Designing for Situation Awareness
Aviation Perspective

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Abstract: In the design of human-machine interfaces and automation, an important question is how to obtain and validate a design that is capable of supporting the operator's understanding and situation awareness of the process under control. Whereas many research efforts address the question of 'what is the operator aware of?' – the awareness – only a few investigations focus on studying what the operator *should* be aware of in the first place, i.e., 'what is the situation?' In this paper we briefly discuss some of our research activities which aim at answering this second question, following an 'ecological approach' to interface design. The clever use of automation tools and novel visualizations will be presented that allows human operators working in aviation (pilots, air traffic controllers) in dealing with complex tasks. The airborne self-separation task will be discussed, as an example of showing how ecological interfaces can support pilots in their decision making.

1 INTRODUCTION

In the design of human-machine systems, interface designers and automation engineers face a number of problems. How to develop automation, and an interface to help the human operator properly use the automation, to create a working environment with a suitable workload, high performance and operator job satisfaction, and guarantee safe, efficient and effective operation? The advent of powerful digital computers and versatile multi-modal interfaces has resulted in an unprecedented freedom in automation and interface design. In aviation, our domain, it has resulted in a socio-technical system that has an unsurpassed level of safety, making air transportation one of the safest means of travel all around the world.

In the highly-automated cockpit of today, computers perform the majority of the work, and the pilots are responsible for monitoring and supervising the automation functions and performance. In the vast majority of cases this leads to a satisfactory performance, but in cases where automation fails, the crew can sometimes be confronted with situations where they must make split-second decisions on how to proceed, causing peak levels of workload, and sometimes putting the aircraft and its passengers in dangerous situations. Examples are when, for instance because of sloppy maintenance or extremely bad weather conditions, basic sensors for measuring the aircraft's velocity and height fail. These failures can propagate through the automated functions, causing automation to function improperly, or fail altogether.

In these situations it is crucial that the pilots have, or quickly regain, a good awareness and understanding of the situation at hand. And indeed, since the rapid increase of automation levels in the cockpit in the late 1980s, 'situation awareness' (SA) studies have dominated research and development of current and novel human-machine systems in aviation. Pioneering work was conducted by Endsley, leading to her three-level model comprising 'perception', 'comprehension' and 'projection' (Endsley, 1995a; Endsley, 1995b) and the following definition of SA: *"the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their status into the future"*. The concept of situation awareness has been the subject of many follow-up studies, and often heated scientific debate on whether it is properly grounded, and overviews showed that quickly after its first inception more than twenty-seven other possible 'definitions' of the SA concept were published in the literature (Breton and Rousseau, 2001).

Apart from the theoretical debate on proper definitions and grounding of situation awareness in cognitive science, the concept is often used in evaluating the quality of human-machine interfaces. It is assumed that a 'good' interface leads to a 'high level'

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of SA, and vice versa. Then, to 'measure' SA, a variety of tools has been developed over the years that allow experimenters to include SA as one of the dependent measures (besides mental workload, human-machine system performance, etc.) in their evaluations. Examples are SPAM, SAGAT, SABARS, WOMBAT, SART, etcetera, that all aim to measure the 'awareness' of the operator; again, see (Breton and Rousseau, 2001) for an overview.

Typical for most studies, is that experimenters have some idea of what the operator *should be aware of*, and then measure the level in which this is correct, or not. An example is whether pilots know the aircraft velocity and height above terrain during an approach to landing, which are indeed crucial for safety and performance. A too low velocity may cause the aircraft to stall, a too high velocity may cause it to hit the runway surface too hard. But apart from these clear-cut cases that are easily understood, and the awareness of which can be easily measured, the analysis of "what needs to be known" by pilots becomes more cumbersome (and more difficult to measure) when the situation becomes more complicated. It is a fact that measuring the operator's awareness of certain system 'states' does not mean that the operator truly and fully understands what exactly is happening, which may require a deeper understanding of the functioning of the system, and the various means available to reach the ends of operating safely and effectively.

As an example, consider the situation where an aircraft is making an approach to landing, using a conventional three-degree glide path as a reference. When the aircraft is, at some point during the approach, flying higher than the reference path with a velocity that is somewhat too low, then surely we can measure the 'awareness' of the pilot of the fact that these two states are off-nominal, by asking her about her altitude and speed relative to the path. However, we do *not* measure the awareness of the pilot that in this *situation* she can easily bring the states back to their nominal values by simply *exchanging* the higher-than-required potential energy (height) with the lower-than-required kinetic energy (speed), through using the elevator control to put the nose of the aircraft down. We argue that the responsibility for understanding this situation lies not only in the pilot, but also in the experimenter, who should ask the 'right' question about what this situation actually means, and analyze the different representations in which one can frame the questions on SA.

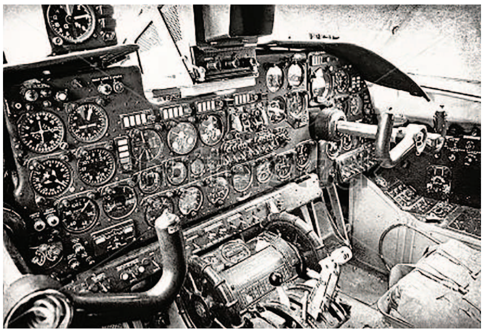
In the work in our lab we therefore aim to obtain knowledge about what 'situations' actually are. That is, whereas many focus on studying the 'awareness' part of operators when dealing with situations which the experimenter has (quickly, if not to say shallowly) analyzed, to ask the operator the 'right' questions to measure SA, we put most of our efforts in understanding the situations (Flach et al., 2004). In this paper we will discuss our approach, which is based on an analysis of the work domain at various levels of abstraction, adopting the key elements and tools of Rasmussen's and Vicente's 'ecological' approach to interface design (Vicente and Rasmussen, 1990; Vicente and Rasmussen, 1992; Vicente, 1999).

