Delft University Environment for Communication and Actuation (DUECA). DUECA is a software environment developed at Delft University of Technology for real-time distributed simulation and facilitates the implementation of a data-flow architecture. The DUECA simulation framework is written in C++ and currently works under Unix-based operating systems.

Aircraft dynamics In all on-line experiments, the aircraft dynamics were modeled using a six degree-of-freedom non-linear mathematical model of a B747-200 model. This model was controlled through an autopilot, manipulated through the virtual MCP, which only reacted to horizontal state change commands. The autopilot remained engaged during the entire run.

Graphics The interfaces were programmed in C^{++} using openGL-based software libraries.

B

Example briefing

This appendix contains an example briefing, used for the XATP-PASAS comparison discussed in Chapter 3 "Introducing XATP, and comparing it with PASAS".

Pilot Briefing

June 10, 2005

First of all thank you for agreeing to participate in this experiment. To prepare yourself for the experiment session please take the time to read through this briefing so you will know what the experiment is about, how the displays work and how the experiment session is setup. In addition to this document, you will be given a short briefing on the day of the experiment, and you will have the opportunity to test the displays. Any questions you may have about the experiment will be answered during that time.

1 Background

In the current system, aircraft fly ATC preferred trajectories. The opposite is called a User Preferred Trajectory (UPT), and this means that the aircraft can fly where and how *they* want to fly, as opposed to flying how ATC wants them to. This has several benefits over ATC preferred trajectories. One concept implementing user preferred trajectories, is Free Flight. The FAA has been spending a lot of resources on Free Flight, and is working closely with different parties in the American airline business to find solutions to the current problems in the National Airspace System and to implement these solutions. Although the FAA is strictly an American instution, the leverage it has is enough to make Free Flight a point of research in the rest of the world. Because of the amount of research done on Free Flight, several implementations have been designed. During this experiment two such implementations will be tested, and compared to each other.

The first implementation is XATP, which has been developed at DUT. The second implementation that is considered is the PASAS system designed by NLR. Both displays aim to provide the pilot with information on what paths are conflict-free but leave the final decision of what path to fly to the pilot.

The goal of this research is to find out which of the two displays is better, both in terms of performance and in terms of workload.

2 Display Designs

One thing that is common to both display designs is the Protected Zone (PZ). This is an imaginary cylinder around each aircraft with a height of 2000ft and a diameter of 10 nautical miles (which corresponds to the current separation minimums above FL290). To prevent aircraft from getting too close to another, no aircraft may *enter* the cylinder of another aircraft.

Since this experiment concerns only the horizontal plane, these cylinders are reduced to circles. These circles are displayed on the ND (see figure 1). In this image you can see three other aircraft. The current positon of our own aircraft is at the intersection of the fuselage and the wings of the aircraft at the bottom center of the image. All aircraft within range (160 NM) appear on the ND as a small icon. Each aircraft is flying in the direction of the arrow inside the white circle (so KL471 has heading 270). The callsign of each aircraft is plotted as is the difference in flightlevels (a positive number indicates the other aircraft is above the own aircraft) (here all aircraft are at the same flightlevel).

The outer circle around each aircraft signifies the PZ of that aircraft. If the PZ is red, then the current aircraft state will lead to an intrusion of that aircrafts PZ within 3 minutes. If the PZ is orange (yellow in the image for KL744) then an intrusion will occur between 3 and 5 minutes from now. Else the PZ is grey.

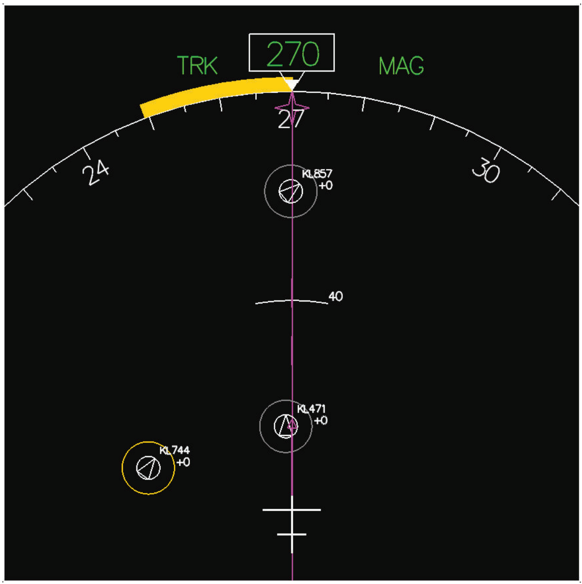
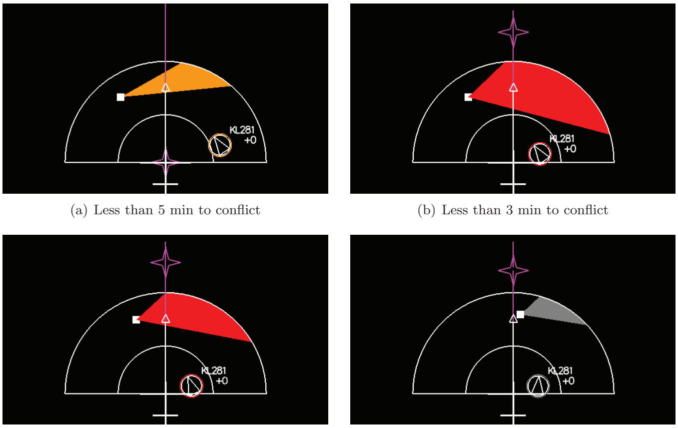


Figure 1: Protected Zones on the ND

2.1 XATP

XATP aims is to provide the pilot with information that allows him/her to select a safe path for the next 10/15 minutes.

In figure 2 you can see an example of an XATP display. This is the so called State Vector Envelope (SVE). There are a couple of elements of interest here. First of all the white arrow that starts at the own position and extends upwards. This arrow represents the own speed. Behind this white arrow is a similar arrow in purple (not visible here, see figure 3 for an example). This purple



(a) Less than 5 min to conflict

(b) Less than 3 min to conflict

(c) Other aircraft is turning

(d) Other aircraft has solved conflict by turning

Figure 2: The progression of an XATP conflict

arrow represents the commanded heading and speed. If you change any of those settings on the MCP, the purple arrow will move.

Since an aircraft has a maximum and a minimum speed, these have also been included in the SVE. The speeds used here correspond to 160 and 390 knots IAS. They are represented by the two white arcs. The white and purple arrows will remain between these two arcs during normal flight. They are an indication of how much the own aircraft state can still be changed in any given direction. The minimum and maximum speed have also been added to the speeddial on the PFD as two red bugs. These bugs are present in both the XATP and PASAS displays.

