Ecological Interface Design for Vehicle Locomotion Control

van Paassen, Marinus M.; Borst, Clark; Ellerbroek, Joost; Mulder, Max; Flach, John M.

DOI
10.1109/THMS.2018.2860601

Publication date
2018

Document Version
Accepted author manuscript

Published in
IEEE Transactions on Human-Machine Systems

Citation (APA)
van Paassen, M. M., Borst, C., Ellerbroek, J., Mulder, M., & Flach, J. M. (2018). Ecological Interface Design for Vehicle Locomotion Control. *IEEE Transactions on Human-Machine Systems*, *48*(5), 541 - 555. https://doi.org/10.1109/THMS.2018.2860601

Ecological Interface Design for Vehicle Locomotion Control

M. M. (René) van Paassen, *Senior Member, IEEE*, C. Borst, J. Ellerbroek, M. Mulder, *Member, IEEE* and J. M. Flach

***Abstract*—Ecological Interface Design (EID) was originally developed in the context of process control, but has been extended into many domains where technology has resulted in both changing work demands and increased opportunities for improved interface applications. This paper gives an overview of the application of EID to the control of vehicle locomotion, either from within the vehicle, as driver or pilot, or from the outside, as operator or (air traffic) controller. It discusses lessons learned from application of EID for the vehicle locomotion control task, and focuses on how the methodology can be applied to this domain. Specific issues identified are that the planning and control of a vehicle simultaneously spans multiple time scales, and that the interface must be designed considering the format in which the control input is defined. Also, due to the extensive standardization of instrumentation and training certification, changes introduced by the new displays must initially be additional to the existing displays. Chosen representations must also be shown in a format that matches the current instrumentation and the directly observable outside world.**

***Index Terms*—Ecological Interface Design (EID), human–machine systems, vehicle control.**

I. Introduction

APPROXIMATELY 25 years ago, Ecological Interface Design (EID) was introduced with publications illustrating its application [1] and its theoretical underpinnings [2]. Over the intervening years the framework has been further elaborated in subsequent textbooks [3]–[5].

The term "ecological" in EID was inspired by James J. Gibson's work on the coupling between perception and action [6] and its implication for control of locomotion. Although not articulated in the formal language of control theory, the essence of Gibson's theory of *direct perception* was that the information feedback available for the control of action was much richer than had been previously thought. Inspired by the early intuitions of Langewiesche [7] about the heuristics that pilots use to achieve safe landings, Gibson suggested that structure in optical flow fields (which he termed optical invariants) directly specified key dimensions (i.e., constraints on state variables) required for skillful control of action:

> Locomotion and manipulation are neither triggered nor commanded but controlled. They are constrained, guided, or steered, and only in this sense are they ruled or governed. And they are controlled not by the brain but by information, that is, by seeing oneself in the world. Control lies in the animal-environment system. Control is by the animal in its world, the animal itself having subsystems for perceiving the environment and concurrently for getting about in it and manipulating it. The rules that govern behavior are not like laws enforced by an authority or decisions made by a commander; behavior is regular without being regulated [6, p. 255].

In describing the "ecology" for locomotion, Gibson's concept of "affordance" reflected his attempt to specify the action- or control-relevant dimensions or constraints. In many respects, this is analogous to the concept of "state space" constraints in control theory, for example when constraints on the state variables are used to describe boundaries for successful action [8]. In a way, the concept of "safe field of travel" with respect to driving [9] can be seen as an attempt to represent the state space constraints for driving. The buffer zones around the field of safe travel shown in Figure 1 reflected the need to consider both position and velocity in order to anticipate and avoid collisions with inertial control systems. Later researchers were able to show that these constraints were well specified by optical angles and angular expansion rates associated with objects in the field of view [10]–[12].

Gibson's research program focused on the content of natural flow fields (i.e., the visual field of regard of a driver or pilot) with the emphasis on revealing the natural richness of information feedback to support skilled action. In contrast, the early generalizations of the ecological approach to interface design focused on domains where the existing interfaces were impoverished relative to the information required for stable control (e.g., nuclear power control rooms). Typically, these interfaces contained all the necessary data, but the data were not organized in a way that made the control-relevant constraints salient. Rasmussen and Vicente [1], [2] framed the EID approach as the need to construct representations (e.g., configural geometries or virtual flow fields) that made the control-relevant relations, for example mass and energy balances, salient to operators. The key idea was to leverage the power of graphical interfaces to create "flow geometries" or visual patterns to specify the control-relevant constraints of a process or "ecology." This resulted in graphical displays that functioned in a way that was analogous to the way that natural flow fields specified the "safe field of travel" for locomotion.

The framework was accompanied by the DURESS example. This application was representative of systems in process control and energy generation, and actual implementation of EID designs in these fields followed in the mid 90s [13]–[16].

M. M. van Paassen, M. Mulder, C. Borst and J. Ellerbroek are with the section Control and Simulation, Faculty of Aerospace Engineering, TU Delft, Delft, The Netherlands

J. M. Flach is with Wright State University, Dayton (OH), USA

Manuscript received December 31, 2016.

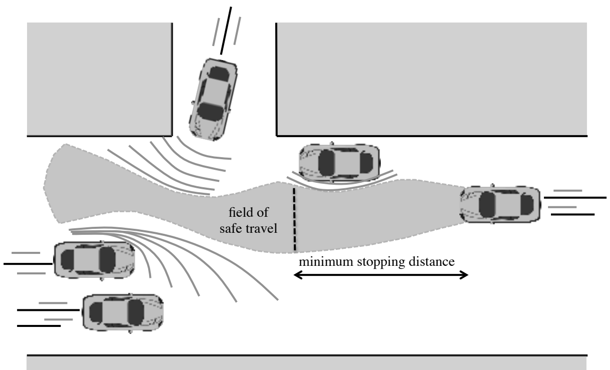


Figure 1. Gibson's "field of safe travel" for automobiles (adapted from [9]).

Several other application fields soon followed, for example medical device operation in 1993 [17]. For a more comprehensive overview of displays realized with the EID approach along with several empirical insights, the reader is referred to [18]–[20].

Given this history, it is not surprising that early applications of the EID approach in aviation [21]–[23] focused on representations of technical processes *internal* to the aircraft that were not well represented by more traditional single-sensor, single indicator displays, notably engine and fuel system control and the control of communication radios. However, even in the earliest days of aviation, it had become increasingly apparent that the natural optical flow fields (along with other natural information sources such as vestibular cues) were inadequate for safe piloting in many situations (e.g., flying in clouds or at night). Although it preceded the formalization of the EID approach, it might be argued that the original Sperry artificial horizon display reflected the spirit driving the EID approach [5]. It essential creates an artificial view on the world (work domain) to compensate for control-relevant state information that was not available by other means.

More recently, advances in sensor technologies (e.g., radar, GPS), advances in automatic control systems (e.g., autopilots), advances in display technologies (e.g., glass cockpits) and increasing operational demands (e.g., higher traffic densities, increasingly decentralized traffic management concepts) have led to thinking more broadly about the implications of the EID framework for enriching the information feedback available to pilots and air traffic controllers, in order to support piloting [24]–[31] and air traffic management [32]–[38]. In essence, we have been exploring alternative ways to specify the "fields of safe travel" to support successful operations in the aviation domain.

The primary goal of this article is to summarize our recent applications of the EID framework in the aviation domain and the lessons we learned with respect to designing more effective control systems. We hope that by explicitly grounding the EID framework with respect to control theory, we will highlight general issues that will have broad implications for how to design graphical representations that can effectively engage human operators and support successful performance in other complex work domains. One aspect that we address is the support for control and planning at different parallel time spans. Previous work [39] addressed temporal coordination for air defense using a tailored framework for temporal coordination of control tasks. In principle, control task analysis should be the proper tool to address this issue [3], [40]. We found that organizing the work domain analysis results according to relevance for tasks with a specific temporal span can be useful in this context.

The discussion is organized in sections that each deal with subsequent design choices we made that led to functional displays. More specifically, these choices entail deciding on the control loop to close, finding the right representation or coordinate system that describes the loop in a productive way, defining the corresponding input vector, choosing a design template, and finally considering the importance of the iterative nature between design and evaluation. Together with several illustrative design examples, we believe the lessons will be valuable to all who are interested in designing more effective interfaces for closing-the-loop through human operators.

II. Vehicle locomotion control: a multi-loop control problem across different time spans

In vehicle locomotion control, motion and time are intrinsically coupled. In a flight, maneuvers, flight phases and trajectory segments integrate into a complete mission. In their work, pilots or operators must focus on the immediate response of the system, but they also need to *prepare* their actions over multiple parallel time spans, ranging from preparing for upcoming maneuvers to planning of vehicle trajectories several minutes to hours ahead, and managing resources over the complete trip. This observation is in accordance with the motto "aviate, navigate, communicate" in aviation, which instructs air crew to focus on flying the airplane first, and in parallel prepare for what comes ahead. For the short term, a pilot is concerned with keeping the aircraft in the air, with a proper attitude and speed. On a slightly larger term, (s)he needs to plan the remainder of the flight and coordinate with fellow crew members and personnel on the ground.

In our work, we focused mostly on support for motion control and planning. There is a practical reason to focus on these aspects of the work rather than on system fault diagnosis. The role of system failure diagnosis on board of vehicles, and particularly land vehicles and aircraft, is limited. The typical

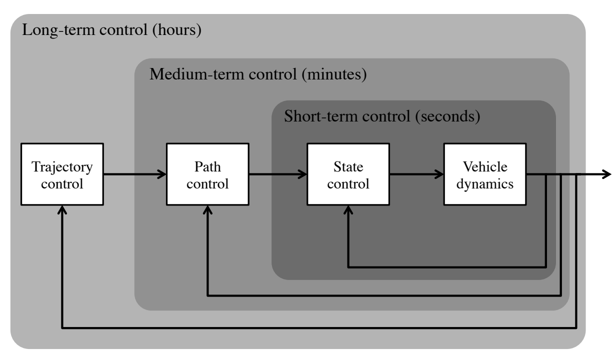
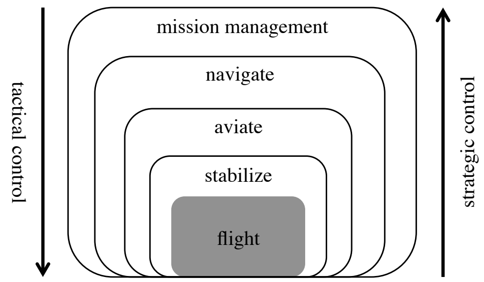
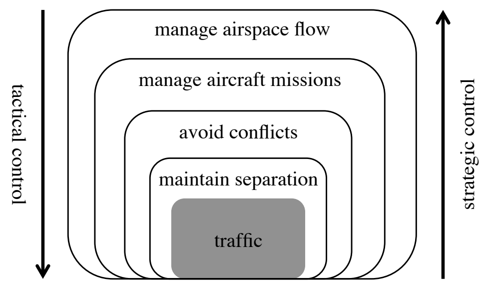


Figure 2. Vehicle locomotion control as a multi-loop control problem.