We focus on aviation, and start with brief introductions of 'classical' flight deck design and the ecological approach in Sections 2 and 3, respectively. We then use an example of how we designed an ecological interface to support pilots in performing the (future) task of self-separation in Section 4. Here, pilots must change their aircraft state (heading, speed, altitude) in such a way that they do not interfere with the trajectories of other aircraft surrounding them. The new interface is expected to provide a better support for pilots than a conventional engineering representation, because it attempts to capture and visualize the separation 'situation' in such a way that a pilot can directly see what the situation "is", what it "means" in the context of being responsible for a safe and productive flight, and "how to respond". The paper will end with some closing statements in Section 5.

2 FLIGHT DECK DESIGN

Fig. 1 illustrates how, in the past 50 years, the classic aircraft cockpit – comprised of many individual electro-mechanical instruments – evolved to become the modern "glass cockpit" – with large electronic and programmable displays. Introducing novel automation has reduced the flight crew to only two persons, and changed the role of the pilot from a manual controller to a supervisor of a highly-automated, complex system (Wiener and Curry, 1980; Billings, 1997).

In the 1960s' cockpits of commercial aircraft, all available information was presented to the pilots, navigators and flight deck engineer on a large array of electro-mechanical instruments. Generally speaking, everything that could be measured was presented, in an attempt to provide the humans on-board with as much information as possible. The crew then had to integrate all this information, and form a "mental picture" of the current state of the aircraft, predict that state and act on it in a way that satisfied the mission goals. Most of the "cognition" was to be done by the human operators and because of the plethora of information and the dial-and-gauge interface design, their workload was high and performance relatively low.



(a) classic

(b) modern

Figure 1: Evolution of the aviation flight deck.

This led cockpit design engineers to conclude that, apparently, despite all their efforts in creating cockpits that contained all information necessary to fly, the task is in fact too difficult for humans and could perhaps be done better by a computer.

Hence, in the modern cockpit most of the basic flying tasks (closing the nested loops of control, guidance, and navigation) have been automated, and most of the work to be done *and the corresponding cognition needed* to perform the job was moved to clever computer algorithms. As a result, most of the time the workload is low, to (steeply) increase only in situations that are unanticipated by the automation designers, causing the automation to malfunction or not function at all. And here it is where the other side of the automation coin appears. Driven away from the basic control loops, the pilots sometimes have low situation awareness, must make split-second decisions in situations that automation cannot handle, potentially contributing to human error.

In the evolution from the classic cockpit to the modern flight deck, several useful and important interface design principles have been developed. Examples are studies that stress the importance of proper illumination, readability, and the use of colors and symbols, and later studies that have led to the 'laws' of integrated, configural or object displays, emergent features and the "principle of the moving part" (Johnson and Roscoe, 1972; Roscoe et al., 1981). These design principles are valid and improve access to data, the transfer of information from sensors to humans. They provide little help, however, for the designer to determine the "right" representation of the world, one that facilitates human-automation teamwork, and support the human pilot's creative abilities.

Classic cockpits are examples of a design philosophy called a "single sensor, single indicator" (SSSI) (Vicente and Rasmussen, 1990), where one presents all information available in a readable format, communicating with the humans on the level of *signals* (Rasmussen, 1983). Since it is very difficult for pilots to integrate all this information, automation was introduced to help them improve their performance and reduce their workload, moving much of the thinking to be done into computer algorithms. Within their limited scope of the problem domain, these algorithms perform automatically, sometimes warning the pilots for potential 'problems', i.e., communicating with them on the level of *signs*, intended to elicit predetermined (trained) solutions to situations that were anticipated in the design of the automation. But what about situations that were not anticipated beforehand, that extend beyond the limited scope of the algorithms? How to deal with the inevitable unanticipated variability in this complex domain?

We believe that, in the absence of some omniscient artificially intelligent entity that can cope with this variability, we should strive for supporting productive thinking of pilots, enabling them to creatively invent solutions to these emergent, unexpected, multi-dimensional problems. This requires that pilots learn and maintain representations of the deep structure of the work domain, through proper training and working with interfaces that communicate situations.

3 ECOLOGICAL APPROACH

In our work, we strive for a human-machine system – defined here as automation and interfaces – that *shares* the cognitive work between the automation and humans. It is clear that much of the work to be done can be performed much better (more accurate, much faster, with many dimensions to simultaneously optimize) by computer algorithms. But since these algorithms are invariably – and perhaps even inevitably – limited in their scope and understanding of the world in which they operate, at some point the crew needs to be involved to decide in situations where automation cannot decide, or interfere in situations where automation fails. We aim for a work environment where the crew is involved, with reasonable workload, high SA, working on representations of the world that can be *shared* between automated and human agents (Woods and Hollnagel, 2006; Van Paassen et al., 2013; Klomp et al., 2016).

