An Abstraction Hierarchy and Functional Model of Airspace for Airborne Trajectory Planning Support

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Abstract
This paper describes the first phase in the design process of an ecological interface for the future flight deck that supports the flight crew in the process of situation awareness acquisition to enable them to effectively plan and manage their own 4D trajectory taking into account all relevant constraints imposed by the highly complex and dynamic airspace environment. For airborne trajectory planning, these constraints are described as the spatio-temporal airspace affordances. To make this high-level, functional information visible on the flight deck, the principles of Ecological Interface Design are applied. A functional description of the work domain is given in the form of an abstraction hierarchy that reveals the airspace affordances. A functional modelling technique is developed to define a common language to communicate about affordances: travel space modelling identifies the 4D travel possibilities.

Keywords: Situation Awareness, Ecological Interface Design, Abstraction Hierarchy, Functional Modelling

1 Introduction
Travel by air nowadays has become a most important form of public transportation for reasons of business and pleasure. While more and more passengers wish to reach more destinations not only cheaper but also faster, the general public demands environmentally-friendly flights in terms of both noise and air pollution. Improvements in airspace capacity and flight handling efficiency may however not go to the detriment of safety. On the contrary, with the expected increase of air traffic movements and the subsequent closer aircraft spacing (Eurocontrol, 2000), additionally to the capacity and efficiency demands, it is of utmost importance to augment the current safety measures.

This paper describes the efforts of the Control and Simulation Division of Delft Aerospace in the innovative design of an ecological interface that enables the flight crew on the future flight deck to efficiently manage a four-dimensional (4D) trajectory within acceptable workload levels and to fully exploit the complex and highly dynamic
airspace. The aim is to design a flight deck interface that supports the flight crew in the process of situation awareness acquisition to enable them to effectively plan their own spatio-temporal (4D) trajectory taking into account all constraints imposed by the highly complex and dynamic airspace environment: airborne trajectory planning. This is realised by the application to the (air) transportation domain of the Ecological Interface Design (EID) principles that were established by Vicente and Rasmussen (1992) and have successfully been applied to a variety of work domains (Vicente, 2002).

The paper is structured as follows. First, the process of situation awareness acquisition in airborne trajectory planning is described, followed by a discussion of the EID principles. The paper focuses on the description of the work domain and thus on the interface content. A functional description of the aircraft-airspace system is given in the form of an abstraction hierarchy. The development of a newly developed functional modelling technique is discussed that yields a common language to describe the environment constraints: travel space modelling. The paper concludes with a discussion on the challenges that are foreseen when further developing the travel space model.

2 Situation Awareness for Airborne Trajectory Planning
For effective planning and decision-making, a pilot must take into account all relevant elements of the situation in light of the long- and short-term goals. In the highly complex and dynamic airspace environment, it is impossible for the flight crew to perceive the environment directly. Aircraft sensors must bring the environment to the pilot via the interface. On the basis of the information presented by the interface, a pilot has to acquire sufficient Situation Awareness (SA). It is clear that both the content and form of the interface play an important role in the process of building complete and correct situation awareness as discussed in the following sections respectively.

2.1 The Content of the Interface – *What to present?*
This section describes what kind of information should be presented to the flight crew for the best support in the acquisition of situation awareness required for airborne trajectory planning. The approach taken is based on Gibson's ecological approach to visual perception (Gibson, 1986). Gibson claims that the decisions and actions of a human being are controlled by the environmental affordances, rather than by physical qualities or properties. Affordances are the goal-relevant (functional) properties that determine the reciprocal relationship between an animal and its environment. In the case of airborne trajectory planning, the affordances considered describe the relationship between the piloted aircraft and the airspace environment. On the one hand, the aircraft-airspace system offers many travel opportunities. The airspace offers several routes to a variety of destinations and the aircraft is able to perform manoeuvres to change course, speed or altitude. On the other hand, the aircraft-airspace system is limited by the boundaries imposed on the airspace (terrain, prohibited areas, etc.) and on the performance of the aircraft (minimum and maximum speed and altitude, etc.). The affordances of the aircraft-airspace system are dependent on the location of that aircraft within that airspace. The affordances are also dependent on time, as the aircraft is moving within the airspace and there are other temporal elements as well, such as for example other aircraft in the same airspace. Therefore, the affordances for air
transportation are spatio-temporal.