(a) pilot perspective (adapted from [41])



(b) air traffic control perspective

Figure 3. Aircraft and air traffic control as a hierarchy of nested control problems at different time scales.

response to a mechanical failure on board aircraft is to reconfigure if needed, monitor and manage resources and find a suitable landing site, leaving further diagnosis and repair to mechanics, a strategy successfully exploited for example for Qantas flight 32 [42]. Procedures, check-lists, electronic support and documentation carried on board support this response to failure, and pilots are advised not to extend their diagnosis beyond the steps supported by the documentation. This shift from diagnosis to motion and resource control also means that the operators in vehicle control might parse the work domain differently: Rather than having to search for malfunction causes, they need to coordinate control actions and plans over different time spans, considering available resources.

Vehicle control requires planning ahead to define a feasible future trajectory, and as the travel is implemented, the set-points for inner control loops continually change. The control problem can be represented as a system with several nested control loops, all acting at different time scales and all with changing targets or set-points, as illustrated in Figure 2. In general, the inner loops control the vehicle's faster dynamics, and the set-points for these loops can change quickly. The outer loops control the path and trajectory, and are inherently dealing with slower dynamics.

In the application of EID for vehicle locomotion control – or for any other domain –, one is essentially designing an interface that aims to support the human operator in closing one or more nested loops. Supporting work over multiple control loops implies supporting work over varying time spans. This requires that the vehicle's operator switches between spans, often making a conscious choice to focus on a time span and thus on a specific aspect of the locomotion control task[1]. In most transportation systems, the inner loop involves maintaining vehicle stability, the middle loop entails maintaining a particular travel direction and the outer loop involves the entire planned trajectory and resource management. In Figure 3, two graphical illustrations of these control loops are made, one for piloting an aircraft and another for controlling an airspace.

Ideally, an interface should support the operator in closing all these loops, and enable operators to easily shift focus from control in the now to control over larger time spans, in our case ranging from maneuvers in the near future to a complete flight. As different control tasks at a specific time scale are considered, different functions identified in the work domain analysis become relevant for the task. In short term control, e.g., when performing an avoidance maneuver, the pilot will generally not consider fuel consumption and its effect on the remainder of the flight. On the other hand, for planning over longer time spans the pilot will not consider or know the detailed path of surrounding traffic ahead. In principle, EID [3] provides tools for modeling these parallel tasks, and different approaches are taken to incorporate temporal aspects in designs [39]. In analogy with Rasmussen's approach [44], [45], as he fashioned work domain analysis after the focus shifts in scope and abstraction observed in expert behavior, we found that there may be an additional need to organize the presentation of the analysis, along an axis related to the control loop that is closed, in this case of the locomotion. One possible extension to incorporate this aspect is presented in the work by Amelink [41], which employs an abstraction-sophistication analysis. The control sophistication here concerns the "level of autonomy" of a vehicle, and with increasing sophistication, wider control loops and larger time spans of the locomotion are covered by automation. The concept of control sophistication was introduced specifically to address Amelink's problem domain, the design and use of unmanned autonomous vehicles with different levels of automation. Increasing layers of automation give the operator the opportunity to interact with the vehicle in its mission at a higher level, making the functions controlled by the automation less relevant for inclusion in the interface to the operator, and shifting the focus to functions more pertaining to tasks with longer time spans (e.g., those related to resource management) as more relevant. Given that Amelink considered progressive loop closure, the term control sophistication makes sense. However, automation support does not always follow this order; a case in point is the ubiquitous use of navigation devices in driving, which close an intermediate loop, leaving the human user tasks at different places in the control loop, such as direct vehicle control on the one hand and input of the destination into the device on the other, while the device essentially uses the entered destination to generate set-points for the locomotion in the form of direction instructions, closing a loop between two loops closed by the human driver. Therefore, rather than labeling it with the term sophistication, here we propose to

[1]The work distribution of task on board a commercial airliner explicitly addresses this; one crew member is assigned to fly or monitor the automation that flies the aircraft, while others may be involved in troubleshooting and planning tasks. [43]

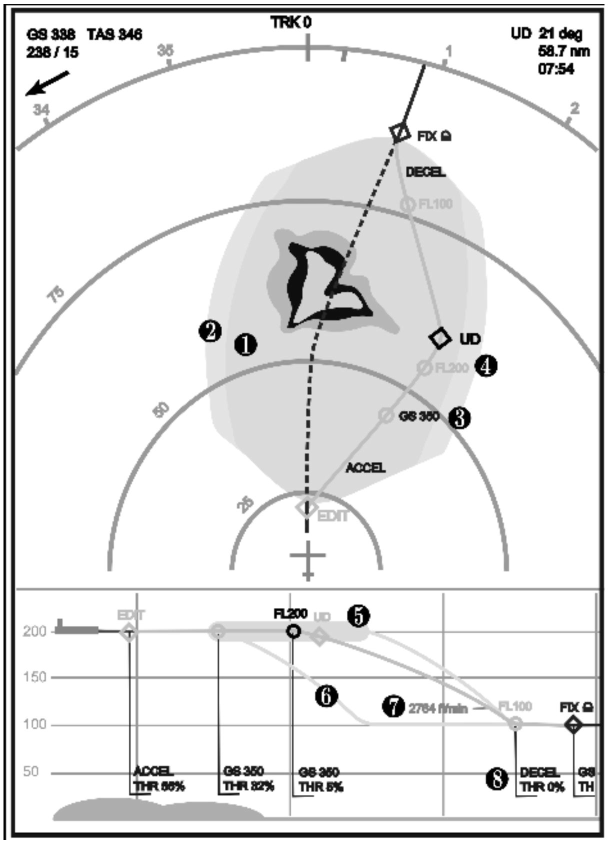


Figure 4. Interface for in-flight trajectory (i.e., mission) management [31], showing the 'waypoint affordance' zone for estimated time of arrival (ETA) equal to required time of arrival (RTA) (1) and ETA within tolerances (2); labels regarding the speed (3) and altitude profile (4); the affordance zone of the top of descent (5) and an outline of the descent envelope (6); the maximum rate of descent (7); and a ground speed and throttle preview (8).

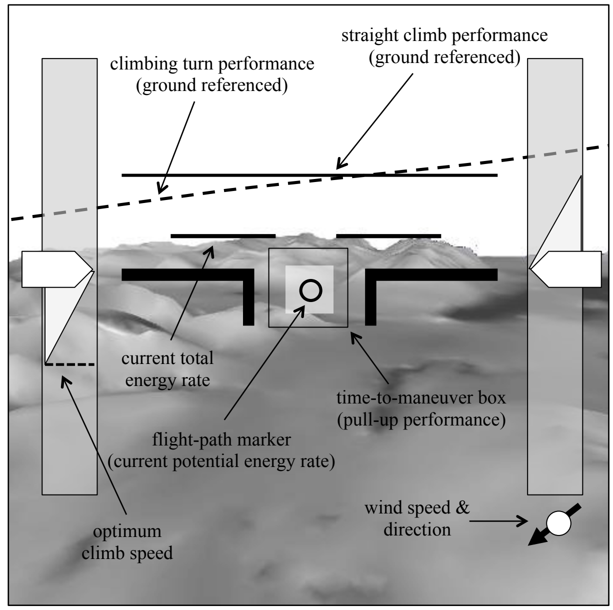


Figure 5. Interface for short- to medium-term terrain avoidance [30], portraying aircraft flight-path performances relative to the terrain on an augmented synthetic vision display.

organize the analysis along the time span relevant for control and planning in a specific setting.

Not in all previous projects the full range of closed loop was considered. Several projects on ecological interfaces for vehicle control [27], [30], [33], [46], a single temporal scope was selected to create the problem formulation, resulting in support for work over a specific time span, in a specific mode of flight operation (manual or using the autopilot) and effectively for one or more of the nested control loops.

As an example, the display illustrated in Figure 4 was designed for pilots in *future* air traffic scenarios, with a high degree of automation and information integration. In these scenarios, aircraft are assumed to follow trajectories defined in four dimensions (three spatial and one temporal). Control is at the level of an aircraft's trajectory, and at a correspondingly large time scale. Another example is the display in Fig. 5, which was developed for supporting pilots in avoiding impending terrain collisions. Here, control is at the level of short-term flight maneuvers, by means of stick, throttle and rudder. The associated time scale is also much shorter than for the work on 4-D trajectory management.

These examples illustrate that addressing the vehicle control problem at a specific time span also has several implications on what to include in the design of an interface. Not only does each control loop have its own set of input/output parameters as will be discussed later in this paper, it also determines what part of the vehicle dynamics should be taken into account. For example, in short-term control tasks, such as in the terrain avoidance display by Borst et al. [30], transients in climbing and turning an aircraft are important to include in the design of the interface. This interface, shown Fig. 5, has a time-to-maneuver box that takes into account the transient related to the pull-up maneuver that is performed before reaching a new stable and sustained climb state – a state where the line representing the total energy rate and the flight-path marker are both aligned with the straight climb performance. The time needed for these transients maneuvers is in the order of seconds. On the other hand, for the 4-D trajectory management tasks addressed in [31], which are performed over much longer time spans, such transients are not relevant, and they need not be taken into account in the calculation and representation of the affordance zone (see Fig. 4).

The lesson here is that the display designer must make a selection for the time spans, and thereby the control loops addressed, for which the display should provide support. The minimal time span that needs support depends on the degree to which inner loop events can be predicted, modeled and automated. Tasks settings for outer loops and longer spans are typically variable, and these might be difficult to formulate and automate, requiring the contribution of a human operator to close the loop. Designs of ecological interfaces for locomotion have generally targeted a specific time span of the work, and design of integrated interfaces supporting multiple time spans still has to be done.