The next element in these images is the most important one; the Forbidden Beam Zone (FBZ). The FBZ is the triangle that has been clipped by the outer arc (orange in the first image, red in the second and third, and grey in the fourth image). The origin of the FBZ is located at the white square. Each aircraft in the vicinity will create its own FBZ. The FBZ shown here is caused by KL281 (also visible in the image).

The position of this white square (and thereby the origin of the FBZ) is determined by the heading and groundspeed of the other aircraft. The distance between the square and the own position is proportional to the groundspeed (in this example this distance is almost equal to the length of the white arrow, which tells us that KL281 is flying at almost the same speed as we are). The angle to the FBZ origin indicates the heading of the other aircraft.

The direction of the FBZ triangle is dependent on where the other aircraft is located with respect to our own position. In this example KL281 is located to the right of us, and slightly ahead. Therefore the triangle also extends to the right and a little bit to the front of the white square. The angle between the two sides of the triangle indicates how close the other aircraft is. In the second image the angle is much larger since KL281 is now closer to our own position.

In the third image we can see how the FBZ changes if the other aircraft changes heading. The angle between the two sides is almost equal to that in the second image, and so is the direction of the triangle. We can conclude that KL281 is in almost the same position as in image two. This is confirmed by the position of the aircraft symbol in the ND. However, the white square has changed position. The distance from the own position to the white square seems to be unchanged, but the angle to it *has* changed. We can conclude that KL281 has not changed speed, but has only changed his heading to the right.

In the last image, KL281 has solved the conflict by turning to an almost parallel course. The angle between the two sides of the FBZ is smaller again (see further for an explanation), but the direction of the triangle is almost the same as in the other figures, so KL281 is still located to the right and slightly ahead of us. From the origin of the FBZ (the white square) we can conclude that KL281 is flying a parallel course at almost the same speed (the white square is located very near the tip of the white arrow).

The colors of the FBZ are linked to the colors of the PZ of KL281. If a conflict will happen within 3 minutes, the FBZ is colored red, if it will happen in 3 to 5 minutes, it is colored orange, else it is colored grey.

The name Forbidden Beam Zone comes from the fact that to remain conflict free, the own speed (white arrow) must not be located inside a FBZ. If it is located inside a FBZ, then at some time in the future an intrusion will occur (the time to intrusion is indicated by the color of the FBZ). In figure 3 the current state (white arrow) would lead to intrusion with two aircraft, so a new heading and speed has been chosen which is outside both FBZs (purple arrow). The autopilot will change the aircraft state to match those of the purple arrow. (Figure 3 also shows how an SVE might look with two aircraft in the vicinity, see if you understand why the FBZs look like they do).

When commanding a change of state, this state change doesn't happen instantaneously. It will take some time before the aircraft has attained the commanded state. If the state changes are large, then this time can be in the order of 30 seconds or more. During this time, the conflict geometry may change. Normally this change is small and insignificant, but when the time to intrusion is very short and the distance between the aircraft is small, the change becomes very significant. Because of this ATP was extended to take into account this change. This works by predicting the future positions of each aircraft and calculating the FBZ at that time. However, these calculations are only guarenteed to succeed if two aircraft are currently in conflict. As you change your state to avoid an intrusion, these calculations will significantly effect the side of the FBZ triangle you are *not* crossing to solve the conflict. At the moment you leave the FBZ, this additional calculation is aborted and the FBZ sides will revert to their position at the current time. This will *not* effect the side you have exited the FBZ by, but the other side could potentially 'jump' back quite visibly. This effect is what causes the FBZ in image 4 to have a smaller angle than in image 2 and 3; the bottom side of the FBZ has just 'jumped' up a bit.

2.2 PASAS

PASAS stands for Predictive Airborne Separation Assurance System and was developed at the NLR. The system is meant to provide information to the pilot so that (s)he may control the aircraft in a safe way in a Free Flight environment. To do this, PASAS displays several items:

- Heading bands
- Speed bands
- Vertical speed bands

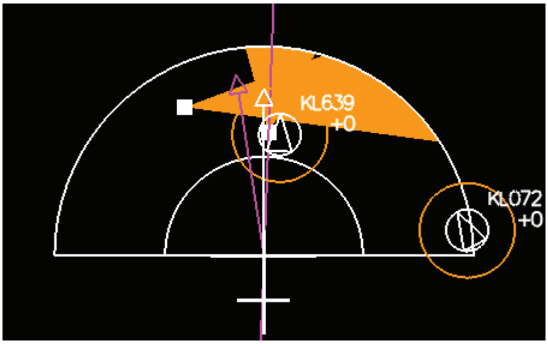


Figure 3: Solving an XATP conflict

These bands are displayed on the PFD (speed and vertical speed bands) and on the ND (heading bands) and represent 'un-safe' zones. Since this experiment only concerns itself with the horizontal plane, the vertical speed bands will not be present during the experiments. All of these bands come in two versions; an amber version, and a red version. If the pilot selects a state inside an amber band, that maneuver will lead to an intrusion of the other aircrafts PZ within 3-5 minutes. Similarly, an intrusion will occur within 3 minutes if a state inside a red band is selected (see also figures 6 and 7). Naturally, these bands are not static, but change according to the movement of both aircraft (the own aircraft, and the aircraft that causes the bands to appear). It is therefore possible that these bands initially do not impose on the current state, but that after a while they enclose the current state of the own aircraft, necessitating action.

In figure 6 an example is given of an aircraft approaching from the right (the same situation as in the XATP example). In the first image a small band becomes visible on the compass of the ND. When KL281 comes closer, this band slowly grows until it encompases our current heading (the second image). At this point, an intrusion will happen within 5 minutes. A red band has also appeared. If we select a heading of 25 deg., we will be placing our heading inside the red band. We will turn toward the aircraft, thereby decreasing the time until intrusion to less than 3 minutes. If we do nothing, the bands will increase (third image). In this case, a heading change to the left would avoid the future intrusion. In the fourth image, KL281 has again made a heading change to the right, such that a parallel course is followed. At this point, KL281 is almost beside us, and barely ahead of us. If we follow our current heading, no intrusion will occur, but if we turn to the right we will create a new conflict.