Based on this ecological approach, Abeloos et al. (2002) have suggested a new definition of situation awareness: Situation awareness is the perception of the spatio-temporal affordances of the environment. This implies that for support in situation awareness, it is essential that the interface communicates not only about the elemental state of the environment, but also and even more importantly, about the functional aspects of the airspace. This means that the functions of the aircraft-airspace system that enable the crew to achieve the goals of air transportation must be made visible.

2.2 The Form of the Interface – How to present?
This section briefly describes some requirements on the form of the interface are briefly described. The question is how to present the 4D travel possibilities to the flight crew. According to Gibson’s theory, in the natural environment, affordances are perceived directly. This means that to enable the pilot to interact with the 4D environment, the spatio-temporal affordances have to be presented so that they are likewise intuitively perceived and understood by the pilot.

The format of the 4D travel possibilities must be such that it supports all levels of human behaviour: skill-, rule-, and knowledge-based (Rasmussen, 1983) and that it does not force the human behaviour on a higher level than necessary. This also implies that the interface must make visible the causal relationships (How? Why?) that exist in the environment. Finally, the interface should be exploratory, enabling direct manipulation of the travel possibilities (What if?).

3 Ecological Interface Design Applied to Airborne Trajectory Planning
For the design of an interface that satisfies the requirements defined above, a theoretical framework exists that postulates a set of general, prescriptive principles for the design of a smart interface that reveals the goal-relevant higher order properties (e.g. affordances) of the complex work domain and provides support for problem solving (Vicente and Rasmussen, 1992). Ecological Interface Design (EID) is a promising methodology because it brings together the human capabilities and limitations with the possibilities and constraints of the environment. A well-designed ecological interface enables the operator to directly perceive and manipulate the constraints and possibilities of the work domain at any level of abstraction. It provides understanding by making visible the causal relationships in the environment.

The EID framework is based on two questions: 1) How to describe domain complexity?, and 2) How to communicate the information? This paper only addresses the first question. In the following, the domain of airborne trajectory planning is described using two methodologies: the abstraction hierarchy and functional modelling.

3.1 Abstraction Hierarchy
An abstraction hierarchy (Rasmussen, 1983) was developed for one aspect of airborne trajectory planning: heading guidance. The only elements considered in the environment are other aircraft and the own aircraft’s destination. Further assumptions are that all aircraft fly level on the same altitude with constant speed on a direct route to their
destination; the own aircraft is limited to horizontal turning manoeuvres and is subjected to normal operating conditions. The abstraction hierarchy is summarised in Table 1. In the following, the hierarchy is explained from bottom to top, and while doing this, the spatio-temporal airspace affordances are identified, because every function realizes affordances on a higher level.

On the level of physical function, three functions are identified that play an informative role. The navigation model determines the own aircraft's position, groundspeed and heading. The airspace model includes the location of the destination and parameters of other aircraft in the vicinity. Finally, the flight performance model defines the limits to the own aircraft’s performance, in this case in terms of heading manoeuvrability in normal flight operations. Mapping the three physical functions onto each other affords the determination of safe, productive, and efficient trajectories. These trajectories are considered at the level of general function. Any of these trajectories affords an abstract function: the safe trajectories afford the assurance of minimum separation with other aircraft, the productive trajectories ensure that the flight continues in the direction of the planned destination, and the efficient trajectory is the direct route to the destination. Finally, the abstract functions afford safety, production, and efficiency, which are the three subgoals of air transportation on the level of functional purpose.

Now that the functional work domain is described by means of an abstraction hierarchy, the challenge remains to find a suitable ontology that can describe goal-relevant and meaningful high-level information in terms of affordances. This common language should support descriptions in four-dimensional space. A suitable common language to describe the spatio-temporal affordances for airborne trajectory planning is in terms of 4D travel possibilities, resulting from the travel space modelling technique as discussed in the next section.

3.2 Travel Space Modelling

To visualise the functions defined in the abstraction hierarchy, functional modelling techniques are used. Existing methods were mainly developed for mass and/or energy flow based physical systems and are difficult to apply to travel space (de Neef and Van Paassen, 2001). Therefore, a new functional modelling technique is developed that provides a common language to describe the spatio-temporal airspace affordances. Travel space modelling transforms the airspace affordances into a set of travel possibilities and preferences (de Neef, 2002). To illustrate this travel space model, it is applied to the simple abstraction hierarchy described earlier, as indicated in Table 1.