III. Work Domain Analysis: discovering alternative problem representations

When a control problem is to be solved using control theory, one typically starts by formulating a model of the to-be-controlled system, often with a state-space formulation. Sensors and control means need to be selected such that the model, and the system state, are both observable and controllable [47]. Similarly, and like any solid design method, EID starts with an analysis of the problem to solve, as an inventory of the requirements and a further analysis of these. The handbook written by Vicente [3] outlines five analysis steps for EID, starting with the Work Domain Analysis (WDA). In selecting this as a starting point, EID differs from contemporary methods, such as user participative design, or design on the basis of task analysis. By starting with the work domain analysis, EID places an emphasis on the environment – ecology – of the work. The starting point makes EID suitable for a revolutionary approach, rather than limiting the method to evolutionary improvements, as user-centered or task-centered approaches would be [3]. The work domain analysis does not require a description of (current) tasks or operator activities, and can thus be performed for new domains or problems. This changes the design problem from creating an interface that supports a known task and procedure, to discovering which representation of the work domain will support *any* task, using *any* path towards the system's purposes. The approach in a sense resembles the approach taken in control engineering by constructing a model of the controlled system, while at the same time differing from control engineering, because it can address problem domains that are too unstructured or even impossible to model in the format needed for a control-theoretic approach.

In general, the WDA starts with defining a scope of the work that needs to be supported. For vehicle locomotion control, we found that defining a scope is essentially making the decision on which time span to support, or in other words, where to intervene in the (nested) control loops. As was explained in the previous section, this choice impacts the input/output parameters and the level of dynamics that needs to be taken into account. Similarly, a work domain analysis can also be done to different levels of detail. Initially, the analysis will identify goals, functions and characteristics of the selected work domain. When continuing to formalize these models using engineering modeling approaches to, e.g., express these functions in numerical terms, one will need to choose state variables; defining variables that characterize a system's momentary state. As an example one can characterize the locomotion of a flying vehicle by means of its speed, altitude and position coordinates, and a full path as segments with specific start and end points. An initial tendency in this choice may be to match engineering conventions, and thus define a vector with state variables from a set of commonly measurable parameters. However, as known from systems theory [48], infinitely many choices are possible for these state variables, and – excluding choices that result in numerical difficulties in computer simulations – all these are capable of adequately describing the system's state.

For performing a work domain analysis that can be efficiently translated into a usable display, we found that it pays to consider alternative selections of the state variables, or maybe to use several alternative selections in parallel. The state variables selected for characterizing a system effectively shape our view on the constraints of a system, and thus determine what we are likely to see as functions at the abstract function level. For aircraft, the velocity and altitude are valid choices for state variables that describe short- to medium-term control. However, kinetic energy and potential energy can be selected as an alternative set of state variables [24], [49]. The question is which representation is a better choice for the WDA and the interface design process?

From an engineering point of view, the standard choice of state variables is acceptable, and calculating the limits or constraints on these variables is straightforward. This would mean that for a specific airspeed, the deceleration, acceleration, rate of climb and rate of descent at minimum and maximum thrust could be calculated and displayed. However, doing so would simply confirm to the pilot that the constraints on maneuvers are complex functions of speed. The alternative set of state variables has a simpler relation – since the total energy is the sum of kinetic and potential energy, and the energy rates follow an equivalent relation.

Using an alternative choice for using energy state variables instead of, or in addition to, the conventional altitude and speed variables can also be motivated by the fact that these variables are "closer" to the control means of a pilot. Throttle regulates total energy rate and the stick (or control column) distributes energy between speed and altitude effects. Figure 6 provides an illustration of the energy management task. In most flight situations limited excess energy is available, particularly in the case with a fully loaded aircraft or at high altitude, and the means of energy dissipation are limited, specifically for modern aircraft in a clean configuration. Switching to other state variables is similar to the practice of using different coordinate systems or scales (e.g., linear versus logarithmic), in graphing quantitative data, to make certain relations easier to see in a graph [50].

A choice for energy variables and energy concepts in the work domain analysis makes the display designer and the pilot aware of the constraints on energy and energy rates, supporting better energy management and prediction of future energy needs. The simpler relation between the two energy volumes and rates (compared to the quadratic relation governing speed and altitude exchanges) helps the pilot to better execute speed and altitude change maneuvers.

To make the conventional targets in terms of speed and altitude compatible with the simpler energy relations, these are then translated into targets in terms of total and potential energy. With the throttle and elevator as control means for total energy and energy distribution, respectively, adding the energy representation further explains the problem in terms of controls. For this representation, the shape of the constraints is also simpler, and the underlying constraints from the aircraft, in this case from the performance characteristics of the airframe and the engine, are more easily understood [24], [51].

Another example of an alternative state representation was

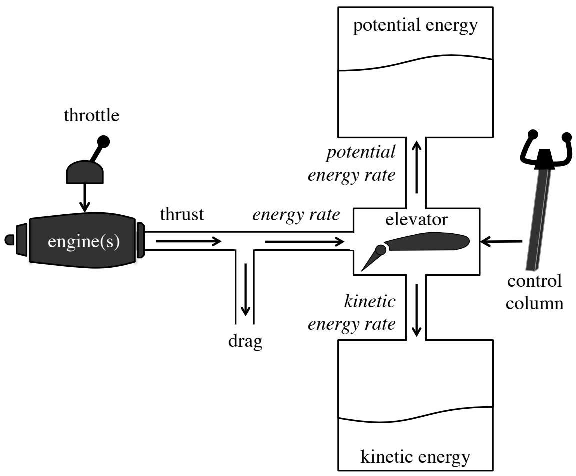


Figure 6. Reservoir analogy of a pilot's energy management task in the vertical plane (adapted from [24]).

found in the work domain of airborne self-separation – a medium-term control task. Common to many designs addressing self-separation is that they are based on flight-path 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 [52]. Typically, these algorithms are implemented in a digital computer, and once the solution can be calculated, the interface designer is brought in to create the interface to inform the pilot. To put things bluntly, an automated solution is generated by a black box, 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? then warn the pilot...) [53]. Such a solution can be illustrated by Figure 7, which shows a simplified CPA model, where the miss distance m represents the CPA. The time-to-CPA is called the tau (τ) parameter, which is estimated by the ratio of the range R and range rate $\dot{R}$ due to the unavailability of accurate speed vector information. This simplified model may be used to alert the pilot when the CPA and τ cross specified thresholds.

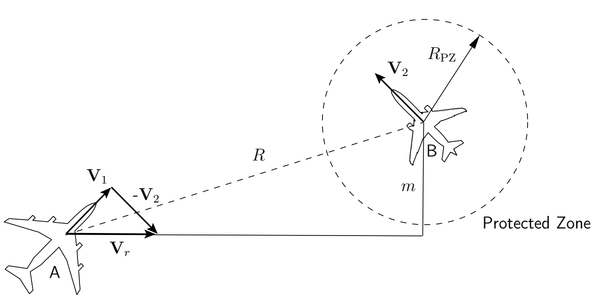


Figure 7. The airborne separation problem in the horizontal plane described from a CPA perspective.

A deeper understanding of this work domain was achieved after several iteration cycles. A crucial step in our understanding of the work domain, and thus of the problem, was the realization that *avoidance* of neighboring traffic was based on *relative* motion, while the flight (*productivity*) depends on

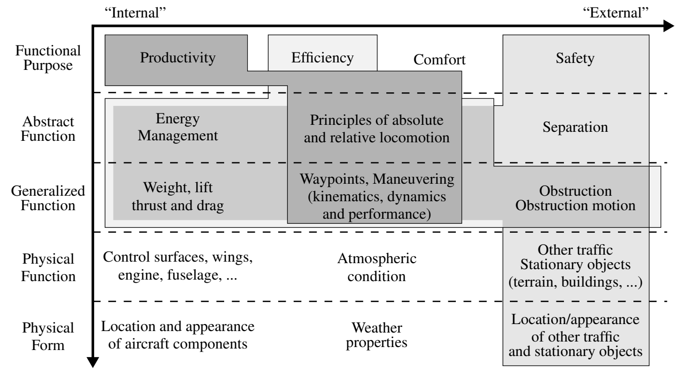


Figure 8. The Abstraction Hierarchy (AH) for the self-separation problem (taken from [54]).

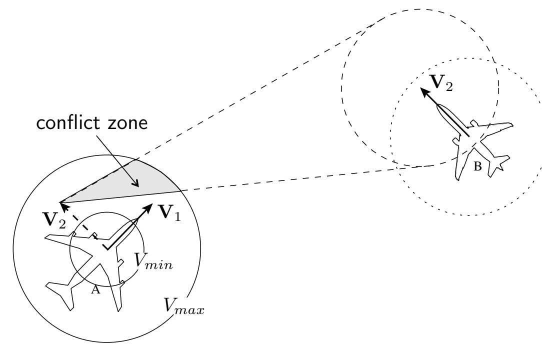


Figure 9. The airborne separation problem described in velocity obstacles.

absolute locomotion. The abstract function level in Fig. 8 thus contains both relative and absolute motion as functions, while these are created by the motion of the own aircraft and the surrounding traffic. These notions were implemented, both as concepts in the work domain analysis, in off-line engineering simulations and in the calculations for the interfaces. Figure 9 shows the separation problem expressed in absolute and relative motion constraints.

A relative velocity vector towards another aircraft can be calculated by subtracting the other aircraft's velocity from the own craft velocity. Unless the other craft is still far enough away (a common measure for this in airborne separation is 5 minutes from the closest point of approach), that relative velocity should not be directed towards the protected zone of the other aircraft B. This creates wedge-shaped zones, called conflict zones, which need to be avoided by adjusting the *relative* velocity vector. However, relative velocities are not a common concept to pilots, with the exception of some pilots, particularly those with military training, who know that by tracking the changes in bearing to another aircraft they can determine whether to expect an encounter with the other craft; this happens in cases when the bearing (relative heading from the own craft) stays constant. The breakthrough was found when we realized that the relative conflict space could be shifted, so that the tip of the relative velocity vector now *coincides* with the tip of a vector representing the aircraft's absolute velocity vector [25]. In case there are multiple neighboring aircraft, the relative velocity spaces of each aircraft can be overlaid on the absolute velocity space.

