The Chicken, the Egg, the Workspace Analysis, and the Ecological Interface.

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The first applications of the design of operator interfaces with Cognitive Workspace Analysis and Ecological Interface Design were in the field of power plants and process control. These applications are similar to the DURESS micro-world, for which the first EID design was made. The workspace analysis for these domains can then be similar to the analysis elaborated for DURESS. At the Faculty of Aerospace Engineering of the Delft University of Technology, in several projects now EID has been applied to a different work domain, namely vehicle control. These projects have focused on, among others, conflict avoidance in aircraft and ships, terrain avoidance and energy management, and on the control of Unmanned Autonomous Vehicles. In applying Ecological Interface Design to vehicle control, the workspace analysis needed to be adapted to a new application domain. The results may serve as inspiration for workspace analyses in the vehicle control domain or other domains.

Introduction

Interface designs based on the principle of Ecological Interface Design (EID), start with an analysis of the operator’s work space. This analysis provides a mapping of the constraints imposed on the operator by this work space, in other words, the do’s and don’ts that are imposed by the environment. The first application of EID was an example application in the process control domain, DURESS (Vicente and Rasmussen, 1990), and many applications in that domain followed. In this paper, we consider the application of EID to the domain of vehicle control. One of the first EID designs for vehicles was created by Dinadis and Vicente (1999). However, this design was not targeted at control of the vehicle’s motion, but at the supervision of the system status of an aircraft in this case. By that virtue, it is an example of process control, but with the process equipment on board of a vehicle.

The control of vehicles is an important everyday activity for professional operators (pilots, helmsmen) and non-professionals alike. In many cases, vehicle control is possible with little or no help from instrumentation and automation. In that case the outside environment is perceived directly, and the vehicle’s driver, pilot or operator determines what are the constraints for that combination of environment and vehicle, and what possibilities the environment and vehicle afford. However, in many situations, instrumentation is added, because the scale and dynamics of the vehicle’s maneuvers make it difficult or impossible to navigate on the external view alone, or to enable all-weather operations.

This paper attempts to give an overview of the application of Cognitive Systems Engineering (CSE) and the development of Ecological Interface Designs for the task of navigating or maneuvering ships and aircraft. As hinted by the title, this was an iterative process, in which the workspace analyses and interfaces for the locomotion domain led to increased insight in developing workspace analyses for this type of application.

Three different applications are discussed, these are:

- Support in altitude and speed control of an aircraft.
- Interfaces for medium term conflict resolution in free-flight airspace.
- Interfaces for avoiding terrain collisions in aircraft.

Workspace analysis for vehicle locomotion

In cognitive systems engineering, the workspace (environment) is analyzed and described in an Abstraction Hierarchy (Rasmussen, 1986), or in more general terms, an Abstraction - Decomposition Space (ADS).
In this paper, we consider first the analysis for the medium term conflict avoidance with aircraft, and later identify differences with the analyses for the other two applications.

As for most systems, three goals for a traveling vehicle can be identified at the functional purpose level, production, economy and safety (Figure 1). This makes the AF function level identical, or at least very similar, to analyses for other work domains.

In the workspace analysis for a conflict avoidance with aircraft, a “Protected Zone” is defined around each aircraft. A conflict occurs when an aircraft enters an other aircraft’s PZ. The crew’s task is to direct the aircraft to its destination along the most effective route (satisfying the economy goal and production goals), while avoiding conflicts. A safe flight in this aspect means that the aircraft does not enter the PZ of other aircraft.

Identification of the functions at the Abstract Function level of the ADS proved to be the most challenging of the analysis. In the example of DURESS, the Abstract Function level describes the system in terms of mass and energy flows, storage, sources and sinks. Vicente and Rasmussen (1992) talk of holonomic constraints. These are the constraints imposed upon us by physics; inescapable, unless our understanding of the physical world proves to be wrong. For the transport domain, an alternative to the mass and energy flow based description needed to be found. The best fit, so far, includes energy relations, describing kinetic and potential energy of the vehicle. Thus, in this aspect the modeling is similar to the modeling for DURESS and similar process control applications. The second set of constraints at this level is given by the kinematics of motion, in short, locomotion. Safety is mainly achieved by locomotion relative to the aircraft or other obstacles in the vicinity, the motion relative to other aircraft should be thus that the protective zone of those aircraft is not entered. Production and economy are achieved by absolute motion, since absolute motion describes whether and how efficiently the aircraft approaches its destination.