One of the main starting points of our work is the classification that a flight deck as an *open* system (Vicente, 1999). It has many "interfaces" with its environment, e.g., weather, other traffic, terrain, air traffic control (ATC). It has an extensive and sometimes rather complicated interaction with the environment, which makes its operation to be unpredictable, and *one cannot imagine and anticipate for all possible events in advance*. In the absence of an infinitely clever computer agent, as we see in science fiction movies (e.g., HAL9000 in "2001 A Space Odyssey"), we continue to depend on the adaptability of humans to deal with the unanticipated variability.

To support humans in their cognitive work, it is important to consider one of the main strengths of the human mind. One of the distinctive features of human intelligence is our amazing capacity to learn, detect and use patterns and relations between our actions and what we perceive. Hence, we attempt to design graphical representations that provide 'natural' patterns that are linked to functionally-relevant relations among the state variables, such that humans become 'aware' of situations with minimal cognitive effort. Our interface designs literally "show" the problem space to the pilot, and allow her to "work" on it, in such a way that she can use the display representation as a template. This "problem space," however, is often not normally visible to the human eye, as in our everyday activities such as eating a meal, walk through a shopping center, and ride a bicycle.

In his "ecological" approach to visual perception, Gibson emphasizes the "direct perception" capabilities of humans, and the direct couplings that exist between perception and action (Gibson, 1966; Gibson, 1986). He introduced the concept of "affordance", possibilities and constraints for actions and achieving goals, specified by the natural environment. Take for example a pile of wood found on a beach. Depending on the situation at hand, a hungry person could use the logs to cook; when cold, one could make a fire to warm-up; Robinson Crusoe would perhaps try to make a raft; when it starts raining one could try to create an opportunity for shelter. This is just a sub-set of possible meanings that the pile of wood may have for an actor in the environment, all specified by the natural display that can be directly perceived.

Vicente and Rasmussen took this stance when proposing their "ecological approach" to design interfaces for complex systems (Vicente and Rasmussen, 1990; Vicente and Rasmussen, 1992). In Ecological Interface Design (EID) one aims to transfer the cognitive process of understanding and interacting with complex systems to a *perceptual* process, where operators interact with representations of that complex process on (usually graphical) interfaces. An important difference with interacting in the natural world is that complex systems do often not allow humans to "step-in and explore". Rather, the interface is the *medium* for interaction, and an ecological interface should try to reveal the deep structure of the work domain in a way that is compatible with human perception, to *make visible the invisible*.

In his book "Cognitive Work Analysis," Vicente proposes six steps in the development of an ecological display: Work Domain Analysis, Control Task Analysis, Strategies Analysis, an Analysis of Social Organization and Cooperation, Worker Competencies Analysis, and finally the interface design (Vicente, 1999). The Work Domain Analysis (WDA) is the most important one, as here the interface designer must analyze the basic functioning of the work domain for which the system has to fulfil its purpose. Rather than trying to understand the cognitive processes that may guide the operator (or computer algorithm) in doing the work, the WDA focuses on the environment and the ways in which the world constraints and physical laws afford actions. Developing an appropriate representation of this "action space," *independent of the human or automated agent* – a representation that is true and valid for both – stands at the center of the ecological approach.

In the past decades we developed several ecological interfaces for the flight deck. Examples are a Total Energy management display for basic aircraft symmetrical flight control, that enables pilots to understand and act on exchanging their aircraft potential and kinetic energy (Amelink et al., 2005), Separation Assistance displays that allow pilots to better understand and act on other traffic (Van Dam et al., 2008; Ellerbroek et al., 2011; Ellerbroek et al., 2013b; Ellerbroek et al., 2013a), an ecological Synthetic Vision display (Borst et al., 2006; Borst et al., 2008; Borst et al., 2010), and a display to work on four-dimensional aircraft trajectories (Mulder et al., 2010; Van Marwijk et al., 2011) We also explored various EID designs for air traffic controllers in current and future air traffic management environments (Tielrooij et al., 2010; Klomp et al., 2011; Van der Eijk et al., 2012; De Leege et al., 2013; Van Paassen et al., 2013; Klomp et al., 2016), and controllers of multiple unmanned aerial vehicles (Fuchs et al., 2014).

A common misconception on EID (Borst et al., 2015) is that the ecological interface is simple, and easy-to-use, one that quickly turns novices into experts. On the contrary, ecological interfaces are designed for complex work and the complexity of the work domain is reflected by the complexity in the visual interface (Flach, 2012). Ecological interfaces are made by experts to be used by experts, and it requires the analyst to understand the problem space of the work domain extremely well. This makes EID a rather difficult and sometimes tedious approach to interface design, one that easily fails. Generally speaking, perhaps the approach better fits engineers than human factors specialists, as it requires the analyst to focus on the governing (often physical, dynamic) principles of "the world" – the environment in which the brain operates – rather than the brain itself. It requires one to study what's happening *outside* of the human head, not inside.

4 EXAMPLE: AIRBORNE SELF-SEPARATION

In the example we discuss the development of an ecological interface that supports pilots in the task of maintaining a safe separation with other traffic flying in the vicinity of their own aircraft. Currently this is a task done by air traffic control, but in the future parts of the airspace may become unmanaged, and here the pilots and their automation systems will become responsible for the separation task (SESAR, 2007).

An airborne separation assistance system (ASAS) involves *"the equipment, protocols, airborne surveillance and <...> which enable the pilot to exercise responsibility, <...> for separation of his aircraft from one or more aircraft"* (ICAO SICASP/6-WP/44). The ASAS functionalities, i.e., the work to be done by automation and/or pilot, include: i) maintaining an overview of the surrounding traffic; ii) detecting potential loss of separation conflicts; iii) resolving conflicts and iv) preventing aircraft from running into new conflicts. Note that a 'conflict' is defined here as a *potential* loss of separation, in the future.