By shifting the conflict zone along the intruder velocity, we can see the conflict now represented in absolute velocity space. With this representation, the magnitude and direction of the absolute speed vector can be directly related to the conflict zone. Finally, the own craft's motion is constrained by the minimum and maximum speed the aircraft can fly. By including these constraints (which arise from the physical function level) in the representation, reachable safe and unsafe travel states (expressed in speed and heading) can be directly seen. This representation formed the basis of all our later ecological interfaces for the aircraft separation task, from both a pilot's perspective as well as an air traffic controller. Note that we later found that analyses similar to the ones used as a basis for the displays had been created in the context of robotics; the collision cone [55], velocity obstacle [56] and maneuvering board techniques [57] were developed for similar locomotion problems. The principles of relative and absolute locomotion were even implemented in a physical calculating device, the Battenberg course indicator. This is a naval instrument used to choose heading and course for ship maneuvers that should be performed relative to other sailing ships in the vicinity, with the first version dating back to 1892 [58].

The lesson here is that finding the right set of coordinates to describe the control problem, and thus framing the analysis, is seldom simple and may require several iterations. Here, the work domain analysis and Rasmussen's Abstraction Hierarchy may help the designer to ask the right questions about the problem to solve, dig deeper into the control problem, and structure the newly obtained insights. We also found that, when stuck in the analysis, a "serious play" approach can help [59]. This starts by performing elementary engineering simulations of the problem at hand, and using these to visualize system behavior for different situations. One example of such an approach was the analysis for the precursor of the airborne conflict resolution displays [60]. This did not immediately lead to a complete analysis and functioning display, however, these batch simulations were instructive in understanding in how far turn dynamics would need to be taken into account in the airborne separation problem, and they produced enough ideas to propel the next step in the iteration towards a usable analysis and display.

IV. Supporting Interaction: Defining the Control Input Shape

After having selected the control loop to close and a reference frame for describing the control problem, the next step is to define the set of inputs (and outputs) that would facilitate the means to influence the system state. In classical control engineering as well as in the design of an interface, the inputs must be chosen such that they provide the means to affect the system's state over the time that matches the scope and the time span of the control problem at hand.

A. Input as function of time

Section II argued that operators of a vehicle organize their planning and control actions over varying planning horizons.

Figure 10. Display for airborne self separation showing velocity obstacles.

For control over short time spans, the input is typically a single new set-point for the vehicle's speed, heading or vertical flight path angle. However, a planning over longer stretches would define the control input as a series of straight path segments between waypoints. The control input needs to be expressed in a suitable format, matching the understanding by the operator. The interface should support the operator in defining a proper control input using this format and show the constraints on this input, which can be challenging if the formulation of the input is complex.

An issue in expressing locomotive control is dimensionality of the control signal. Consider the task of self-separation with the airborne conflict resolution display in Fig. 10, or air traffic control with the Solution Space Display (Fig. 11(a)); the control task typically consists of selecting a new heading and speed, leading to a control input that can be expressed as a *vector* with two input elements. One can compare this to the controls for a single energy and mass balance of DURESS [3], if one considers the inflow valve, energy from the heater and outflow valve, half of DURESS (i.e., a single energy/mass balance) would have a control input vector with three elements. When the elements in this input vector are manipulated, the DURESS ecological display can visualize the current state (flows, energy and mass content, temperature), and the trends in that state. With that information, an operator can verify present achievement of the system's purpose and inspect trends that show whether the purpose is (still) achieved in the future.

The self-separation task has actors *external* to the flight crew. Compared to for example DURESS, in Vicente's terms, it is more "open", in that there is a larger and more varied interaction with the outside world. It is also more "correspondence driven", in that the pace of the developments is controlled not only by the vehicle's *own* dynamics, but in this case also by the dynamics of *outside* agents. This forces one to take timely action; adjusting the control input alone may not be enough, a maneuver needs to be made with the proper timing and a proper size of the control input.

A slow adjustment of the inputs in the DURESS microworld would simply lead to a delayed moment in which the goals of the system are met. A slow or late turn to a new heading and adjustment of the speed in the self-separation task might lead to a *failure* to maintain separation, and present a safety risk. This makes the input vector much more complex than a choice for two control input values; the time at which the maneuver is started, and the nature of the turn, tight or wide, and the duration of an intervention affect the achievement of the system's goals as well. Since the timing and the pace at which heading and speed changes are implemented affect the resulting path and the separation from surrounding traffic, the input vector must actually be seen as a vector with two variables that both are a *function of time*.

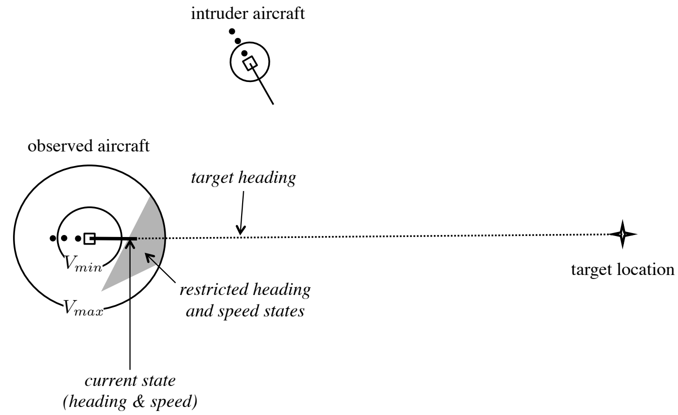
Considering the control input of a system as a function of time is not needed for the abstracted dynamics of the DURESS micro-world, but we expect that many other work domains, through the presence of external actors with their own pace or own dynamics, or through the interaction with chemical or biological processes with a given timing, might also have this characteristic.

An ecological interface should show constraints in the work domain in such a manner that the affordances become clear to the operator, in terms of what actions can be taken and what their effect will be. When we consider the input as an arbitrary function of time, however, creation of a display becomes an impossible task. Such an arbitrary function could be converted to a discrete set of input vectors with a large number of elements, each for a different future time, resulting in a description with too many dimensions to effectively determine the consequences of all these possible input functions and to effectively visualize these. To still produce a workable display, the constraints identified with the WDA must be combined with conventions for input shapes derived from the control task analysis. By constraining the support to common work practices, which in the case of flight are turns with a commonly chosen bank angle, typically 25 to 30 degrees, and acceleration and deceleration with thrust selected as advised in the operations manual, a simplifying assumption on the shape of the input functions can be made, and presentation of the effects of the input again becomes feasible.

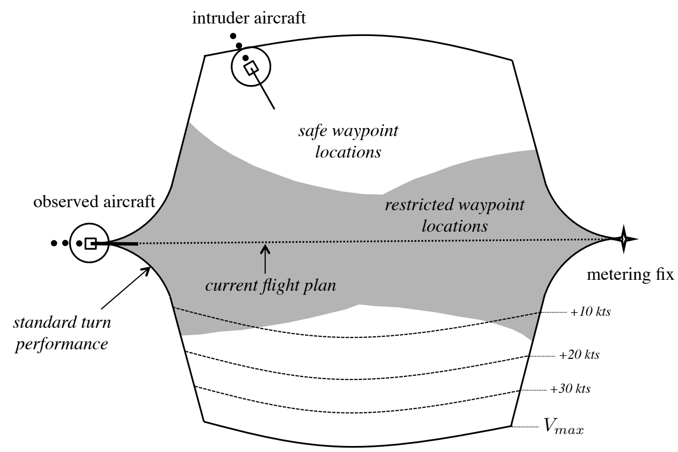
The design for the airborne separation displays uses these assumptions to refine the display. In the first iterations of the self-separation display, the legs of the displayed conflict zone were calculated assuming an instantaneous turn to the new heading. However, changing the aircraft's heading takes some time, and picking a new heading and speed just outside the zone resulted in a velocity vector that after the turn and/or acceleration has completed would not have cleared the conflict zone. For later versions, an assumption on the type of input given – once the pilot acts on the display – is used to adjust the zone to account for the time spent in the turn, so that selecting a heading in the free zone, assuming the maneuver is flown by autopilot or in the customary manner by the pilot, indeed resolves a conflict [61].

B. Relation to the chosen scope

The shape and the number of degrees of freedom used to define the control input signal differ considerably for the different designs created for aerospace locomotion in the overview. For the energy display for example [46], the inputs are an engine setting and the pilot's choice for flight path angle, while for the Travel Space Representation display for modifying pre-planned 4D trajectories, Fig. 11(b), the input consists of a set of waypoints and prescribed speeds on the trajectories between these waypoints.



(a) Solution Space Diagram (tactical control)



(b) Travel Space Representation (strategic control)

Figure 11. Air traffic control at a tactical level (current practice) and at a strategic, spatio-temporal level (future). The Solution Space Diagram shows safe and restricted fields of travel in heading and speed within an aircraft's performance envelope, whereas the Travel Space Representation shows safe and restricted intermediate waypoint locations within an envelope that ensures reaching the metering fix on the original planned time.

The formulation of this input function is related to the temporal scope for which a display is created, and thus to the control loop that is to be closed (Fig. 2). Outer loops work over longer time spans, and the formulation of the control input needs to match those longer spans. This input in turn provides the set-points for the more inner loops, where control and local adaptations to the control input take place. As an example one can consider maneuvers to avoid weather cells or conflicting traffic.

As argued above, if one wants to show the effect of these many input choices on meeting the work domain constraints, the displays quickly become complex. With assumptions on the execution of a maneuver, the 2D solution space display for air traffic control and 2D airborne conflict avoidance display can still show the effect of a maneuver on a flat display screen. When more dimensions in the input are required, either multiple views, using multiple displays, are needed [26], or the effect on functions and constraints cannot be shown in one step, and must be shown through animated "what if" manipulation in the display, which is an approach used when specifying speed changes with the travel space representation [62].

A parsimonious definition of such control inputs, by means of a common or reasonable practice in parameterizing what is essentially an input *function*, is therefore an essential choice in developing ecological interfaces for locomotion control.