At the generic function level, common functions in aircraft are lift, propulsion, maneuvering, navigation (in the sense of determining ones own position) and surveillance, i.e. determining the position and path of surrounding aircraft.

Moving to the next less abstract level, and considering how the generic functions are achieved, provides the description at the physical function level. At this level the system is generally described in terms of its function providing devices or components. In the present work domain analysis, relevant functionalities are the wings, to provide lift, the engines for thrust, the tail for stability, control surfaces and systems for achieving maneuvering, navigation sensors and systems, receivers and transmitters for communicating with aircraft in the vicinity and the fuselage for combination of the above functions and protection of the cargo.

The lowest abstraction level in this analysis, the physical form level, describes the physical details of the systems, such as shape, material use, etc. Especially in aerodynamics, the details on shape determine all functionality.

Each of the levels describes the system’s functionality at a certain level of abstraction. From the description at each level of abstraction, different constraints on the system can be inferred. The functional purpose level describes these constraints in terms of what we want and value of the system. Violating these constraints, means failing to meet the purposes formulated here, which results in a system that might be unsafe, too expensive, or of limited use. The abstract function level describes the system in terms of the basic physics. For vehicles, this means for example that one needs velocity, and thus kinetic energy, for locomotion. The constraints at this level simply cannot be broken.

Generalized functions describe the general principles by which the processes at abstract function level are implemented. In design, system choices are often made at this level; one could for example use either lift, buoyancy or a (road, rail) contact force to keep a vehicle from giving in to gravity.
Physical functions describe the functions provided by components in the system. Constraints at the physical function level are usually in the form of limits on the functionality, for example maximum lift that one can obtain from a certain wing. These constraints are rooted in the physical form level, which provides the detail, for example on wing size, profile, strength, that determine the limits on functionality.

In arriving at these analyses, the main difficulty in developing the analysis was determining the representation at the abstract function level. Adopting the description of mass and energy flows as used in the process control domain, and most notably the example of DURESS, leads to a very poor representation which captures only a small part, namely fuel flow and engine energy, of the work domain. Although deceivingly simple, a description of abstract functionality in terms of the kinetics of locomotion, proved efficient. For other domains, description of the system behavior in terms of different “laws”, for example in the field of information theory, monetary values or probability theory may be required.

As an example, one might consider the use of a private car and the possibility of being fined for speeding. Leaving aside driving for pleasure, this possibility would be related to the economy goal, and to the production goal. At the abstract function level, one would include the probability theory for describing the chance of being caught, and the economics for describing the cost of fines relative to economic means.

As an alternative to the Abstract Function level, label Values and Priority Measures for the second level of the ADS is sometimes used. Then this level describes the criteria for measuring progress in the fulfillment of the functional purpose (Naikar, 2006). For our purpose, this approach does not seem useful. Primarily because it breaks the means-ends relation (the what-why-how chain) in the abstraction axis. A level in the ADS should be the means to realizing\(^1\) the functions at the next higher level. Measurement or evaluation of the functionality realized (whether at the functional purpose level or at any of the other levels), is a different topic, and one that does not need to be specified in the ADS. The fact that a measured value satisfies a certain criterion tells us that a goal is achieved. However, the value is not part of a workspace analysis, only the function on which we can measure the value is.

\(^1\)Although Rasmussen (1986) uses achieve, we prefer the term realize here, since it does not suggest an exclusive relationship with purposes and goals.

Time scale of the input

Of the many controls for an aircraft, just a few are used in controlling the primary motions. These are the control wheel (alternatively, a center stick or side stick may be used), the rudder pedals and the throttle. In the EID interface created for DURESS, the controls are present as sliders operated by the mouse or a similar computer input device. The time scale of the dynamics of DURESS and similar processes makes this possible. Vehicles, with the exception of large ships, have much faster dynamics, and operation of a vehicle with sliders on a graphical user interface would be impossible or dangerous. It proved useful in this case, to single out a part of the vehicle’s motion that is relevant to the workspace, and include only that part in the workspace analysis and subsequent interface design.