The development of ASAS systems has received a lot of attention in the past decades and various prototypes have been built and tested (for an overview see (Hoekstra, 2001)). Common to many ASAS designs is that they rely on trajectory prediction algorithms which compute the "closest point of approach" (CPA) and then have another computer algorithm "reason about" the best way to deal with situations where the CPA is predicted to become too small. Typically these algorithms are programmed into a computer, and then the interface designer is brought into play to create the interface. In the light of the discussion in Section 2: cognition is being put into the computer, hidden from the pilot, and communication is done at the level of signals (where is the other aircraft?) and signs (are we moving too close? warn the pilot!).

Not surprisingly, in many ASAS evaluations the typical 'ironies' of automation (Bainbridge, 1983; Parasuraman and Riley, 1997) appeared: hidden rationale, confusion of the automation intent, disagreement, lack of trust or complacency, low situation awareness. "Why does the automation propose this solution?", "What will happen when I follow the automation's advice?", and "What if I don't?".

Apart from these issues, it is a fact that there will always be cases which the automation designers and engineers did not think of, because of the open and complex nature of interaction of the aircraft in its environment. In addition, cockpit automation is typically only aware of a *part* of the situation (e.g., it considers traffic) and ignorant of other constraints to flight (e.g., terrain). Current automation does not fully support pilots in these multi-constraint situations.

Before we start with the WDA, one should keep in mind that self-separation problems typically evolve very slowly. ASAS systems work with time horizons of 3 to 5 minutes, with aircraft flying several hundreds of miles apart, requiring pilots to zoom out their navigation display to see the other aircraft, moving very slowly on the display. This makes it very difficult for them to detect possible conflict situations, and manage their resolution. Clearly, there is a need here to make the separation task more "compatible" to human perception, and make visible the invisible.

4.1 Work Domain Analysis

In our work on the ASAS problem, which took us several years, we were interested in finding a different representation of the traffic separation problem, other than the CPA-based solutions developed before. Would there be a way to communicate with the pilot at the "symbol" level, such that she would understand the separation situation at a glance, directly act on it, with or without the help of automation?

In an effort to construct a proper Abstraction Hierarchy (AH), we started with numerous computer simulations of approaching aircraft, trying to figure out what are the physical laws and abstract functions that govern the dynamics of the separation control problem. We applied Rasmussen's AH (Rasmussen et al., 1994), at the five common levels of abstraction: Functional purpose, Abstract function, Generalized function, Physical function and Physical form. Fig. 2 illustrates one of the AH's resulting from the analysis. At each particular level, one considers the work domain at that level of abstraction, answering the question "WHAT" happens on this level? Going one level

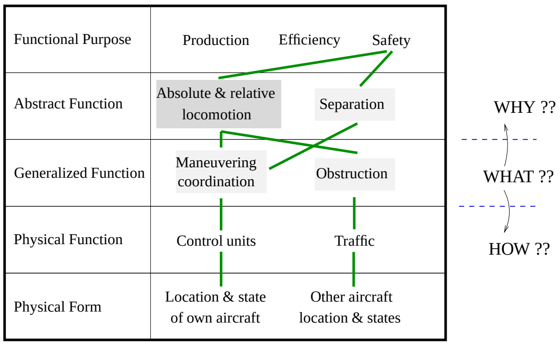


Figure 2: Abstraction Hierarchy for the separation assistance work domain.

up then answers the question of "WHY" we have this function, and moving one level down then answers "HOW" the function is being performed.

An analysis of computer simulations of aircraft flying in a two-dimensional airspace led us to the insight that two "travel functions" form the core of the separation problem. These act at the Abstract function level of the AH: 'absolute and relative locomotion', and 'separation' (Van Dam et al., 2008). Manipulating the relative motion of aircraft requires aircraft to maneuver, and these maneuvers should be coordinated such that separation is maintained; these are the Generalized functions.

At the highest level, Functional purpose, the goal of having an ASAS system is defined: ensure safety at all times. This was obvious from the start, but our simulations led us to add two more: be productive and efficient. For particular geometries we discovered that some maneuvers were indeed safe, but would lead to situations where aircraft needed to make a more than 90 degree turn, or even fly back, or that it would take very long for the conflict to be resolved.

Fig. 2 shows that at the Physical function level we see the actual traffic that flies within the vicinity of the own aircraft, and the control units that pilots have to manipulate the generalized functions: their cockpit interfaces to autopilot, throttle and flight management systems. At the Physical form level we see the state of the own aircraft and the locations and states of the other aircraft involved.

This AH has had numerous iterations, as can be seen in our publications over the years (Van Dam et al., 2008; Ellerbroek et al., 2011; Ellerbroek et al., 2013b). Indeed, we have been struggling with it for quite some time as, other than in process control where the abstract and generalized functions can be quickly connected to the physics of the plant being controlled (Vicente, 1999), in this separation problem the "physics" were not clear from the beginning. Of course, the physics of aircraft flight dynamics are known, but these are not very helpful in this particular problem; they well describe the motions of one aircraft, but not the physics of separating two (or more) aircraft. Hence, we developed our own "meaningful physics" (Van Paassen et al., 2005) for this problem through the computer simulations stated above, yielding the "travel functions."