V. Toward a functioning display: design constraints and matching viewpoints

In classical control engineering, ensuring goal-oriented behavior requires comparing the system's output with a desired reference target and tuning the gains to mitigate undesired oscillations, damp overshoot and guarantee system stability. Whereas control engineers have many possibilities for having a computer to close the loop and tune the gains, the designer of an interface is faced with the challenge to create usable interface mappings that productively represent the 'comparator problem' [10] in a way that ensures system stability when the control loop must be closed by human operators. The comparator problem is the operator's task to formulate or observe both the desired system state, observe the current system state and determine the difference. As opposed to control engineering, the design solutions are often more limited and constrained (especially in vehicle locomotion control) as they must retain "meaning". That is, the interface must not only become the operator's window to the deep structure underlying the control problem, but also serve as a workspace for cognition.

A. Design constraints

In his 1999 textbook, Vicente argues that EID permits a revolutionary approach to interface design [3, pp. 134–135]. This promises a clean slate approach for new interfaces based on EID. However, instrumentation for vehicle control, and in particular for aircraft flight decks, is well established, with many operators trained on the currently used instrumentation. There are also extensive certification systems in place for acceptance and testing of equipment, display formats, and training and certification. Combined with the fact that the total work domain is very extensive, a complete replacement of current instrumentation by ecological displays is a questionable approach. Vicente agrees that EID may be applied in existing practices, what he terms as an evolutionary approach.

A more practical approach would thus be to combine new ecological interfaces, and possibly new work practices, with existing instrumentation and existing work practices. In this case, views across the new ecological interfaces and the existing legacy interfaces should be compatible. In addition, from most vehicles it is possible to directly observe the outside world. In that case it should also be possible to correlate information on an ecological display with the directly observed view. Information obtained across different displays and from out-of-the window viewing should be easy to integrate and reconcile into a coherent view of the work domain, and displays should consider the visual momentum [63]. This places additional demands on the display which, given that constraints identified in the work domain analysis are still correctly visualized, should not affect the quality of the final design. We found that the first step in realizing a functional display is by analyzing whether an existing display can be augmented to show the functions identified in the work domain analysis. This has the advantage of ensuring compatibility of the presentation with existing information, and the new display will not take up any additional screen real estate.

B. Examples of integration with existing ecology

Augmentation of an existing set of instrumentation and displays by addition of visualizations based on EID principles may happen in other application domains as well, and thus providing a connection with existing displays is important, e.g., by applying concepts such as visual momentum [63]. Interfaces must often also facilitate the integration of information directly perceived from the outside world with the representation of the work domain in the display. This in most cases suggests the use of either a map with symbols depicting constraint information, the integration of constraint information within a virtual view of the outside world, or otherwise the use of displays that can add a virtual augmentation overlay on the operator's direct view of the outside world [64].

Aside from being forced by the constraints of project resources, the integration of EID within existing instrumentation displays for flight decks or ship bridges is also a wise tactic; this enables existing crew training, certification and experience to be leveraged. In the aviation domain in particular, equipment and display formats need to be certified. Alternative display formats, however well designed and argued they may be, will in most likelihood first be offered as an optional visualization, selectable along with the proven and certified display formats, until they are recognized as valuable and dependable by the users and certification authorities.

In addition, caution must be exercised when replacing displays in high-risk domains. The current instrumentation is the result of an evolutionary process, with the most convenient and appropriate formats surviving the test of time. This does not imply that these are necessarily the best or optimal display formats, but they are accepted and known by the community. Before taking the step of supplanting or augmenting such forms with alternative displays, whether designed through EID or otherwise, careful consideration of the effects of such changes on the operator's cognitive work needs to be done [65], [66]. The nominal design specifications for the existing generation of tools alone are not sufficient to understand current work practices. Users adapt their workplace, so in addition to the functional requirements drafted by the designer, the user's adaptations and work practices must be understood to appreciate the full functionality of a tool. One example of this was the replacement of paper-based flight information by electronic flight bags; early versions of the electronic replacement lacked the organization possibilities that pilots, using yellow tags, earmarks, etc., had come to rely on [67].

Another issue to consider is the choice for the physical control device. Vicente states [3, page 326], "*EID suggests* *that, whenever possible, commands should be communicated by directly acting on the display*". In this case however, the nature, time scale and environment of the flight task do not easily permit direct action on the display. In addition, it is also more practical to connect with the current practice of flight, using either the Flight Management System (for following pre-programmed flight paths), the autopilot (through the Mode Control Panel, typically for implementing tactical maneuvers), or manually (manual control is currently used to practice flying skills or to quickly override automated solutions). Rather than implementing this whenever *possible*, it should be done whenever *appropriate*. Due to the time scale of a manual flying task, and the environmental conditions, such as turbulence, the most appropriate means for direct manual control is still a set of solid manipulators. Control of the automation *can* at times be done by directly acting on the display, but in that case a fall-back must be present for turbulent conditions.

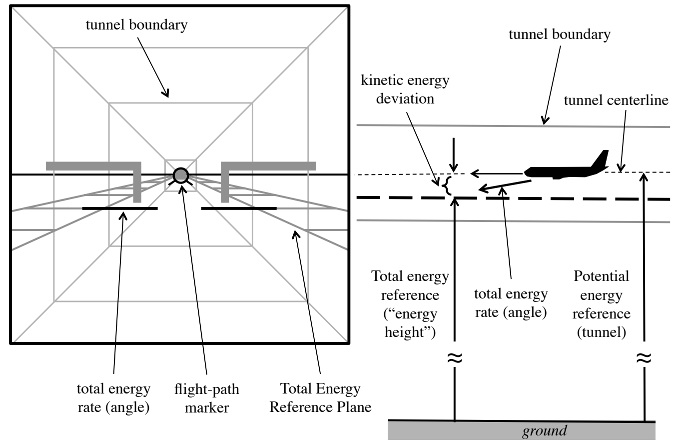


Figure 12. Display for the energy management task, extending an existing tunnel-in-the-sky display with energy cues. Here, the cues show the pilot that the potential energy target has been met (aircraft is in the center of the tunnel), but deviates from the kinetic energy target by flying faster than required (aircraft is above the total energy reference height).

C. Matching the operator's viewpoint

For operators on-board the vehicle that is being controlled, such as pilots or helmsmen, it is natural to take an *egocentric* view of the surroundings. For an on-board actor, a moving map or perspective view organizes constraints such as terrain, destination waypoints or conflicting traffic. Constraints that are further away in time and urgency are also further from the center of the display that represents the location of the own actor, or drawn smaller when a perspective display is used.

A case in point here is the display for kinetic and potential energy management of an aircraft. A part of the analysis for this display was converted to a graphical form, and presented already in Figure 6. In abstract terms, the energy balancing and management problem is similar to the problem in DURESS. For the DURESS ecological interface, the energy inventory is represented using an animated funnel analogy. This isolates the energy inventory, and its trend, onto a specific section of the display. Proximity and lines linking the energy inventory to surrounding elements on the display denote the relations with other functions in the system, such as the heater, the mass balance and the inflow and outflow.

Despite having a similar balances at the heart of the problem, the energy display for aircraft and the DURESS display use different visualizations (Fig. 12). There are two reasons for this. First of all, the display "real estate" in aircraft is already claimed by an array of existing displays, and adding a separate display would not be accepted, so the display was designed as an extension of a tunnel-in-the-sky display, which is already a possible replacement for the primary flight display. Second, aside from this pragmatic reason, the concepts in the display also needed to be connected to the other functions in the system. In this case, the relation between the kinetic and potential energy and the locomotion of the aircraft need to be made clear. The tunnel display presents an egocentric view, and within this view the kinetic and potential energy *rates* can be represented as flight path *angles*. To show the kinetic and potential energy levels, the pilot's perspective viewpoint into the display is treated as the current kinetic, as well as the current potential energy level, and the required kinetic and potential energy levels are depicted as a virtual objects in the 3D world. For the potential energy level, which corresponds to the height of the aircraft, the tunnel-in-the sky representation is its target level, and for the kinetic energy level a separate "energy tunnel", on the same lateral location as the conventional tunnel-in-the-sky, but with a separate height, is presented. The two representations are overlaid, but now in 3D egocentric view, and the shared point between the representations is the pilot's viewpoint.

This shows how the locomotion task, in this case for an operator on board the vehicle, required a specific adaptation of the display format. The displays developed for air traffic control tasks on the other hand emphasize a global, *exocentric*, view of the problem (see Fig. 11(a)). In initial designs for a support display, a conventional air traffic control "plan view" display was combined with a display of the solution space in a separate area of the screen, and the currently selected aircraft's solution space would be shown there, in effect requiring the operators to combine an exocentric view with a local egocentric view for the selected aircraft. In evaluations it appeared that participants would sometimes be confused about the currently selected aircraft and it proved to be more convenient to overlay the solution space visualization over the plan view display. As in the case of the airborne separation problem, by overlaying the traffic constraints over the map display, this again linked the effects of choosing a resolution for an aircraft to both the avoidance of other aircraft and to the visualization of travel towards the aircraft's destination (Fig. 11(a)), and it reduced problems with lack of visual momentum [63].

D. Integrated presentation of constraints using overlays

As was explained in Section III, the self-separation displays were created by shifting the velocity obstacle constraints from a relative velocity space to absolute velocity. Here we will further analyze the layered nature of these displays. The display effectively combines constraints on three overlaid graphs. Each of these overlays shows constraints on the aircraft in its own coordinate system. Thus, physically, the display is simply an overlapping view of three graphs, and the display itself can be viewed at the *physical function level* as an overlap of the following three spaces:

- Absolute (Map) Space. This space shows the aircraft location and the topology of the surroundings in a moving map.
- Velocity Space, which shows the aircraft's velocity as a vector. The vector's base is at the aircraft current location. Its length is scaled according to the vehicle's airspeed, and the aircraft's operating limits are added, to show velocity in relation to vehicle capabilities.
- Velocity Obstacle Space(s); for each intruder vehicle this shows the relative velocities that would lead to loss of separation. The origin of this velocity obstacle space, representing zero relative velocity, is kept at the tip of the velocity vector in the velocity space.

The effect of the arrangement of these three spaces in the display can also be viewed at a higher functional level, as providing a meaningful representation in three ways:

1) It provides a direct mapping between the action/control capabilities of the pilot, in terms of selecting a new aircraft velocity and heading, and the consequences relative to the predetermined flight plan and the destination, through the combination of the map space and the velocity vector.
2) It also provides a direct indication of the range and limits of possible actions, by the representation of minimum and maximum velocity
3) It explicitly represents the potential consequences of the action relative to other aircraft (in other words, it shows conflicts) to allow adaptation to information not available in the flight planning stage. This information can be derived from the overlay of the velocity obstacle space and the velocity space.