For the conflict avoidance displays, the kinematic relationships between the airplane’s heading and velocity and the relative and absolute motions of the airplane are included in the analysis. All other dynamics and kinematics, describing the relationship between the pilot’s controls and heading and velocity, are left to the pilot. In that aspect the EID does not cover the full work domain, and constraints in the “pilot’s part”, such as airplane handling, preventing stall, etc., cannot be included in analysis nor interface.

In the “energy” display (Amelink, Mulder, van Paassen and Flach, 2005), the exchange between kinematic and potential energy associated with the control of the speed and altitude of an aircraft along a pre-defined speed and altitude profile is visualized in a perspective tunnel in the sky display. Here, only the attitude control of the aircraft is left to the pilot. The display visualizes the relationships between the resulting flight direction and the functional purpose, as well as the constraints between the resulting “energy” direction, i.e. changes in total energy, and the functional purpose in an energy sense.

Complexity of constraint shapes

Different systems vary in the degree with which they have interaction with the (uncontrolled) environment. A system is said to be more “closed”, when it has little interaction with the environment, and “open” when there is more interaction. For most stationary plants, such as in the process industry, the interaction can be characterized by a limited number of measured variables. For example, outside temperature and wind strength and direction affect the process. For a vehicle, vehicles in the vicinity represent an interaction with
the environment. The number and complexity of interactions with the environment determine the degree of openness of a system.

In the conflict avoidance task, each of the neighboring vehicles can be described with a limited number of measured variables. Each neighboring vehicle introduces a new set of constraints in the work domain, as can be seen in Figure 2. In this case, the constraints introduced by another vehicle, when visualized in a speed and heading plane, have a triangular shape. In terrain avoidance, the constraints have a more complex shape, reflecting the complexity inherent in the shape of the terrain itself, see Figure 3. The openness of the system is thus reflected in the complexity of the constraints, and so, if these constraints are visualized completely, the complexity of the information on an EID. It also affects the display design in a more practical way. The evaluation of the constraints in the conflict avoidance or the energy control application can be done in a mathematically closed form. For the terrain avoidance displays, a brute-force calculation method is used. If a closed-form solution is at hand, as is the case for the conflict avoidance and the energy displays, this closed form solution can form a basis for the design of the display.

Evolution of analyses and displays

Of the three interfaces considered, the displays for airborne conflict resolution had the longest evolution. It began with the idea that empty airspace provides a function to aircraft traveling in that airspace, and that the “shape” of that function, i.e. where one can travel and at what speed, depends on fellow travelers in the same airspace (van Paassen, 1999). However, that analysis did not take into account the time it would take to turn the aircraft to a new heading or accelerate/decelerate to a new speed. A further development was the analysis of this function that airspace provided with the inclusion of the turn dynamics (de Neef and van Paassen, 2001). Presentation of only the headings that would avoid a conflict proved to be incomplete, since one could not see which action would result in an efficient maneuver.

The next step started from a work domain analysis (van Paassen, Mulder and Van Dam, 2004; Van Dam, Abeloos, Mulder and van Paassen, 2004; Van Dam, Abeloos, Mulder and van Paassen, 2005), and ignored the turn and acceleration dynamics again. That step also resulted in the first prototype display, which was
Figure 4: Exploration of aircraft pull-up, climb and glide performance with a full non-linear model (blue continuous lines), suggests an approximation with a circle and cone (red dotted lines), respectively (Borst et al., 2006).

Figure 5: The abstraction hierarchy resulting from the analysis for the control of speed and altitude showing the energy relations on the middle levels as intermediate control goals, from ? implemented as hand-drawn lines on a set of transparencies. This, and later prototypes, served to discover more properties from the work domain. Subsequent developments re-introduced the turn dynamics (Appleton et al., 2006), and include information on the intent of the other aircraft (Van Dam, van Paassen and Mulder, 2007).