4.2 Traditional and Ecological Approach

Reflecting on the "typical engineering approach" in the context of the AH that results from the WDA, we see that the computer algorithms are programmed to "understand" and "work on" especially the Abstract function and Generalized function levels. Through the cockpit interfaces, the pilots are shown the elements of the physical environment (other aircraft), the Physical form level, they have their control buttons and dials to provide new set-points to their automated agents, the Physical function level, and they are trained to understand the signals and signs that the ASAS system provides them at the Functional Purpose level. In this design, pilots will understand why the system is there (functional purpose), they are trained how to work with the system (physical function, physical form), but they get little insight into how the system actually works and deals with the environmental constraints (abstract and generalized function levels).

In other words, the rationale behind the signals and signs is "hidden" in the automation, and the pilot has little insight into understanding how the computer has interpreted and dealt with the traffic situation at the Abstract and Generalized function levels. And indeed this is typical for many of the human-machine systems and automated tools that have been developed for the flight deck, hiding the rationale from the pilots, putting the real cognition and processing of data and situations into actions and advice in pieces of automation that are non-transparent, leading to low situation awareness, workload peaks, and all the ironies of automation.

Clearly then, in an ecological interface design approach the rationale of the automated algorithms and the invisible but crucial elements of the world domain should be visualized. In our designs we therefore aim at "making visible the invisible", showing pilots the "world behind the glass" (Mulder, 2014) at the abstract and generalized function levels, such that with or without automated help they can reason about the traffic situation themselves. Without automation they should be able to detect and resolve conflicts themselves and also to do it in a way that is safe, effi-

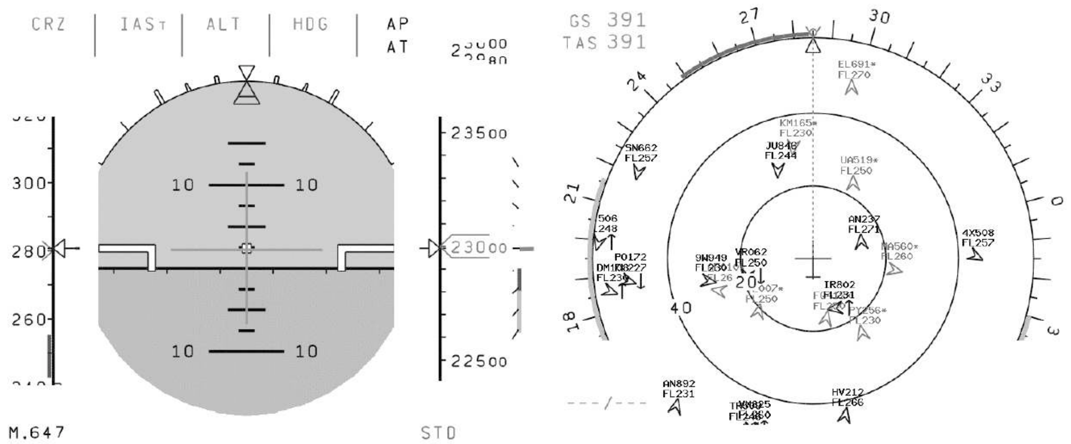


Figure 3: Predictive ASAS, an earlier design for airborne assistance. On the Primary Flight Display (left): speed bands and vertical speed bands; on the Navigation Display (right): heading bands. Figure obtained from (Ellerbroek, 2013).

cient and productive. With automation in place pilots should be able to (much) better understand the signals and signs (warnings and resolution advisories) that the automation provides, as the communication will also show the deep structure that provides a context for interpreting the meaning of these signals and signs as situations (Flach et al., 2004).

4.3 Traditional Design

In the past 25 years much research has been conducted on the self-separation problem, for instance in the context of the "Free Flight" programs that ran in the late 1990s. Numerous attempts were done to support pilots in understanding the essence of traffic conflicts and how the automation deals with them. Early visualizations showed the point of closest approach (CPA) on the navigation display, often graphically put onto the display as ellipsoidal "no-go" zones.

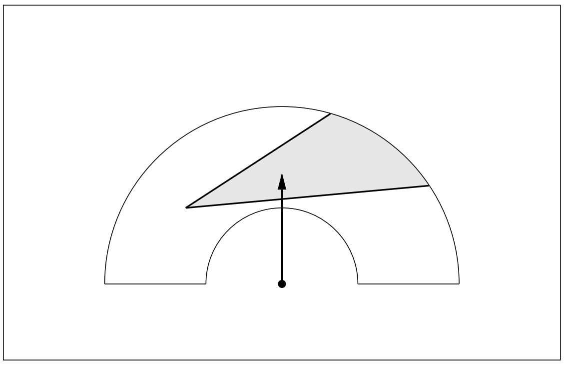
Evaluations with these no-go zones showed that new conflicts were triggered by maneuvers initiated to resolve other conflicts. Engineers then came up with predictive ASAS, based on computing "heading bands" and "speed bands", which show all possible headings of the own aircraft that would result in a conflict (*assuming constant current speed*) and all possible speeds that would result in a conflict (*assuming constant current heading*), respectively. Fig. 3 illustrates how the traditional Primary Flight Display (left) and Navigation Display (right) were extended with the speed bands and heading bands overlays. Here, the own aircraft is safe from conflicts, but the pilot must not initiate any heading changes to the left that are smaller than 35 degrees (heading band), or fly 15 knots slower (speed band).