The important characteristic of this particular form of presentation is that it both shows the size and the location of the aircraft's own velocity vector, illustrating the means to approach the current destination, and the relative speed with respect to the neighboring aircraft, illustrating the means to avoid loss of separation. The pilot's influence is over the *own* velocity vector, and with the presentation he/she can simultaneously consider the constraints of the own aircraft, those imposed by the other traffic and those related to the flight towards the destination. These constraints are shown in overlaid spaces, with the tip of the own velocity vector common to *all* these constraint spaces, so that the normally "hidden" ecology of the work domain is now related to the control means of the pilot, to, in Vicente's words [2], "make visible the invisible".

The combination of different parallel representations, in this example the relative velocity representations and the absolute velocity representation, is a key element in finding effective visualizations for the work domain constraints. Through combination of the different spaces in overlays, with in this case the tip of the velocity vector as choice for the "control variable" and common point, the display can clarify this relation between control means and goals.

E. The display as a workspace for cognition

The word interface, in the sense of a device connecting two systems or components, has a misleading connotation in the context of EID. A new view is needed on how a display should function.

Theory on display design, e.g. [68], focuses on providing the right format to get the right message across. Hints can be found for best uses of colors, sizes of symbols, fonts, indicators, alignment and orientation of symbology, movement, etc., captured in guidelines [68]–[70], and consistent application of ergonomic theory and the guidelines for information organization can make displays more effective in information transfer. Such optimization can be argued to be rooted in a dyadic view of the semiotics that describe the relation of the human user with the environment. In this view the interface is an information channel between a sender (the system and its sensors) and a receiver. Display design efforts are targeted at achieving a wide-band communication channel, that passes messages undistorted and unhindered from the system being controlled to the operator.

With its emphasis of first discovering the constraints of the work domain, and only after that step passing to the creative stage of composing the display, EID pushes for another approach, one which is much more compatible with a triadic view of the communication of humans with their environment [71], [72]. It is important to realize that the interface should not simply be a communication channel. In a triadic view of semiotics, a message or sign is both related to its source, in this case to the ecology of the work domain, and it has a connection to its interpretation, or meaning to the observer. With a properly chosen ("smart") representation, information from the work domain can be shown such that the interface becomes a space for problem solving and decision making; the user of the interface can "see" the issues in the work domain in the representation, and the work could become trivial, because simple actions on the interface (or to controls that have a predictable effect on the interface) can solve the work.

This achieves the guideline by Vicente and Rasmussen [1] that an interface should not force behavior to a level higher than strictly necessary, thus, if a task can be solved with skill-based behavior, deficiencies in the interface should not force the operator to resort to using rule-based or knowledge-based behavior. This guideline must not be misunderstood to mean that an ecological display is intended to help (lazy?) operators to get by with performing at the lowest level of behavior possible. For example, the developed airborne separation display permits pilots to apply a skill-based strategy, by letting them simply select a heading and speed that lie outside the zones depicting the velocity obstacles (Fig. 10). If operators only use the display in that manner, the same result can be achieved by "command interfaces" that present solutions to conflict without showing the structure of the work domain. In experiments we found that with an ecological interface, pilots will seldom immediately act on the signals, and instead use the representation to understand the conflict geometry, gaining insight into the implications of a solution and the future evolution of conflicts, with the interface supporting their cognitive process. In a comparison with command interfaces, pilots indicated that they prefer the additional insight from the ecological presentation [73].

The proper power of a good ecological display can be seen by observing professionals at work with the displays, at the magic moment when their vocabulary changes, and terms denoting phenomena in the work domain are intermingled with (and start replacing) terms describing the reflections of these phenomena on the display, indicating that they now see the work domain with new eyes. Rather than allowing skill-based behavior on the task, the display becomes an instrument in the joint cognition performed by the operator, the work domain, and the interface [74], much in the way that traditionally evolved and proven interfaces and tools can be used to create a cognitive ecosystem with their users [65]. With a well-designed ecological interface, the operator is no longer communicating through the interface, but with the interface (s)he is *directly interacting with* the “work”. In Vicente’s terms, the interface becomes a transparent window on the work domain.

VI. Iterative steps in analysis, design and testing

The five phases in cognitive work analysis make it seem as if creating an ecological interface is a linear process that starts with the WDA and ends with a usable interface. However, the key to success in design is often to prototype, evaluate the prototypes and improve/refine these based on empirical insights. Our experience has been that closing the loop in the design process by taking iterative steps in analysis, design and testing is of specific importance in the design of an ecological interface. The iterations often provided new ideas and insights on how to refine the problem analysis and sparked ideas on spanning the creative gap between work domain analysis and the design of interface mappings.

For example, the first iteration of the airborne conflict resolution display relied primarily on an abstraction hierarchy analysis; a control task analysis and strategies analysis were not explicitly elaborated. It would not have been possible to perform these in much detail anyway, as no one at that stage had a clear picture of the control task and strategies that would emerge; the only known simulations of airborne conflict resolution used recommendations or commands from automated resolution algorithms. Initial tests with the display (unpublished), and later experiments with an improved prototype [75] showed how subjects quickly developed a sense for the work domain and developed strategies to handle typical conflicts. Further evaluations in a multi-actor experiment [54], and a comparison of the display with an alternative, comparable solution [76] taught us how pilots designed their tasks in this new setting, and also informed us about the issues encountered when multiple agents are involved in the task. These insights made further steps in the cognitive work analysis, as in [76], more effective. In hindsight, performing the five analysis steps as listed in [3] in a single analysis and design cycle would not have brought us any great advantage, since the work domain was new (pilots do not currently perform self-separation in this context) and any analysis beyond the WDA would have remained generic at that early stage. Experimentation with, and evaluation of the prototype display did provide us with the insight to make further steps in the analysis later on, and we think that for cases where a new task has to be supported, an *iterative approach* to display design, prototyping and evaluation is indeed the most efficient way to approach EID.

There is a creative step in any design, and the design of the airborne conflict resolution displays has been the fruit of tinkering and trial and error. Several authors have tried to support the creative step in EID by providing examples and recipes [5], [77], [78]. When such recipes do not provide a solution, an alternative means to speed up the design process might be to raise awareness of the coordinate systems in which the constraints of a work domain are expressed. As explained in Section V-D, the airborne conflict resolution display shows constraints in three different coordinate systems, overlaid in such a manner to present the pilot with the combined constraint in relation to possible action. A shortcut to creating such a fused visualization might be to identify and visualize the individual constraints first, and then combine the visualizations. Thereto the space – and thus the coordinate system – in which the constraints are to be drawn must be chosen so that the constraints show up as predictable and recognizable shapes. If the constraint shapes in addition are three-dimensional, choosing proper views on the constraints becomes important. This was explored in [26], with as result a usable display for airborne separation. A different visualization for the same task was explored in [54], however on that display the shapes of the constraints appeared too complex to be usable.

VII. Conclusion and outlook

EID is an approach to interface design, and being a design activity, there are no simple rules or recipes that provide good results across all application domains. In our work on supporting control and planning of locomotion, we developed several insights through the application of EID to vehicle locomotion. Particularly we found that in vehicle operation the focus of the work is often more on planning and control than on diagnosis. In other words, the emphasis needs to be on the coupling of perception-action relative to achieving the system’s functional purpose, as reflected in Gibson’s Ecological Approach to the perception of affordances [6].

The interface must function as a cognition/decision support system, *not* simply as a data source or open-loop communication channel. As a decision support system, it must help the human operators to understand what the data mean in relation to the functional objectives or goals, and in relation to specifying the options for acting to correct any potential deviations from those goals. In this manner EID addresses a meaning processing (semantic) problem, rather than an information processing problem [5].

A. Summary of main lessons

In their control of vehicle locomotion, operators need to plan their control according to several different time spans, effectively closing multiple control loops in parallel. The designer of the interface should select over which time spans to support the work, effectively also selecting a system boundary, a choice that will affect the scope of the resulting work domain analysis. This has a resemblance to Amelink's abstraction-sophistication analysis, where a set of nested work domain analyses has been used to describe automation at different levels of sophistication.

To support parallel work on multiple time spans, vehicle locomotion must be planned ahead of time, refined and finally implemented. Thus after considering the choice of which time spans are to be supported, the designer must also choose how to formulate the input or set-points for the vehicle, matching both the chosen control span(s) and the capabilities of the operator to enable comprehension and formulation of the input (the plan). Formulating the input as a function of time affects the ability to visualize the constraints and consequences of this input; an input must be efficiently parameterized, implying that the complexity of the input function must be limited, to enable a meaningful visualization.

We found that in performing the work domain analysis, it pays off to consider alternative formulations for characterizing system state. Playing around with simulations and formulations, through "serious play", can be used to trigger a search for representations that simplify relations in the work domain or simplify the shape of constraints.

For the design of the displays we chose for an incremental approach, adding ecological displays to the existing instrumentation of vehicles, or even enhancing existing displays to incorporate EID elements. This was seen as the approach that provides the highest likelihood for later adoption of the display designs by industry. The resulting displays must also be compatible with existing instrumentation and out-of-the-window perception of the environment, supporting integrated perception of the work domain through all information sources, thereby providing the necessary visual momentum. The resulting displays typically employ overlaid layers, with each layer visualizing constraints in a different parameter space. Through proper alignment and scaling of the layers, the display can provide an integrated view on the constraints and affordances, also when screen space is limited.

B. Outlook on new challenges

The past work has resulted in the range of ecological interfaces for locomotion, supporting the planning and control of locomotion over different time spans. A future challenge will be to design interfaces that support closing all loops, i.e., the whole range of control and planning, from short term maneuvering, through the scale at which tactical path changes are performed, to monitoring and planning of a complete mission, or even learning and adaptation over missions. This will require analysis of the work domain not only along abstraction and whole-part axes, but also along a planning horizon axis. The interfaces should preserve visual momentum not just across information sources but also across time spans.