Figure 7 shows an example of a slower aircraft directly ahead of us. In the first image, all is well. We can see that if we increase IAS to 360 knots, we will intrude upon the aircrafts PZ in 5 minutes. In the ND (not shown here), no bands will be visible because no heading leads to intrusion within 5 minutes. In the second image, we have begun to catch up to the other aircraft, and although we are still safe, the increase needed to intrude within 5 minutes is almost nothing. In a few seconds the band will enclose the current IAS. At this point, heading bands will appear on the ND as well, enclosing our current heading. In the third image, we are so close that even at the current speed we will intrude within 5 minutes. If we do not take action, the red band will soon enclose our current IAS, signifying 3 minutes until intrusion. The heading band will have widend a bit. To avoid this intrusion we can either slow down (to 260 knots at the time of the third image), or change heading. In this case, the latter option would be preferable (see below for an explanation).

The PASAS displays seem very straight forward. However, there is a small detail that you should be aware of. Because the bands only indicate which states will lead to an intrusion within 5 minutes, a state outside the bands, is not guarenteed to remain conflict free (it could lead to an intrusion in 6 or 7 minutes). In the second example (the overtaking of a slower aircraft) we could have taken action at the time of the second image. By lowering our speed 10 or 20 knots, the band would not have enclosed our own speed at that point. However, we would most probably still have been flying faster than the other aircraft, and so the speedband would have enclosed our future speed as well at some point. We would then have to take additional action. This property is different from XATP; a state outside all FBZs in an XATP display will remain safe if no aircraft changes state, whereas a state outside all bands in PASAS might become unsafe in a couple of minutes.

2.3 MCP

A virtual MCP will be located above the ND. Only three things can be controlled; the viewing range of the ND (the left green circle), the indicated airspeed (the middle green circle) and the heading (right green circle).

Figure 4: The virtual MCP

3 Experiment Design

The experiment will be performed in the Human Machine Laboratory at the Aerospace Faculty of the Delft University of Technology. This lab houses a fixed-base flight simulator, with no outside visuals. You will be seated in the co-pilot position. Flight instruments (PFD, ND and MCP) are displayed on two 18" LCD screens. MCP and ND are shown on the center screen which is vertically oriented, PFD is shown on the right screen (directly in front of the co-pilot position). The autopilot will be engaged during the entire run, and you will control the aircraft state using only the autopilot, by controlling the virtual MCP with a touchpad. Vertical aircraft control will be disabled, since this experiment only investigates performance in the horizontal plane. To measure workload, a secondary task consisting of a tracking task will be shown on the same screen as the PFD. This tracking task is controlled with a side stick.

The experiment will be conducted with a non-linear B747-200 model with six degrees of freedom. This model will be controlled through an autopilot which only has two degrees of freedom (heading and speed). The aircraft is trimmed to fly at an altitude of 30000ft at an airspeed of 300 kts IAS.

Primary Task *Your primary task will be to follow the track given by the waypoints. During this flight you may not intrude in the Protected Zone of other aircraft in the vicinity.*

During the run you are expected to keep to an airspeed of 300 kts IAS when there is no conflict. When solving a conflict you may deviate from this airspeed, but you should return to it once you feel it is safe to do so. You are expected to follow the track created by the waypoints as closely as you can, but you may deviate from the course to avoid a conflict. When you feel it is safe to do so, you are expected to return to the track. No preference is give as to how you solve a conflict, by speed change or heading change, or a combination of both. The displays will assist you in this task.

Secondary Task *Your secondary task will be to perform a tracking task.*
The purpose of this secondary task is to measure your workload. As such, it is important that you do your best at this task, but *not* at the expense of the primary task.

This tracking task is a critical tracking task. This means that as the error between the position to follow, and the controlled position increases, it becomes more difficult to diminish that error. An example of a critical tracking task is an inverted pendulum, or broomstick. If you put an inverted broomstick on your hand and then release it, it will start to fall over. By moving your hand you can prevent it from doing so. However, the further it has fallen before you take action, the more action you need to take and the harder it is to prevent it from falling over entirely. This tracking task is similar to that. However, the longer you are able to successfully control the task, the more difficult it will become. This can be compared to the broomstick getting shorter if you are successful in keeping it upright. A shorter broomstick becomes more difficult to control.

The time you can keep the pendulum within certain limits is a measure of the amount of attention you are giving to the secondary task. If you are giving the secondary task your full attention, you should be able to keep the pendulum within bounds. After it falls over, it will immediately start again (although you should have time to return the side stick to it's neutral position). Do not be bothered by the failure of keeping the pendulum balanced, this is by design.

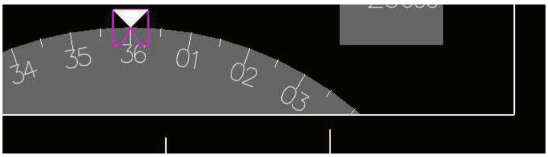


Figure 5: Tracking task

The tracking task is located beneath the PFD. The longer line (with a slightly reddish color) is the line you control. The shorter line in the center is the target. The target is stationary. The task requires you to move the tracker back to the center position. This will require a deflection of the sidestick *in the direction of the center.*

3.1 Conditions

During the experiment three different conditions will be changed; *display configuration*, *traffic density* and *conflict geometry*.

3.1.1 Display Configuration

Two displays will be used. The difference between the two displays is the core of this experiment.

PASAS A display that shows no-go bands on the speeddial on the PFD and on the compass in the ND.

XATP This display show a State Vector Envelope on the ND, which creates a no-go zone.

3.1.2 Traffic Density

In an attempt to see how the displays will perform in the future two different traffic densities will be tested. The lower traffic density should be about equal to current day density, whereas the higher traffic density will be about three times as high.

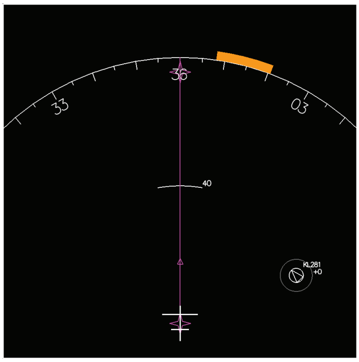
3.1.3 Conflict Geometry

To test the performance of both displays in different conflict geometries, you will encounter several different situations. Each situtation has a different optimal solution.