Later a computer-aided "optimal" solution was also shown, usually a *combination* of speed and heading change, that was the best and most efficient way out of the conflict (Hoekstra, 2001). With the speed and heading bands, and the optimal solution presented, pilots indeed can see how to avoid other aircraft. They have a hard time, however, finding out themselves what would be the most efficient way to resolve the conflict and especially to see and check whether the computer-aided solution and heading and speed bands are in fact correct. And the optimal solution often appears right into the heading and speed bands that act as "no go" states, as it consists of a combination of heading and speed changes that are smaller than resolving the conflict with either heading or speed. This causes confusion and a lack of confidence, an automation irony at work. In addition, when the own aircraft is involved in a multi-aircraft conflict, more and more no-go bands are presented and it becomes difficult for pilots to relate these to the individual aircraft involved. This iteration of typical engineering and interface design did not end up with an easy-to-use interface. The representation of the problem taken – CPA, heading and speed bands – has in fact obscured the way the world works.

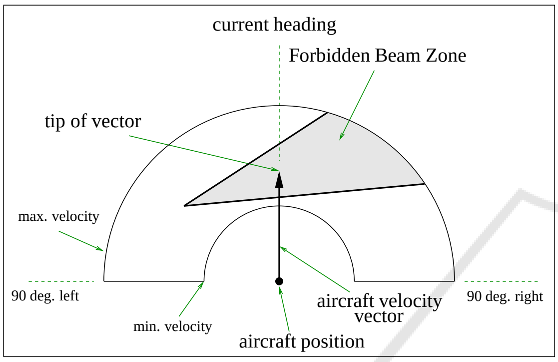
4.4 Ecological Design

We took a different approach to the problem, based on visualizing the full affordances of relative and absolute motion. For a comprehensive description of the design and the process we have gone through, the reader is referred to (Van Dam et al., 2008).

When the locations and velocities of all aircraft flying near the own aircraft are known, then we can compute the set of relative velocity vectors that will bring the own aircraft into a conflict situation with



(a) ecological overlay



(b) display elements

Figure 4: Simplified version of the Ecological separation assistance display: the "state-vector" envelope for 2D motion (top); elements of the display (bottom).

each other aircraft. The pilot must change the velocity *vector* of her own aircraft – its direction (=heading of the own aircraft) and/or magnitude (=speed of the own aircraft) – in such a way that its tip does not belong to this set. In this way we developed an own aircraft-centered presentation of this relative motion, which shows the affordances of "hit" and "avoid" that can be directly perceived and acted upon by the pilot (or automation). We later found out that in robotics similar solutions were developed (Tychonievich et al., 1989; Chakravarthy and Ghose, 1998; Fiorini and Shiller, 1998); we also found the Battenberg course indicator (dating back to 1892) which visualizes ship maneuvering constraints in a similar way. We extended and unified all existing solutions to their full *2D + time* potential in (Mercado-Velasco et al., 2015).

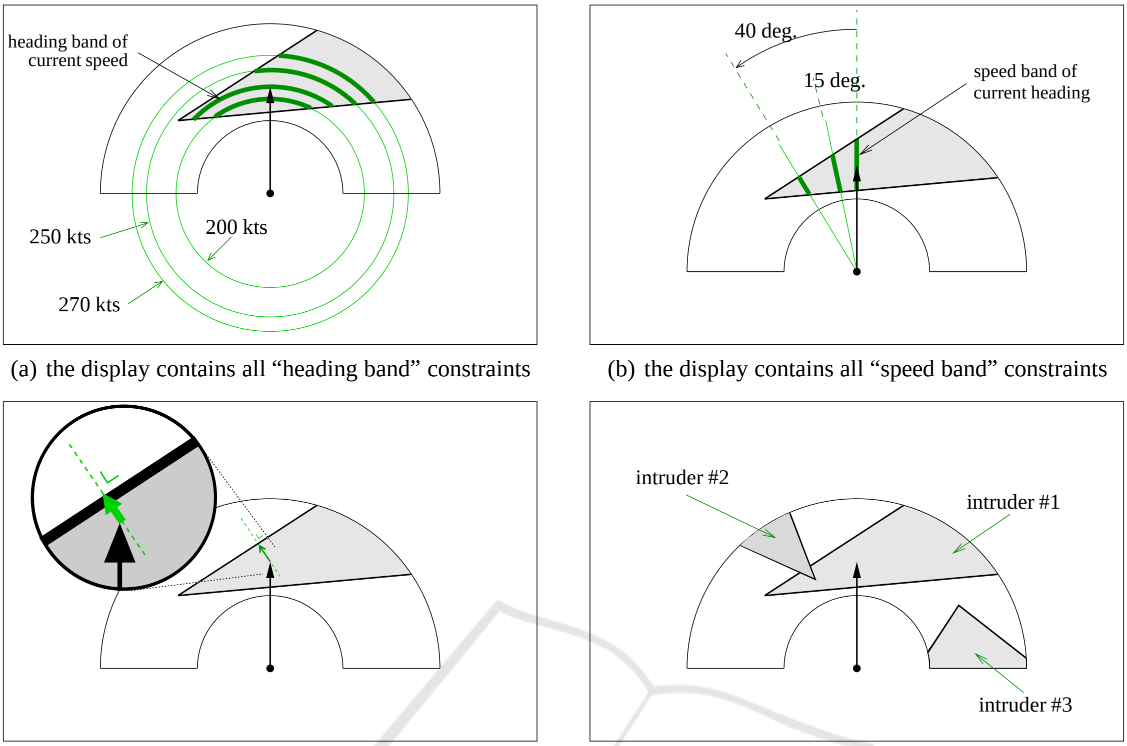
Fig. 4(a) shows the ecological ASAS display, in its most elementary form: a two-dimensional semi-circular presentation used as an overlay on the current Navigation Display, Fig. 3. Later we also developed vertical (Heylen et al., 2008), co-planar (Ellerbroek et al., 2013b; Ellerbroek et al., 2013a) and 3-D orthogonal (Ellerbroek et al., 2011) presentations.