Another major challenge is scaling designs to collaboration and coordination in vehicle locomotion, and in other domains with parties that might have conflicting goals and compete for resources. Our previous work on 4D trajectory management, focusing on perturbation management in collaboration with automation, addresses only a small part of the problem. In a real-world application both air traffic controllers, their support automation, external influences such as the weather and the pilots on board of aircraft will all affect the planned and implemented trajectories, forming a challenge with many agents, in a correspondence-driven, time-critical and safety-critical work domain.

ACKNOWLEDGMENT

The authors would like to thank the many MSc and PhD students from the TU Delft Faculty of Aerospace Engineering Control and Simulation section, who in their graduation work performed the numerous design iterations and experimental evaluations that gave us novel insights and inspiration.

REFERENCES

[1] K. Vicente and J. Rasmussen, "Ecological interface design: Theoretical foundations", *IEEE Transactions on Systems, Man and Cybernetics*, vol. 22, no. 4, pp. 589–606, 1992.

[2] ——, "The ecology of human-machine systems II: Mediating "direct perception" in complex work domains", *Ecological Psychology*, vol. 2, no. 3, pp. 207–249, 1990.

[3] K. J. Vicente, *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. Mahwah, N.J: Lawrence Erlbaum Associates, 1999, 392 pp.

[4] C. M. Burns and J. Hajdukiewicz, *Ecological interface design*. CRC Press, 2004.

[5] K. B. Bennett and J. Flach, *Display and interface design : Subtle science, exact art*. Boca Raton; London: CRC Press, 2011.

[6] J. J. Gibson, *The ecological approach to visual perception*. Hoboken: Taylor & Francis, 1986, OCLC: 958134763.

[7] W. Langewiesche, *Stick and rudder : An explanation of the art of flying*. New York: McGraw-Hill, 1944.

[8] J. M. Flach, R. Jagacinski J., M. R. H. Smith, and B. McKenna, "Coupling perception, action, intention, and value: A control theoretic approach to driving performance", in *Handbook of Driving Simulation for Engineering, Medicine and Psychology*, D. L. Fisher, M. Rizzo, J. K. Caird, and J. D. Lee, Eds., Boca Raton (FL): Taylor & Francis, CRC Press, 2011, pp. 43.1–43.16.

[9] J. J. Gibson and L. E. Crooks, "A theoretical field-analysis of automobile-driving", *The American Journal of Psychology*, vol. 51, no. 3, pp. 453–471, Jul. 1, 1938.

[10] M. R. H. Smith, J. M. Flach, S. M. Dittman, and T. W. Stanard, "Monocular optical constraints on collision control", *Journal of Experimental Psychology: Human Perception & Performance*, vol. 27, no. 2, pp. 395–410, 2001.

[11] J. M. Flach, M. Mulder, and M. M. Van Paassen, "The Concept of the Situation in Psychology", in *A Cognitive Approach to Situation Awareness: Theory and Application*, S. Banbury and S. Tremblay, Eds., ISBN 0754641988, Ashgate Publishing, Oxon (UK), 2004, pp. 42–60.

[12] T. W. Stanard, J. M. Flach, M. R. H. Smith, and R. Warren, "Learning to avoid collisions: A functional state space approach", *Ecological Psychology*, vol. 24, no. 4, pp. 328–360, 2012.

[13] J. Itoh, A. Sakuma, and K. Monta, "An ecological interface for supervisory control of BWR nuclear power plants", *Control Engineering Practice*, vol. 3, no. 2, pp. 231–239, Feb. 1995.

[14] N. Naito, J. Itoh, K. Monta, and M. Makino, "An intelligent human-machine system based on an ecological interface design concept", *Nuclear Engineering and Design*, vol. 154, no. 2, pp. 97–108, Mar. 1995.

[15] G. Jamieson, “Ecological interface design for petrochemical process control: An empirical assessment”, *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 37, no. 6, pp. 906–920, 2007.

[16] G. Jamieson, C. Miller, W. Ho, and K. Vicente, “Integrating task- and work domain-based work analyses in ecological interface design: A process control case study”, *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 37, no. 6, pp. 887–905, 2007.

[17] K. Canfield and K. Petrucci, “Interface design for clinical information systems: An ecological interface design approach”, in *Human Computer Interaction*, T. Grechenig and M. Tscheligi, Eds., vol. 733, Berlin, Heidelberg: Springer Berlin Heidelberg, 1993, pp. 391–402.

[18] K. Vicente, “Ecological interface design: Progress and challenges”, *Human Factors*, vol. 44, no. 1, pp. 62–78, 2002.

[19] C. Borst, J. M. Flach, and J. Ellerbroek, “Beyond Ecological Interface Design: Lessons from Concerns and Misconceptions”, *IEEE Transactions on Human-Machine Systems*, vol. 45, no. 2, pp. 164–175, 2015.

[20] R. C. McIlroy and N. A. Stanton, “Ecological interface design two decades on: Whatever happened to the SRK taxonomy?”, *IEEE Transactions on Human-Machine Systems*, vol. 45, no. 2, pp. 145–163, Apr. 2015.

[21] D. Beevis, K. J. Vicente, and N. Dinadis, “An exploratory application of ecological interface design to aircraft systems”, in *Proc. RTO HFM Symp. Collaborative Perform. Complex Oper. Syst*, Apr. 1998, pp. 2–1–2–9.

[22] N. Dinadis and K. J. Vicente, “Designing functional visualizations for aircraft systems status displays”, *The International Journal of Aviation Psychology*, vol. 9, no. 3, pp. 241–269, Jul. 1999.

[23] S. Chery, K. J. Vicente, and P. S. E. Farrell, “Perceptual control theory and ecological interface design: Lessons learned from the control display unit”, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 43, no. 4, pp. 389–393, Sep. 1, 1999.

[24] M. H. J. Amelink, M. Mulder, M. M. van Paassen, and J. M. Flach, “Theoretical foundations for a total energy-based perspective flight-path display”, *The International Journal of Aviation Psychology*, vol. 15, no. 3, pp. 205–231, 2005.

[25] S. B. J. Van Dam, M. Mulder, and M. M. van Paassen, “Ecological interface design of a tactical airborne separation assistance tool”, *IEEE Transactions on Systems, Man and Cybernetics, Part A*, vol. 38, no. 6, pp. 1221–1233, 2008.

[26] J. Ellerbroek, K. C. R. Brantegem, M. M. van Paassen, and M. Mulder, “Design of a coplanar airborne separation display”, *IEEE Transactions on Human-Machine Systems*, pp. 1–13, 2013.

[27] J. Ellerbroek, K. C. R. Brantegem, M. M. van Paassen, N. de Gelder, and M. Mulder, “Experimental evaluation of a coplanar airborne separation display”, *IEEE Transactions on Human-Machine Systems*, vol. 43, no. 3, pp. 290–301, May 2013.

[28] C. Borst, H. C. H. Suijkerbuijk, M. Mulder, and M. M. van Paassen, “Ecological Interface Design for Terrain Awareness”, *The International Journal of Aviation Psychology*, vol. 16, no. 4, pp. 375–400, 2006.

[29] C. Borst, F. A. Sjer, M. Mulder, M. M. van Paassen, and J. A. Mulder, “Ecological Approach to Support Pilot Terrain Awareness After Total Engine Failure”, *Journal of Aircraft*, vol. 45, no. 1, pp. 159–171, 2008.

[30] C. Borst, M. Mulder, and M. M. van Paassen, “Design and Simulator Evaluation of an Ecological Synthetic Vision Display”, *Journal of Guidance, Control & Dynamics*, vol. 33, no. 5, pp. 1577–1591, 2010.

[31] B. J. A. Van Marwijk, C. Borst, M. Mulder, M. Mulder, and M. M. van Paassen, “Supporting 4D Trajectory Revisions on the Flight Deck: Design of a Human-Machine Interface”, *International Journal on Aviation Psychology*, vol. 21, no. 1, pp. 35–61, 2011.

[32] M. M. van Paassen, C. Borst, R. E. Klomp, M. Mulder, P. van Leeuwen, and M. Mooij, “Designing for shared cognition in air traffic management”, *Journal of Aerospace Operations*, vol. 2, no. 1, pp. 39–51, 2013.

[33] R. Klomp, C. Borst, M. M. van Paassen, and M. Mulder, “Expertise level, control strategies, and robustness in future air traffic control decision aiding”, *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 2, pp. 255–266, 2016.

[34] A. van der Eijk, C. Borst, A. C. In ‘t Veld, M. M. van Paassen, and M. Mulder, “Assisting Air Traffic Controllers in Planning and Monitoring Continuous-Descent Approaches”, *Journal of Aircraft*, vol. 49, no. 5, pp. 1376–1390, 2012.

[35] A. M. P. De Leege, M. M. Van Paassen, and M. Mulder, “The Time-Space Diagram as an Assistance for ATC in Monitoring Closed Path Continuous Descent Operations”, *Journal of Aircraft*, vol. 50, no. 5, pp. 1394–1408, 2013.

[36] J. Lodder, J. Comans, M. M. van Paassen, and M. Mulder, “Altitude-extended solution space diagram for air traffic controllers”, in *Proceedings of the 16th International Symposium on Aviation Psychology*, J. Flach, M. Vidulich, and P. Tsang, Eds., Dayton (OH), Apr. 2011, pp. 345–350.

[37] M. M. van Paassen, “Visualization of pairwise conflict resolution for air traffic control”, in *17th International Symposium on Aviation Psychology*, P. Tsang and M. Vidulich, Eds., Dayton (OH), May 2013, pp. 371–376.

[38] G. A. Mercado Velasco, C. Borst, J. Ellerbroek, M. M. van Paassen, and M. Mulder, “The use of intent information in conflict detection and resolution models based on dynamic velocity obstacles”, *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 4, pp. 2297–2302, Aug. 2015.

[39] P. M. Sanderson and N. Naikar, “Temporal coordination control task analysis for analysing human-system integration”, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 44, no. 1, pp. 206–209, Jul. 2000.

[40] C. Miller and K. J. Vicente, “Comparative analysis of display requirements generated via task-based and work domain-based analyses: A test case using DURESS II”, Cognitive Engineering Laboratory, Toronto, CA, CEL 98-08, Aug. 9, 1998, p. 34.

[41] M. H. J. Amelink, “Ecological Automation Design – Extending work domain analysis”, Ph.D. Dissertation, Faculty of Aerospace Engineering, Delft University of Technology, 2010.