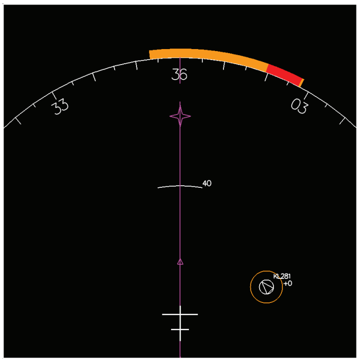
3.2 Schedule

The experiment will begin with a short briefing, meant to clarify any questions you may have, and to give some more examples of how the displays behave and how they change during a conflict. After this briefing, you will have the chance to test the two displays during a couple of short test runs. Additional questions on the behavior of the displays will be answered as they come up. When you feel at ease with the displays, the measurement runs will begin. There are 14 runs in total, each lasting about 10 minutes. Breaks can be taken as needed. After all runs have been completed, a subjective questionnaire needs to be filled out.

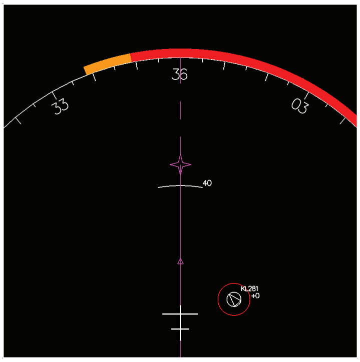
The complete experiment should take about $4\frac{1}{2}$ hours.



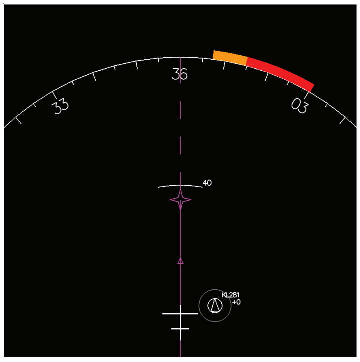
(a) No conflict within 5 min



(b) Less than 5 min to conflict

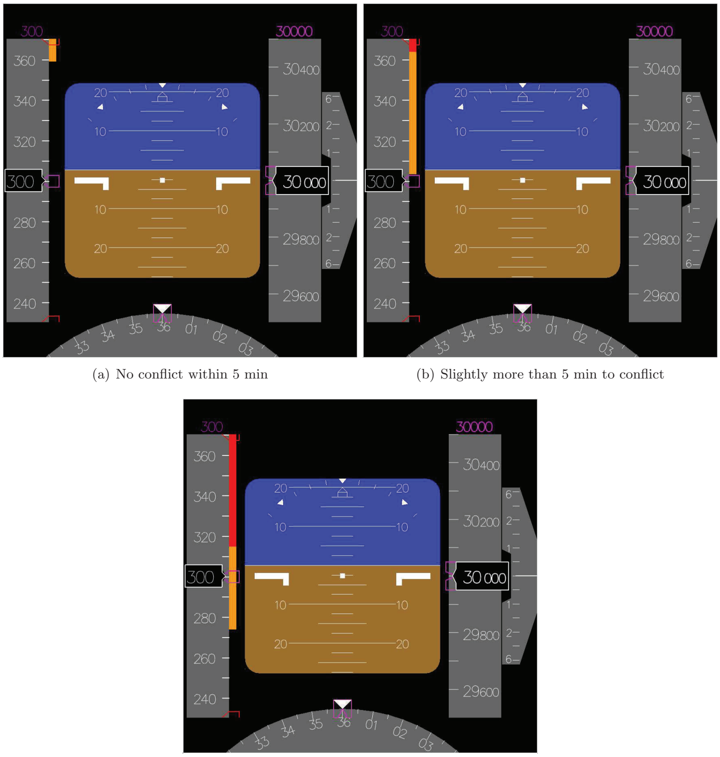


(c) Less than 3 min to conflict



(d) Other aircraft has solved conflict by turning

Figure 6: The progression of a PASAS conflict



(a) No conflict within 5 min

(b) Slightly more than 5 min to conflict

(c) Less than 5 min to conflict

Figure 7: The progression of a PASAS conflict with a slower aircraft

C

Example questionnaire

This appendix contains an example questionnaire, used for the XATP-PASAS comparison discussed in Chapter 3 "Introducing XATP, and comparing it with PASAS".

Pilot Questionnaire

Pilot Information

Name: ....
Date: ....
Year of birth: ....
Training: ○ Military ○ Civil

In the table below, indicate the total amount of flight hours you have for the different aircraft types you have flown.

Aircraft type	Number of hours

In the table below, indicate if you have had experience with the following experiments or instrumentation systems, and your level of knowledge in their use.

System	None	Low	Medium	High
(E)GPWS				
TCAS				
ACAS				
(P)ASAS				
ATP				

PASAS

PASAS was the display with the orange and red bands on the speedscale and on the compass in the ND.

Acceptance

What is your general opinion of the PASAS display after the experiment?

( ) The displays are confusing. I would never want this implemented in real instruments.
( ) The displays are not useful to me. I am not bothered by their presence, but they have no additional value to me.
( ) The displays are useful, even though they do not enhance my situational awareness.
( ) The displays are extremely useful, both in helping me navigate conflicts and in improving my situational awareness. I would like to see this implemented.
( ) other:
....
....

Behaviour

When do you begin an avoidance maneuver?

( ) I try to avoid conflicts before they happen by staying out of the bands when they are growing towards my current state.
( ) I wait until the bands contain my current state, and then I take action to put my state just outside the bands.
( ) I take a look at the situation and how the bands are evolving and then change my state to what I think will be a safe state.
( ) If a situation looks threatening I will take action immediately, if it seems less threatening I will wait to see how it evolves before taking action.
( ) other:
....
....

If your current state is conflict free, do you pay attention to the PASAS bands?

( ) I don't pay attention to them until they cover the current state.
( ) I look at them to see where I can't go should I wish to make a manoeuvre.
( ) I use them to get a clearer image of the traffic around me.
( ) I check the trend. How are the bands evolving? I am safe now, but will it stay that way?
( ) other:
....
....

After solving the conflict(s), what steering strategy do you use to return to the original track?

( ) I try to keep close to the edge of the bands, by making many small adjustments.
( ) I wait until the state I need to return is free and only then start a recovery maneuver
( ) I wait until the entire conflict has passed and I have free airspace in front of me before returning.
( ) other:
....
....

Awareness

Did you know how much time you had until the conflict took place)?

( ) No, not at all.
( ) Some notion.
( ) Yes, I had a pretty good idea.

Did you know how much time you had left before you had to make a manoeuvre?

( ) No, not at all.
( ) Some notion.
( ) Yes, I had a pretty good idea.

How did you decide how urgent a conflict was?

( ) Proximity of other aircraft on the Navigation Display.
( ) Color of the bands.
( ) Evolution of the bands.
( ) The time that bands had already been on the display.
( ) other:
....
....