Fig. 4(b) shows the display elements. The own aircraft 'velocity vector' is the first key element. The size of the vector can be changed, indicating speed changes: it can be made larger (fly faster) or smaller (fly slower), but the length cannot exceed the velocity limits indicated by the two semi-circles. The tip of the velocity vector cannot move out of these limits, which represent constraints "internal" to the own aircraft; they depend on performance limits (physical function). The direction of the vector can also change, i.e., rotated to the left and right, indicating heading changes. Heading changes larger than 90 degrees left or right are possible but are considered to be not very productive (functional purpose).

The second key element of the display is the triangular-shaped zone that visualizes the set of own aircraft velocity vectors that will result in a conflict with another near-by aircraft. All heading and speed settings of the own aircraft that result in the tip of the velocity vector to be located within this "forbidden beam zone" will be unsafe (functional purpose). Vice versa, all heading and speed settings of the own aircraft that result in a velocity vector tip outside this zone are safe. These constraints to our own aircraft motion are caused by the other aircraft, the "external" constraints to flight (abstract function).

With our display, pilots can directly perceive whether they are in conflict, and also that many options exist to get out of trouble by changing their aircraft speed, or heading, or both (generalized function). In the situation illustrated in Fig. 4, pointing the own aircraft velocity vector below the zone (i.e., slow down) means that the other aircraft will eventually pass us in front; pointing the vector above the zone (speed up) means that we will pass the other aircraft in front. We could also choose to maintain current speed, and turn the vector clockwise with, say, 40 degrees, which will also resolve the conflict and have the other aircraft pass us in front. Hence, the display shows the future consequences of our possible actions in a directly perceivable way. It explicitly visualizes the dynamics of relative motion (abstract function) and the ways to fulfill our functional purposes through manipulating this relative motion (generalized function). Our display properly visualizes and connects the means of flying (change heading, speed) with the ends of flight (being safe, productive and efficient), a true ecological interface (Van Dam et al., 2008).

Working with this representation led to some important insights. First of all, our display shows the complete "solution space" to pilots, and includes all possible heading bands (see Fig. 5(a)) and speed bands (see Fig. 5(b)) of the traditional design. That is, when reducing speed to, say, 200 kts, and then changing the aircraft heading, the part of the 200 kts-circle



(a) the display contains all "heading band" constraints

(b) the display contains all "speed band" constraints

(c) the display specifies the "optimal solution": the smallest state change

(d) the display specifies the constraints of multiple aircraft conflicts

Figure 5: Example of how the ecological separation display specifies all the constraints.

that coincides with the forbidden beam zone, equals the heading band computed by the predictive-ASAS algorithm. The forbidden beam zone represents all possible heading bands for this particular conflict, see Fig. 5(a). Similarly, for each possible heading change, like 40 degrees left of the current heading, the part of the 40 degree line that coincides with the forbidden zone, shows the velocities which lead to a conflict, the speed bands, see Fig. 5(b).

With this visual, *symbolic* presentation of the self-separation situation the pilot can also directly see the optimal solution: the smallest state change of the own velocity vector that will move the tip of the vector outside of the zone, see Fig. 5(c). Here, as shown by the zoomed-in inset of the figure, a small heading change to the left, combined with a small speed increase, will bring the tip of the own aircraft velocity vector outside of the zone, avoiding the conflict; the pilot can also directly see that she will then pass the other aircraft in front.

One of the most interesting characteristics of our display is that, when more aircraft are flying nearby, these may all cause external constraints that limit the own aircraft motion possibilities, limiting the solution space; see Fig. 5(d) for a situation with three other 'intruder' aircraft. In this rather complex situation, which may happen in very dense parts of the airspace, the pilot can directly see that a way to resolve the conflict with intruder #1, one that does not lead to conflicts with the other two intruders, would be to speed up, and move the tip of the velocity vector above the forbidden beam zone caused by the first intruder. He will then pass that aircraft in front, and also pass the other two aircraft in front. Hence, the display is also suitable for resolving multi-aircraft separation problems, although in these cases determining the best, optimal maneuver may be less obvious and could perhaps be found by an automated agent.

Fig. 6 shows the Navigation Display augmented with the ecological overlay at the bottom center. Here we have a conflict with two aircraft (callsigns AA386 and AA387), and one way to solve both conflicts would be to speed up, such that the own aircraft passes both other aircraft in front. Another solution (of many solutions!) would be to speed up a little and turn 30 degrees to the right, such that we pass AA386 in front, and we pass AA387 behind.