[42] Anon., “In-flight uncontained engine failure airbus a380-842, VH-OQA, overhead batam island, indonesia, 4 november 2010”, Australian Transport Safety Bureau, AO-2010-089, Jun. 27, 2013, p. 284.

[43] R. L. Helmreich, A. C. Merritt, and J. A. Wilhelm, “The evolution of crew resource management training in commercial aviation”, *The International Journal of Aviation Psychology*, vol. 9, no. 1, pp. 19–32, Jan. 1999.

[44] J. Rasmussen, *Information processing and human-machine interaction : An approach to cognitive engineering*. New York: North-Holland, 1986.

[45] N. Naikar, “Cognitive work analysis: An influential legacy extending beyond human factors and engineering”, *Applied Ergonomics*, vol. 59, pp. 528–540, Mar. 2017.

[46] M. H. J. Amelink, M. M. van Paassen, and M. Mulder, “Total energy-based perspective flight path display for aircraft guidance along complex approach trajectories”, in *Proceedings 12th International Symposium on Aviation Psychology*, Dayton (OH), 2003.

[47] K. Ogata, *Modern control engineering*, 3rd ed. Upper Saddle River, N.J: Prentice Hall, 1997, 997 pp.

[48] G. Olsder, *Mathematical systems theory*. Delft: VSSD, 2011, OCLC: 782159198.

[49] A. Lambregts, “Vertical flight path and speed control autopilot design using total energy principles”, presented at the Guidance and Control Conference, Gatlinburg, TN: American Institute of Aeronautics and Astronautics, Aug. 15, 1983, pp. 559–569.

[50] E. R. Tufte, *The visual display of quantitative information*, 2nd ed. Cheshire, Conn: Graphics Press, 2001, 197 pp.

[51] M. C. L. van den Hoven, P. M. A. de Jong, C. Borst, M. Mulder, and M. M. van Paassen, “Investigation of energy management during approach - evaluating the total energy-based perspective flight-path display”, in *AIAA Guidance, Navigation and Control Conference*, AIAA-2010-7542, Toronto, CA: AIAA, Aug. 2010, p. 21.

[52] J. Hoekstra and R. C. J. Ruigrok, *Conceptual design of free flight with airborne separation assurance*. Nov. 4, 1999.

[53] J. Rasmussen, “Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and other Distinctions in Human Performance Models”, *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 13, pp. 257–266, 1983.

[54] J. Ellerbroek, M. Visser, S. B. J. Van Dam, M. Mulder, and M. M. van Paassen, “Design of an airborne three-dimensional separation assistance display”, *IEEE-SMCA*, vol. 41, no. 5, pp. 863–875, Sep. 2011.

[55] A. Chakravarthy and D. Ghose, “Obstacle Avoidance in a Dynamic Environment: A Collision Cone Approach”, *IEEE System, Man and Cybernetics - Part A: Systems and Humans*, vol. 28, no. 5, pp. 562–574, 1998.

[56] P. Fiorini and Z. Shiller, “Motion Planning in Dynamic Environments Using Velocity Obstacles”, *International Journal of Robotics Research*, vol. 17, pp. 760–772, 1998.

[57] L. Tychonievich, D. Zaret, J. Mantegna, R. Evans, E. Muehle, and S. Martin, “Maneuvering-Board Approach to Path Planning with Moving

Obstacles", in *International Joint conference on Artificial Intelligence*, 1989, pp. 1017–1021.
[58] Anon. (2004). Battenberg course indicator, [Online]. Available: http://www.gwpda.org/naval/ou5274.htm (visited on 11/25/2016).
[59] M. Schrage, *Serious play: How the world's best companies simulate to innovate*. Boston, mass: Harvard Business School Press, 2000, 244 pp.
[60] R. M. de Neef and M. M. van Paassen, "Functional modelling of airspace", presented at the 20th European Annual Conference on Human Decision Making and Manual Control, Kongens Lyngby (DK): Dansk Teknisk Universitet, 2001, p. 6.
[61] S. B. J. Van Dam, M. Mulder, and M. M. van Paassen, "Airborne self-separation display with turn dynamics and intruder intent-information", in *IEEE International Conference on Systems, Man and Cybernetics*, Montreal, Oct. 7, 2007, pp. 1445–1451.
[62] R. Klomp, C. Borst, M. M. van Paassen, and M. Mulder, "Designing for joint human-automation cognition through a shared representation of 4d trajectory management", in *17th International Symposium on Aviation Psychology*, P. Tsang and M. Vidulich, Eds., Dayton (OH), May 2013, pp. 518–523.
[63] D. D. Woods, "Visual momentum: A concept to improve the cognitive coupling of person and computer", *International Journal of Man-Machine Studies*, vol. 21, no. 3, pp. 229–244, Sep. 1984.
[64] M.-C. Ostendorp, J. C. Lenk, and A. Lüdtke, "Smart glasses to support maritime pilots in harbor maneuvers", *6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015*, vol. 3, pp. 2840–2847, Jan. 1, 2015.
[65] E. Hutchins, *Cognition in the wild*, second printing. Cambridge, Mass: MIT Press, 1995, 381 pp., OCLC: 248968842.
[66] ——, "How a cockpit remembers its speeds", *Cognitive Science*, vol. 19, no. 3, pp. 265–288, Jul. 1995.
[67] D. Chandra and S. Mangold, "Human factors considerations for the design and evaluation of electronic flight bags", vol. 2, IEEE, 2000, 5A1/1–5A1/7.
[68] C. D. Wickens, *Engineering Psychology and Human Performance*, 2nd. HarperCollins, 1992.
[69] S. L. Johnson and S. N. Roscoe, "What Moves, the Airplane or the World?", *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 14, no. 2, pp. 107–129, 1972.
[70] S. N. Roscoe, L. Corl, and R. S. Jensen, "Flight Display Dynamics Revisited", *Human Factors*, vol. 23, no. 3, pp. 341–353, 1981.
[71] J. M. Flach, "Situation awareness: Context matters! a commentary on endsley", *Journal of Cognitive Engineering and Decision Making*, vol. 9, no. 1, pp. 59–72, Mar. 1, 2015.
[72] J. M. Flach and F. Voorhorst, *What matters? putting common sense to work*. Dayton (OH): Wright State University Libraries, 2016.
[73] R. Appleton, M. Mulder, and M. M. van Paassen, "Comparison of two interfaces for supporting pilots in airborne self-separation tasks", in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA-2006-6062, Keystone, CO, Aug. 2006.
[74] M. M. van Paassen, "The fading line between self and system", in *Risk Management in Life Critical Systems*, ser. Risk Management and Dependability Series, P. Millot, Ed., London, UK: Wiley-ISTE, Nov. 2014, pp. 183–210.
[75] R. Appleton, M. Mulder, and M. M. van Paassen, "Comparison of Two Interfaces for Supporting Pilots in Airborne Self-Separation Tasks", *Proc. of the AIAA Guidance, Navigation and Control Conference, Keystone (CO), USA, August 21-24*, no. AIAA 2006-6062, 2006.
[76] C. L. M. Steens, S. B. J. Van Dam, M. Mulder, and M. M. van Paassen, "Comparing Situation Awareness for two Airborne Separation Assistance Interfaces", *Proc. of the AIAA Guidance, Navigation and Control Conference, Honolulu (HI), USA, August 18-21*, no. AIAA 2008-7155, 2008.
[77] J. P. Hansen, *Information nesting in configural interfaces for process control*, ser. Risø-R 616. Roskilde: Risø National Laboratory, 1992, 28 pp., OCLC: 248239727.
[78] J. P. Hansen, "Representation of system invariants by optical invariants in configural displays for process control", in *Local Applications of the Ecological Approach to Human-Machine Systems*, P. Hancock, J. M. Flach, J. Caird, and K. J. Vicente, Eds., Hillsdale, NJ: Lawrence Erlbaum Associates, 1995, pp. 208–233.

Marinus (René) M. van Paassen (M'08, SM'15) received the M.Sc. and Ph.D. degrees from TU Delft, The Netherlands, in 1988 and 1994, respectively, for his studies on the role of the neuromuscular system of the pilot's arm in manual control. He is currently an Associate Professor at the section Control and Simulation, Aerospace Engineering, TU Delft, working on human-machine interaction and aircraft simulation. His work on human-machine interaction ranges from studies of perceptual processes and manual control to complex cognitive systems. In the latter field, he applies cognitive systems engineering analysis (abstraction hierarchy and multilevel flow modeling) and ecological interface design to the work domain of vehicle control. Dr. van Paassen is an Associate Editor of the IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS.

Clark Borst received the MSc (2004, with honours) and PhD degrees (2009) in aerospace engineering from the Delft University of Technology, The Netherlands, where he is currently working as an Assistant Professor in aerospace human-machine systems. His work and research interests lie in developing human-centered aviation automation through the application and empirical evaluation of Cognitive Systems Engineering and Ecological Interface Design principles.

Joost Ellerbroek received the MSc (2007) and PhD (2013) degrees in aerospace engineering from the Delft University of Technology, The Netherlands, where he is currently working as an Assistant Professor. His research interests lie in the field of Communication, Navigation and Surveillance (CNS) and Air Traffic Management (ATM), and in human-automation interaction.

Max Mulder (M'14) received the MSc degree and PhD degree (*cum laude*) in aerospace engineering from TU Delft, The Netherlands, in 1992 and 1999, respectively, for his work on the cybernetics of tunnel-in-the-sky displays. He is currently Full Professor and Head of the section Control and Simulation, Faculty of Aerospace Engineering, TU Delft. His research interests include cybernetics and its use in modeling human perception and performance, and cognitive systems engineering and its application in the design of "ecological" human-machine interfaces. Prof. Mulder is an Associate Editor of the IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS.

John M. Flach Received his Ph.D. in human experimental psychology from The Ohio State University in 1984. After more than 30 years teaching and supervising graduate research in universities, he recently joined Mile Two LLC as a Senior Cognitive Systems Engineer. John has written extensively about Cognitive Systems Engineering (CSE) and Ecological approaches to human performance and design (including 3 co-authored books; 3 co-edited books; and more than 180 archival publications). After many years of talking and writing about CSE and EID, he welcomes the opportunity to test what he has learned against the challenge of designing practical solutions to contemporary business problems. To learn more about John, check out his Perspicacity blog: https://blogs.wright.edu/learn/johnflach/author/w001jmf/