Did you feel you could go through the bands to attain a better solution?

( ) Yes.
( ) Yes, but I didn't do it because I wasn't sure.
( ) No.

Did you know which aircraft caused which band?

( ) Yes.
( ) Most of the time.
( ) Sometimes.
( ) No.

Traffic

The following questions only refer to the PASAS display.

Did you notice a difference between the different scenarios in the density of the traffic?

( ) Yes.
( ) I'm not sure.
( ) No.

If you did notice a difference, in which density did the PASAS display aid you most and why?

( ) High density.
( ) Low density.
( ) Equal.

Interface Design

What are in your opinion the biggest shortcomings of PASAS?

....
....
....

Is there any information you miss on the PASAS display?

....
....
....

Do you have any suggestions for improving the PASAS display?

....
....
....

XATP

XATP was the display with the triangles in the center of the ND.

Acceptance

What is your general opinion of the XATP display after the experiment?

( ) The display is confusing. I would never want this implemented in real instruments.
( ) The display is not useful to me. I am not bothered by it's presence, but it has no additional value to me.
( ) The display is useful, even though it does not enhance my situational awareness.
( ) The display is extremely useful, both in helping me navigate conflicts and in improving my situational awareness. I would like to see this implemented.
other:

Behaviour

When do you begin an avoidance maneouvre?

( ) I take action before a FBZ encompasses my state.
( ) I wait until a FBZ contains my current state, but is still grey.
( ) I wait until a FBZ turns orange, indicating 5 minutes to collision.
( ) I wait until a FBZ turns red, indicating 3 minutes to collision.
other:
....
....

What strategy do you use when avoiding a conflict?

( ) I try to avoid conflicts before they happen by staying out of a FBZ when it is growing towards my current state.
( ) I take action to put my state just outside a FBZ.
( ) I take action to put my state quite a bit outside a FBZ, just to be on the safe side.

If your current state is conflict free, do you pay attention to the FBZ(s)?

( ) I don't pay attention to the FBZ(s) until it covers the current state.
( ) I look at the FBZ(s) to see where I can't go should I wish to make a manoeuvre.
( ) I use the FBZ(s) to get a clearer image of the traffic around me.

After solving the conflict(s), what steering strategy do you use to return to the original track?

( ) I try to keep close to the edge of the bands, by making many small adjustments.
( ) I wait until the state I need to return is free and only then start a recovery maneouvre.
( ) I wait until the entire conflict has passed and I have free airspace in front of me before returning.

Awareness

Did you know how much time you had until the conflict took place)?

( ) No, not at all.
( ) Some notion.
( ) Yes, I had a pretty good idea.

Did you know how much time you had left before you had to make a maneouvre?

( ) No, not at all.
( ) Some notion.
( ) Yes, I had a pretty good idea.

How did you decide how urgent a conflict was?

( ) Proximity of other aircraft on the Navigation Display.
( ) Color of the FBZ.
( ) Evolution of the FBZ.
( ) The time that the FBZ had already been on the display.

Did you feel you could go through a FBZ to attain a better solution?

( ) Yes.
( ) Yes, but I didn't do it because I wasn't sure.
( ) No.

Did you know which aircraft caused which FBZ?

( ) Yes.
( ) Most of the time.
( ) Sometimes.
( ) No.

Traffic

The following questions only refer to the XATP display.

Did you notice a difference between the different scenarios in the density of the traffic?

( ) Yes.
( ) I'm not sure.
( ) No.

If you did notice a difference, in which density did the XATP display aid you most and why?

( ) High density.
( ) Low density.
( ) Equal.

Because:
....
....

Interface Design

What are in your opinion the biggest shortcomings of XATP?

....
....
....

Is there any information you miss on the XATP display?

....
....
....

Do you have any suggestions for improving the XATP display?

....
....
....

Comparison

Which display did you find most useful for conflicts which required a heading change to solve?

( ) PASAS by far
( ) PASAS a little bit
( ) Equal
( ) XATP a little bit
( ) XATP by far

Which display did you find most useful for conflicts which required a speed change to solve?

( ) PASAS by far
( ) PASAS a little bit
( ) Equal
( ) XATP a little bit
( ) XATP by far

Which display did you find most useful for conflicts which required both speed changes and heading changes to solve?

( ) PASAS by far
( ) PASAS a little bit
( ) Equal
( ) XATP a little bit
( ) XATP by far

Which display did you find needed less concentration during use?

( ) PASAS by far
( ) PASAS a little bit
( ) Equal
( ) XATP a little bit
( ) XATP by far

Which display helped your situational awareness most?

( ) PASAS by far
( ) PASAS a little bit
( ) Equal
( ) XATP a little bit
( ) XATP by far

Which display did you prefer and why?

( ) PASAS by far
( ) PASAS a little bit
( ) Neither
( ) XATP a little bit
( ) XATP by far

Because:
....
....

Space for comments:

....
....
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Abbreviations

ADS-B	Automatic Dependent Surveillance - Broadcast
$ANOVA$	Analysis of Variance
$ASAS$	Airborne Separation Assistance System
AH	Abstraction Hierarchy
ATP	Airborne Trajectory Planning
CPA	Closest Point of Approach
CSE	Cognitive Systems Engineering
CWA	Cognitive Work Analysis
CTA	Control Task Analysis
DL	Decision Ladder
EID	Ecological Interface Design
FCU	Flight Control Unit
FM	Functional Modeling
FMS	Flight Management System
FBZ	Forbidden Beam Zone
HTF	Heading Travel Function
MCP	Mode Control Panel
ND	Navigation Display
NLR	National Aerospace Laboratory
$PASAS$	Predictive ASAS
PFD	Primary Flight Display
PZ	Protected Zone
SA	Situation Awareness
SRK	Skills, Rules, Knowledge
SVE	State Vector Envelope

$SHTF$	Speed-Heading Travel Function
TCP	Trajectory Change Point
TCR	Trajectory Change Report
TSR	Trajectory State Report
$XATP$	eXtended Airborne Trajectory Planning
WDA	Work Domain Analysis

Subscripts

int	intruder aircraft
own	own aircraft
rel	relative
on	FMS on, MCP-FCU mode
off	FMS off, FMS-RNAV mode

Samenvatting

Toekomstige concepten voor luchtverkeer voorzien dat, in het ongecontroleerde deel van het luchtruim, de vliegers de taak en verantwoordelijkheid krijgen om separatie van hun vliegtuig te waarborgen voor ander verkeer. Dit met als doel de werklast bij verkeersleiders en de resulterende beperkingen op de capaciteit van het luchtruim te reduceren. Er zijn al technologie-gedreven separatie-displays voor piloten ontwikkeld die hen helpt om conflicten af the handelen door middel van het tonen van expliciete geautomatiseerde oplossingen. Deze systemen bieden geen transparante kijk op de logica van de automatisering, waardoor het voor piloten moeilijk is om de juistheid van de geautomatiseerde oplossing te valideren, of om zelf alternatieve oplossingen te bedenken die voldoende veilig zijn. De fundamentele vraagstelling die dit proefschrift onderzoekt is te bepalen 'welke informatie' en 'in welke visuele vorm' het best het toestandsbewustzijn (Eng. Situation Awareness, SA) van de piloot kan bevordered, zodat deze op een veilige en efficiënte manier kan omgaan met het omringende verkeer. Om dit te onderzoeken zijn verscheidene prototypes van een cockpit traject-planningstool ontworpen en geëvalueerd.