In the development and evolution of the displays, the work domain analysis was in most cases supplemented with simulations of the aircraft dynamics to explore the constraints of the work domain, and more specifically the constraints of the vehicle. A typical example is found in Figure 4, which shows an exploration of the optimum climb and glide performance for an aircraft. The development of the energy Augmented Tunnel In the Sky (EATIS) display started with the idea that pilots could be aided with energy management information when flying tunnel-in-the-sky trajectories. The role of energy relations was clear from a technical point of view as an aircraft, as all physical objects, obeys the law of conservation of energy. For an aircraft it means that total energy changes are limited to fairly slow rates: total energy is increased by thrust and decreased by drag. The exchange of energy, by trading speed versus height (kinetic versus potential energy), can be realized fairly quickly. These implications govern flight, not only from a technical point of view but also from the piloting point of view. EID was applied to the design process from the start and work domain analysis (WDA) made the designer think of the structure of the work domain and look beyond traditional constraints.

That energy management was indeed part of piloting was identified when structuring the flight control problem in the ADS (Figure 5). The result shows that the elevator and throttle control the energy state directly; the throttle controls total energy and the elevator the exchange of energy. The final control goal, speed and height is achieved by controlling the energy state as an intermediate control goal. In EATIS the energy representation is a graphical format that is fully integrated in the Tunnel in the Sky display (Figure 6). The total energy rate is presented by the total energy angle which directly responds to drag and trust. The total energy level is represented by the total energy reference plane which shows the deviation from the target state. This three-dimensional representation shows the variables and their physical relations in a way that supports both goals of EID: support on the three levels of cognitive processing (SRK taxonomy) and not forcing the level of cognitive processing to a higher level than required by the task, in this case skill based behavior (Vicente and Rasmussen, 1992).

The construction of an ADS can be a laborious task and often we have found ourselves debating what should go to which level, how should the levels be labeled and how many levels should be used. This builds understanding of the problem space and is a good start of the analysis. However, anyone who starts with ADS analysis can find him or herself in a situation where the ADS seems to be turning into the goal of the analysis. When that happens it is best to take a distance and realize that the result that counts is an understanding the problem space, and not the ADS itself. Our understanding of how pilots control energy implicitly (present) and explicitly (with EATIS) grew with the
Figure 6: Energy augmented tunnel in the sky display showing the energy angle (1), and total energy reference profile (2)

evolution of the display and the analysis evolved with our understanding. We have found it useful to show our understanding in one or more ADS representation but its value lies in the structure it gives to the problem space.

Conclusions

This paper outlines the efforts done at the Faculty of Aerospace Engineering of the Delft University of Technology to create several interfaces with Cognitive Workspace Analysis and Ecological Interface Design. For some projects this process has clearly been iterative, with several iterations in which both the workspace analysis were refined and the interfaces improved.

Finding a suitable representation of the workspace at the abstract function level proved to be a challenge. A description in the style of the Abstract Function level description as given for the DURESS micro-world, i.e., In the form of mass and energy flows, only captures a small part of the work domain for traveling vehicles, and otherwise seems to completely “miss the point”. Our alternative, in the form of a description of relative and absolute locomotion, supplemented with an energy description that describes potential and kinetic energy, seems simple, but captures the essentials of vehicle abstract functionality.

The relationship between the analysis and the design of the display is mutual. Since the displays designed in the discussed projects are new, design of the display after a single step in the analysis proved to be difficult.

After initial workspace analysis, prototype display designs often produce ideas to improve the analysis. Of particular help is the opportunity to implement a live version of a display and experience the workspace constraints firsthand. Exploration of the constraints of the vehicle, with simulations, are also important. Often, the level of detail with which one can describe the vehicle’s behavior is very high, and one needs this exploration to find simplified versions of the constraints that can be visualized in a display.

A difference with many process control systems is in the step of task analysis. Locomotive systems, with the exception of ships, have much faster dynamics than power and process plants. These dynamics make these systems unfit for control via controls on the display, such as sliders. The faster part of the dynamics must then be controlled by the pilot or operator. In the energy displays, for example, the flight path vector and the energy bar are comparable to the slider inputs in DURESS. The pilot, however, does not have a mouse to manipulate these, but an airplane.

Now the question remains, what came first, the chicken or the egg, the analysis or the interface? In the evolution of the chicken and the egg, egg-laying animals appeared long before our domestic chicken. So the chicken and its egg came slowly, and together. So did the analysis and the interfaces.

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