4.5 Lessons Learned

When considering the differences between traditional designs and ecological designs, the latter are richer

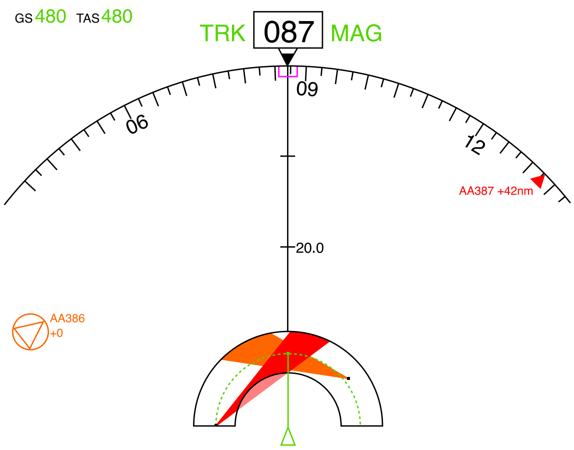


Figure 6: Ecological airborne assistance overlay added to the Navigation Display.

and provide more meaningful information about the conflict situation. It allows pilots to quickly obtain a good understanding of the situation, and the visualization of relative motion allows the pilots to directly observe the possibilities for actions and the consequences of taking an action. We think this is what traffic 'situation awareness' is all about.

At the core of the design is the work domain analysis, which helps the analysts and designers to become experts in the problem at hand, understanding the functional means-ends relationships of the system-to-be-built, independent of who or what will do the actual work. It shows what aspects of the work domain are so crucial that they have to be visualized on the display, and will help to explore what possible representations of the world exist and could be used for the system design. The iterations that follow, involving prototyping and testing may lead to novel insights into the problem and may result in adaptations of the analysis, the representation, and the interface.

Note that the ecological interface design does *not* prohibit the use of automated help. *We do not plead against automation*. On the contrary, the ecological interface could well be the "transparent window to the automation" that is mandatory when pilots are responsible to verify the automated agents' advice. The internal and external constraints as visualized on the ecological interface are constraints of "the world" which also hold for automation: the WDA and corresponding ecological interface are actor-independent.

In this respect, we have successfully applied the same concepts to air traffic control. Here, an analysis showed that close to 50% of all short-term conflict alerts were caused by operator's responses to previous alerts (Lillo et al., 2009). That is, with the current radar-like interface, when air traffic controllers 'solve' a conflict (which are commonly detected by computer algorithms, warning the controller) their solution triggers new conflicts later. Fig. 7 shows our ecological overlay positioned on an experimental ATC interface. When the automation has warned the controller, she can click on one of the aircraft involved, and *directly see* solutions that solve the conflict *and do not lead to new conflicts in the near future*.

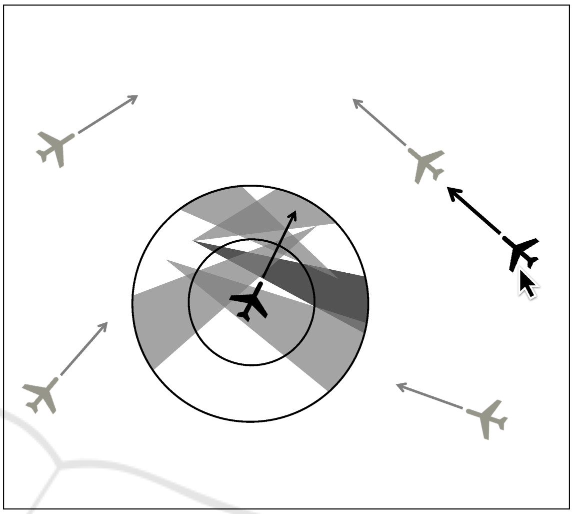


Figure 7: Evolution of the ecological airborne assistance display to an ecological plan view ATC interface; the Solution Space Diagram.

It is a nice example of automation and humans working as a team, and this set-up allows also to move back and forth between several levels of automation authority. That is, one could opt for not only warning the controller, but also presenting a resolution advice to her. When equipped with the solution space overlay, the controller can then check very easily whether the automation advice is correct, and how the traffic situation will emerge in the near future. We are confident that, with the help of our ecological overlays, the 50% of conflict alerts triggered by the controller's earlier responses can be brought down to a minimum, yielding a safer and more efficient air transport.

5 CLOSING STATEMENTS

At the start of this paper, we have asked ourselves the question whether there exists an approach to automation and interface design that helps pilots in performing their cognitive work, and leads to higher level of situation awareness. In our view, it is the ecological approach to human-machine systems design that allows the analysts to capture the essence of what is needed, to construct interfaces and automation that allow human and automated agents to work together.

Note that a good ecological interface reflects the complexity of the work domain. This means that in order to construct one, the analyst should become an expert herself. In addition, when the work domain analysis is done, their is no recipe for creating the actual display itself. In our experience, several iterations are needed, often in combination with human-in-the-loop evaluations of prototypes. Deciding on what system 'state variables' are used to design the interface and automated tools is crucial. Aviation has several examples where, because of (on hindsight) unfortunate design decisions early on in the development of systems – like in autopilots, see (Lambregts, 2013) – interfaces and automation are not complete. The resulting (human factors) problems will continue to pop up now and then, but the real problem is rooted deeper inside these legacy systems.

In properly representing situations to pilots, it is not our intention to put the automation aside. On the contrary, our ecological interfaces are there to facilitate coordination between humans and automation, creating the transparency that is needed for pilots to understand situations and judge the logic underlying the automation's actions or advices. A joint cognitive human-machine system should be strived for in cockpits, in which cognition can be dynamically distributed, moving back and forth between human and automated agents. The ecological interface provides pilots the "window on the world", based on a representation that can be used by humans and automation to understand and act upon emerging situations.

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