De ecologische interface ontwerpmethode (Eng. Ecological Interface Design, EID) is een formatieve ontwerpmethode die zich richt op het visualiseren van begrenzingen. Deze methode werd toegepast teneinde een 'ecologisch' cockpit hulpsysteem voor gedecentraliseerde separatie te creëren. De ecologisch benadering geeft voorrang aan de operators' omgeving, of 'ecologie', en focust op hoe deze omgeving beperkingen oplegt aan het werk van de operator. In vergelijking met normatieve, taak- en gebruikers-georiënteerde ontwerpmethodes, zou de EID methode moeten leiden tot een verbetering van het operator's toestandsbewustzijn en van de systeemveiligheid, in het bijzonder wanneer zich situaties voordoen die ontwerpers vooraf niet hadden konden voorzien.

EID start met een analyse van het werkdomein (Eng. Work Domain Analysis (WDA)). De WDA is een activiteit-onafhankelijke analyse die zich richt op het identificeren en onderzoeken van doel-relevante begrenzingen (en hun onderlinge relaties) die het gedrag van de mens en de automatisering mee bepalen. Oorspronkelijk werd EID toegepast op procesbesturing en de toepassing van WDA op het gebied van voertuigbesturing heeft enkele veranderingen met zich meegebracht op de vijf gebruikelijke niveaus van functionele abstractie. De meest betekenisvolle uitdaging vond plaats op het niveau van de Abstracte Functie. Hier werden de typische beschrijvingen uit de literatuur, gebaseerd op massa- en energiestromen, vervangen door beschrijvingen van de fysische vliegtuigbewegingswetten, absolute en relatieve beweging en de geometrische eigenschappen van het separatieprobleem.

Vervolgens gaat de methode verder met het feitelijke ontwerp van de interface. De literatuur herkent dat er in deze fase een ‘creatieve kloof’ bestaat tussen de cognitieve werkdomeinanalyse en het feitelijke ontwerp van de interface. Deze thesis toont aan dat het mogelijk is deze kloof te dichten door het vinden van ‘betekenisvolle fysica’: alternatieve beschrijvingen van de begrenzingen (in het bijzonder op het niveau van de abstracte functie). Deze beschrijvingen geven enerzijds een meer ‘praktische’ koppeling tussen de voertuigbesturing en de weergave van de begrenzingen, en anderzijds een ‘functionele’ koppeling tussen de objectieven van het systeem en deze weergave. De praktische koppeling werd bereikt door vliegtuigbeweging te beschrijven in een beperkt aantal dimensies die overeenkomen met de huidige vliegpraktijk en het huidige ontwerp van cockpit displays. De functionele koppeling kwam tot stand door de interne begrenzingen, veroorzaakt door de vliegprestaties, te beschrijven in samenhang met externe bewegingsbegrenzingen, veroorzaakt door het omringende verkeer.

Uit dit onderzoek blijkt dat een conflict situatie tussen twee vliegtuigen niet op een gepaste wijze gevisualiseerd kan worden in een ‘absolute bewegingsvlak, dit omdat het dynamisch gedrag van de geometrische conflict-eigenschappen te dynamisch en complex is. Wanneer beweging echter ‘relatief’ aan het conflicterende vliegtuig wordt beschreven, dan worden deze eigenschappen veel ‘statischer’ en beter te begrijpen. Op basis van deze bevinding werd het weergave-concept van de conflictzone (Eng. Forbidden Beam Zone, FBZ) ontwikkeld. Om de koppeling met het vliegen in de praktijk te versterken, werd de FBZ naar het absolute bewegingsvlak getransleerd, en werd het separatie-probleem terug naar het natuurlijke (snelheidsvector) actie-ruimte van de piloot gebracht. Als gevolg hiervan illustreert de FBZ op een bijna perfecte manier hoe de conflictgeometrie de navigatiemogelijkheden van het eigen vliegtuig beperkt.

Om verdere integratie met de hedendaagse displays te faciliteren, werd de ecologische visualisatie verder geïntegreerd in de bestaande (horizontale en verticale) navigatiedisplays. De beste overeenkomst met de 'huidige ecologie' van het vliegen werd bereikt door de oorsprong van de bewegingsruimte te plaatsen op de positie van het eigen vliegtuig. Hierdoor ontstaat een directe visuele mapping tussen de conflictzones (FBZs) en de locatie van conflicterende vliegtuigen die deze FBZ's veroorzaken. De resulterende interface wordt de (eXtended) Airborne Trajectory Planner (X)ATP genoemd.

Tijdens het onderzoek voor deze thesis werd duidelijk dat bij elke iteratie van werkdomeinanalyse, interface ontwerp en experimentele evaluatie, ook de relaties tussen verschillende delen in de functionele abstractie hirarchie van de WDA op hun beurt veel duidelijker werden. De ecologische laag maakte niet alleen op het display direct zichtbaar hoe men efficiënt een conflict kan vermijden, het voorzag de piloot ook met een uitgebreide set van 'betekenisvolle' contextuele informatie. Deze informatie heeft het potentieel om het toestandsbewustzijn tijdens conflictsituaties significant te verbeteren. De rijkdom aan informatie op het display is verbazingwekkend en zelfs tot op het einde van dit project werden nog steeds nieuwe nuttige eigenschappen ontdekt.