The travel space is constrained by limitations to the own aircraft’s performance as well as boundaries of the airspace. The former is modeled in the flight performance model which describes how heading changes should be performed, resulting in a specific turn geometry for the aircraft speed given. The flight envelope model consists of a set of possible trajectories that are limited by the look-ahead time as illustrated in Table 1. The boundaries imposed by the airspace, in this case only because of other aircraft, are modeled in the airspace model. As mentioned before, the mapping of the navigation, airspace and performance model afford the determination of safe, productive, and efficient trajectories.

To achieve the safety goal, the aircraft must maintain a minimum separation from other aircraft in the vicinity. For modelling purposes, every intruding aircraft is
surrounded by a protected zone, a circular zone with a radius equal to the minimum separation criterion. Safe separation is assured as long as the own aircraft stays clear of this protected zone. The difficulty with separation assurance from other aircraft is that the airspace boundary imposed by the intruder’s protected zone is moving with the intruder’s velocity. For the determination of the manoeuvres that would lead to an intrusion of the protected zone, the flight performance model is therefore transferred to the relative velocity field, thereby eliminating the time dimension. By subtracting the intruder’s velocity vector from the own aircraft’s possible velocity vectors, the possible trajectories are now referenced to the relative situation, i.e. as if the intruder is not moving. The unsafe trajectories can then easily be determined because any trajectory that crosses the intruder’s protected zone violates the minimum separation criterion.

The determination of the productive and efficient trajectories is easier. To achieve the production goal, the aircraft must at all times proceed in the direction of the destination, i.e. the ground speed vector must have a component that points from the current aircraft position into the direction of the destination. This cancels out all tracks that are directed away from the destination. Finally, to achieve the efficiency goal of direct routing, the aircraft should point its ground speed vector directly to the destination, which results in a single preferred trajectory. The combination of the safe, productive, and efficient spatio-temporal airspace affordances results in a model of the travel space that describes the travel possibilities and preferences.

4 Challenges for future work
To provide situation awareness for airborne trajectory planning, an ecological interface should represent the spatio-temporal affordances of the environment. The abstraction hierarchy reveals the affordances and the travel space model provides a common language to describe the travel possibilities and preferences for heading guidance.

The assumptions made have resulted in a relatively simple abstraction hierarchy and travel space model. The challenge now is to make sure that the models can also handle non-moving elements in the environment (e.g., terrain and special use airspace), to include other efficiency factors and optimisations (e.g., fuel consumption, noise pollution, passenger comfort, cruise climb, time slots) and to further develop the models into the other dimensions.

Freedom in the vertical dimension means that the navigation model includes both level and climbing/descending aircraft and the flight performance model represents horizontal as well as vertical or combined manoeuvres. In a subsequent design step, the additional freedom in the time dimension means that aircraft velocities are no longer maintained constant. The flight envelope model then represents all possible manoeuvres: heading changes, vertical speed changes, ground speed changes, or a combination thereof. The extension in the time dimension is necessary to enable 4D trajectory planning, i.e. planning to be at a certain point in space at a certain time. It is expected that speed changes will rather be used to reach a specific point, e.g. an entry point to managed airspace, than to avoid a certain area, e.g. the protected zone of another aircraft.

Another important issue that needs to be discussed is the format of the interface. This is related to the second question of the EID principles: How to communicate the 4D
travel possibilities to the flight crew on a flat display and how to make visible the abstraction hierarchy so the support is given on all levels of human behaviour? Further, the EID principles applied to airborne trajectory planning calls for an exploratory interface that enables the flight crew to directly manipulate the 4D travel possibilities presented (What if?).

5 References
Eurocontrol (2000): Air Traffic Management Strategy for the Years 2000+,
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Table 1. A simple abstraction hierarchy for heading guidance, illustrated with the functional modelling technique for airspace.

<table>
<thead>
<tr>
<th>FUNCTIONAL PURPOSE</th>
<th>Safety</th>
<th>Production</th>
<th>Efficiency</th>
</tr>
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<tbody>
<tr>
<td>ABSTRACT FUNCTION</td>
<td>Assure minimum separation</td>
<td>Proceed towards destination</td>
<td>Direct routing</td>
</tr>
<tr>
<td>GENERAL FUNCTION</td>
<td>Safe trajectories</td>
<td>Productive trajectories</td>
<td>Efficient trajectories</td>
</tr>
<tr>
<td>PHYSICAL FUNCTION</td>
<td>Navigation model: State of own aircraft</td>
<td>Airspace model: Destination and other aircraft</td>
<td>Flight performance model: Normal flight operations for heading changes</td>
</tr>
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