In de vele domeinen waar EID toegepast wordt, blijft het objectief vergelijken van traditionele taak-georiënteerde displays met ecologische displays een van de fundamentele uitdagingen. In deze thesis werden twee separatiedisplays met elkaar uitgebreid vergeleken: enerzijds predictive-ASAS (PASAS), een traditioneel ontwerp, anderzijds XATP, het resultaat van de ecologische ontwerpmethode. De PASAS banden werden uitgekozen als een levensvatbaar technologiegedreven alternatief voor het ecologische ontwerp. Vanuit een evolutionair perspectief werden deze 'no-go' banden in de snelheids- en heading taper ontwerpen om het ontstaan van nieuwe conflicten te vermijden wanneer piloten automatische ASAS oplossingen implementeerden. Deze banden zijn in feite ook een presentatie gebaseerd op de visualisatie van begrenzingen, met het verschil dat deze presentatie een in essentie tweedimensionale snelheid-heading oplossingsruimte uitgesplitst in twee ééndimensionale 'speed-only' en 'heading-only' oplossingsruimtes.

In een eerste experimentele vergelijkingsstudie tussen XATP en PASAS, werd voor dit laatste concept enkel de 'no-go' banden gebruikt teneinde een eerlijke vergelijking op basis van een gelijke automatiseringsgraad te bekomen. Omdat in het traditionele display een geautomatiseerde oplossingsadvies ontbrak, was de verwachting dat wanneer er tussen de twee systemen verschillend pilootgedrag werd waargenomen, er een rechtstreeks verband bestond met de verschillen tussen beide display representaties. Er werden echter tussen beide displays geen verschillen in de vorm van vliegerprestaties en werklast geïdentificeerd. Dit leidde tot de conclusie dat er geen direct verband bestaat tussen het toestandsbewustzijn van de piloot enerzijds, en taak-prestatie en werklast anderzijds.

Dit gegeven leidde op zijn beurt tot een verschuiving in de evaluatiemethodologie van een cognitieve taak-georiënteerde aanpak gebaseerd op het meten van werklast en taakprestatie naar een aanpak waar toestandsbewustzijn in conflictsituaties direct gemeten wordt. Hierbij werden de PASAS heading- en snelheidsbanden vervolledigd met een expliciet geautomatiseerd oplossingsadvies op basis van taper markers. De resultaten van deze vergelijking toonden aan dat het ecologische display de piloot meer ondersteuning biedt bij het omgaan met onvoorziene situaties en het creëren van een beter mentaal model van een conflict situatie. In het algemeen was het toestandsbewustzijn hoger maar dit resulteerde niet in betere prestaties. Wat betreft het evalueren van ontwerpen in onvoorziene gebeurtenissen, bleek dat de introductie van onwaarschijnlijke voorvallen zoals een 'vijandige manoeuvre' van een nabij vliegtuig, weinig succes had. Dit zal nog steeds een uitdaging blijven. Om voldoende experimentele data te verkrijgen, is het namelijk noodzakelijk deze voorvallen meerdere keren te herhalen, wat dan weer de 'waarschijnlijkheid' van het voorval beïnvloedt.

De experimentele resultaten tonen verder aan dat de één-dimensionale banden in complexe situaties in minder toestandsbewustzijn voorzien en meer cognitieve inspanning vragen om de situatie te begrijpen in vergelijking met XATP, waardoor de meerderheid van de piloten het ecologische display verkiest in deze condities. Er is bewijs gevonden voor de hypothese dat wanneer men de dimensie van de oplossingsruimte reduceert (zoals het geval is bij de PASAS banden) dit weliswaar voordelig zou kunnen zijn door verlaging van de cognitieve belasting nodig voor het selecteren en uitvoeren van geautomatiseerde oplossingen. Het desintegreert echter ook de 'conflict situatie' en zou dus in feite van piloten een grotere cognitieve inspanning vragen om zich een correct en compleet mentaal model van de situatie te vormen; dit laatste met een gunstig effect op het toestandsbewustzijn van de piloot, en van de luchtverkeersveiligheid.

Tenslotte blijkt uit alle experimenten die in dit proefschrift werden uitgevoerd dat gebruikers van ecologische interfaces meer uitgebreide instructies en meer gebruikservaring (training) nodig hebben alvorens zij het gedrag en de dynamica van werkdomeingrenzen gevisualiseerd op de interface beginnen te begrijpen. De tijdschaal van vele piloot experimenten was te beperkt om dit effect te kunnen merken. Ecologische interfaces zijn niet bedoeld voor onervaren gebruikers, en het ligt ook niet in de verwachting dat zulke displays onervaren gebruikers snel zullen omvormen tot experten. Ecologische interfaces zijn expert-interfaces gemaakt voor experts, en zouden op deze manier ook behandeld moeten worden.

Dit proefschrift toont verder aan dat een ecologisch separatie-display door piloten gebruikt kan worden om separatie met het omliggende verkeer te verzekeren zonder enige hulp van automatisering. Desalniettemin werd bij verscheidene situaties opgemerkt dat de basispresentatie van de FBZ mogelijk niet voldoende ondersteuning biedt. Ten eerste, teneinde de beste 'globale' optimale oplossing te krijgen tijdens multi-conflict situaties zou automatisering een rol kunnen spelen door de beste weg uit het conflict uit te rekenen voor alle vliegtuigen, en door aan te geven welk vliegtuig als eerste zou moeten manoeuvreren. Ten tweede, de effecten van onmiddellijke of geplande intentie-informatie op de representatie van grenzen zijn gemodelleerd, en prototypes voor visualisaties werden ontwikkeld. Hierbij blijkt dat het toevoegen van verkeersintentie onvermijdelijk meer grenzen in het werkdomein introduceert in verscheidene dimensies, en mogelijk leidt tot een overvolle interface die moeilijk te gebruiken is.

Deze bevindingen brengen ons wederom tot de fundamentele vraag: Welke graad van automatisering is nodig om effectieve mens-machine interactie te garanderen? Enkele opties om de overweldigende complexiteit te reduceren zou kunnen zijn: de beslissing welke van de betrokken piloten eerst moet reageren automatiseren, de beslissing van het aan en uitzetten van de actieve automatiserings-mode automatiseren, het introduceren van een zeker vorm van expliciet advies, enzovoort. Ongeacht het antwoord op deze vraag, gelden de grenzen van het werkdomein, die door ecologische displays gerepresenteerd worden, evenzeer voor de piloot als voor de automatisering, en bijgevolg zijn dit steeds geldige displays die dienst kunnen doen als een venster op de rationale achter de geautomatiseerde oplossing (of suggestie) waardoor de transparantie van de automatisering merkbaar toeneemt. Dit resulteert waarschijnlijk ook in een hogere mate van vertrouwen van de piloot in de automatisering en zou kunnen betekenen dat piloten oplossingen met een hogere graad van automatisering accepteren.

In deze thesis werd de vliegveiligheid gemeten aan de hand van de minimale afstand tussen twee vliegtuigen en het verlies van separatie. In het algemeen tonen de experimenten aan dat zowel met de ecologische als traditionele interfaces slechts enkele kleine schendingen van de separatie-norm is voorgekomen. Het visualiseren van de uiterste grenzen voor acties heeft soms als effect dat piloten deze begrenzingen meer opzoeken. Dit effect van risico-migratie is eigen aan alle mens-machine systemen. Het wordt aanbevolen om het bestaan en de toepasbaarheid van ecologische maateenheden voor veiligheid te bestuderen. Een juiste modellering van de geometrische eigenschappen van de FBZs kan leiden tot meer ecologische beschrijvingen voor de ernst en urgentie van conflicten in het bijzonder, en voor vliegveiligheid in het algemeen.

Uit dit proefschrift concluderen we het volgende. Allereerst toont dit werk duidelijk aan dat een ecologisch display die een diepere laag van informatie voorziet zonder enige hulp van automatisering in de vorm van expliciete adviezen, even veilig en effectief kan zijn als traditionele displays die hoofdzakelijk expliciete automatische adviezen presenteren. Ten tweede, het ontwerp van ecologische interfaces in domeinen waar de abstracte functies minder vanzelfsprekend zijn, zoals het probleem van gedecentraliseerde separatie hier bestudeerd, haalt voordeel uit een oplopende, evolutionaire benadering. EID is inderdaad geen recept. Ten derde, de vergelijking met het meer traditionele ontwerp maakte duidelijk dat ondanks dat het reduceren van de dimensies van de oplossingsruimte voordelig is doordat het de cognitieve last reduceert, het uiteindelijk kan leiden tot meer cognitieve last voor operatoren teneinde een correct en compleet mentaal model van de situatie op te bouwen. Ten vierde, en in verband met het vorige, alhoewel een gepaste ecologisch-geïnspireerde interface de piloot minder afhankelijk maakt van een expliciet dwingend advies, kan het toevoegen van dimensies aan de besturingsacties van de piloot (bv. rekening houdend met meer en meer begrenzingen) het ecologische display te complex maken om gebruikt te worden zonder enige vorm van automatisch advies.

De aanbevelingen van deze thesis zijn de volgende. Ten eerste, alhoewel er bewijs werd gevonden voor de hypothese dat ecologische interfaces piloten beter ondersteunen bij zeldzame en onvoorziene situaties, blijft dit een belangrijke punt voor toekomstig onderzoek. Ten tweede, de horizontale en verticale ontwerpen zouden beter geïntegreerd moeten worden teneinde de volledige dimensionaliteit van het drie-dimensionale separatie-probleem. De ecologische displays zouden ook in staat moeten zijn om 4D routebeheer te faciliteren, omdat alles te herleiden is tot de relatieve beweging van voertuigen in ruimte en tijd. Ten derde zou het erg interessant zijn om ecologische interfaces experimenteel te evalueren in situaties waarbij meerdere piloten de interface tegelijkertijd en in dezelfde ruimte gebruiken, aangezien er meer kans bestaat op voorvallen waar het onvoorziene gedrag van één van de betrokken piloten weer onvoorziene en ‘willekeurige’ gebeurtenissen tot gevolg heeft. Deze gebeurtenissen zijn het moeilijkst te definiëren op voorhand. Ten vierde, de bevindingen in deze thesis vragen om het mogelijke gebruik van ecologische interface ontwerpen als trainingsmiddel te onderzoeken, aangezien dit het leereffect over de fysica die het werkdomein bepaalt, op lange termijn bevordert. Dit is mogelijk door het tonen van de ecologische laag als beslissingshulp terwijl men de dimensies van de taak leert alsook de onderliggende redenering van de automatisering begrijpt. Deze benadering zou ook een succesvolle introductie van ‘hybride’ systeemontwerpen in de toekomst kunnen aanmoedigen.

Uiteindelijk vormen de ecologische interface-‘lagen’ die ontwikkeld zijn in deze thesis wellicht de ontbrekende schakel om tot het ontwerp van een Joint Cognitive System (JCS) te komen. De ecologische laag kan namelijk gebruikt worden om het gat te dichten tussen het toestandsbewustzijn gedeeld tussen de automatisering en de piloot, en hierdoor stelt het piloten in staat om beter de betrouwbaarheid van de voorgestelde oplossing te beoordelen, en, in het geval de automatisering faalt, om alternatieve oplossingen te vinden die voldoende veilig zijn. In die zin sluiten traditionele taak-georinteerde displays en ecologische displays elkaars gebruik in één systeem niet uit. Integendeel; waar taak-georiënteerde ondersteuning in eenvoudige standaardsituaties de cognitieve last beperkt door de beschikbaarheid van gebruiksvriendelijke geautomatiseerde instructies, toont de ecologische beslissingsondersteuning de 'totale situatie' zodat de operator een expert kan worden en zodat hij met onvoorziene gebeurtenissen kan omgaan. Bij de inspanningen om tot een JCS ontwerp te komen, bestaat de sleutel uit het gebruik van automatisering als een middel om cognitieve last te verlagen en beslissingen te verbeteren op zo'n manier dat het de voordelen van de ecologische eigenschappen van het ontwerp niet teniet doet.

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Curriculum Vitae

Stijn Van Dam was born on 25 April 1979 in Duffel, Belgium. From 1991 to 1997, he attended the Sint-Teresiacollege in Kapelle-op-den-Bos, obtaining the certificate of General Secondary Education.

In 1997 he enrolled as a student at the Faculty of Aerospace Engineering at the Delft University of Technology. As part of the masters programme he received an Erasmus exchange grant at the Universidad Politécnica de Madrid. In April 2004 he received his Master of Science in Aerospace Engineering, graduating at the section of Control and Simulation. The graduation work concerned the initial ecological interface design for the horizontal plane, and formed the basis of this PhD thesis.

After graduation, Stijn remained attached to the same university as a researcher at the Aerospace Software and Technologies Institute, ASTI. His research concerned the design of ecological human-machine interfaces for vehicle navigation and traffic management in the aviation and maritime domains. In 2005 he started as an PhD student within ASTI supervised by the section Control and Simulation of the Aerospace Engineering faculty, TU Delft.

Stijn is currently working as an IT consultant involved in the development and integration of Information Management systems in work domains such as Plan Management and Design Engineering.