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A HUMAN-MACHINE INTERFACE FOR REPLANNING OF 4D TRAJECTORIES

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To accomplish air traffic growth in a safe and efficient way, future air traffic management concepts require aircraft to accurately plan and execute 4D trajectories. A trajectory planned prior to takeoff, may, however, require in-flight revision. To support the flight crew in their task of accurately re-planning a flight plan up to a meter fix, in four dimensions, a dedicated planning interface has been designed. The interface allows direct manipulation of the ground track and the descent profile. Constraints on trajectory planning are mapped onto candidate waypoint locations, highlighting the possibilities for acceptable ground track geometry in the horizontal situation display. In the vertical situation display, these constraints are mapped onto candidate top and bottom of descent locations.

It is hypothesized that the designed interface enables pilots to efficiently plan suitable 4D trajectories, while allowing for adaptive behavior and supporting situation awareness, even under high workload conditions.

To increase airspace capacity, future air traffic management (ATM) environments will not only require greater diversity and flexibility in the routes that can be flown, but also greater accuracy and timeliness with which aircraft adhere to these routes. This has major consequences for both ground-based ATM and airborne navigation planning. Indeed, in most of the proposed new ATM systems, the capability to accurately plan, implement, and execute a flight plan in four dimensions (4D), that is, in space and time, is a central ingredient (Swenson, Barhydt & Landis, 2006). The planning, guidance and navigation tasks of the flight crew will change when adhering to strict time constraints becomes of key importance.

Currently, airborne planning, implementation, and execution of a flight plan is automated with the help of the flight management system (FMS). Although the FMS has evolved at an exceptional rate in available features and functionality (Lidén, 1994), programming a flight plan still is a cumbersome task. The specification of the sequence of waypoints, flight levels, speed and time constraints, etc., needs to be entered alpha-numerically through the keypad of the command and control display unit (CDU).

The need for pilots to exploit the powerful functionality of the FMS quickly and accurately, in accordance with future ATM concepts, calls for a re-design of the navigation planning interface. This paper proposes a flight deck interface to the FMS, which allows for direct manipulation of the flight plan by the flight crew, during the task of airborne trajectory revision. In other words, the interface allows the crew to directly manipulate their flight plan in space and time (see also Kaber et. al, 2002; Winterberg, 2002; Vandenbussche, 2005; and Mulder, Winterberg, van Paassen & Mulder, 2009).

The design goals were threefold: 1. To find a suitable representation of constraints; 2. To support adaptive behavior of expert workers; and 3. To lower the required level of cognitive behavior for the trajectory revision task to skill and rule based behavior, allowing pilots to perform revisions under high workload conditions.

The proposed interface is designed in accordance with the principles of Ecological Interface Design (EID), see, for example, Rasmussen (1999), Borst, Suikerbuijk, Mulder & van Paassen (2006), and van Dam, Mulder & van Paassen (2007). To find suitable representations of the work domain and task constraints, a cognitive work analysis of the airborne trajectory revision task was performed as part of the preliminary design phase, see, for example, Vicente (1999). Experienced pilots with backgrounds in commercial aviation and research were asked to provide input on the design work.
Cognitive Work Analysis of the Airborne Trajectory Revision Task

The process of cognitive work analysis (CWA) consists of five steps, which involve quite a diverse set of modeling methods. Vicente (1999) formulated these five steps as follows:

1. Work Domain Analysis – What are we working with? With what purpose?
2. Control Task Analysis – What must be done?
3. Strategies Analysis – How can it be done?
4. Social Organization and Cooperation Analysis – Who can best perform each (sub)task?
5. Worker Competencies Analysis – How can human actors be supported in their task?

Work Domain Analysis

System Boundaries. A detailed scenario of an aircraft requesting a trajectory modification would involve numerous interacting systems. However, this research focuses on supporting the crew during the (re-)planning task, not on subsequent interactions with for instance the air navigation service provider. The system considered for work domain analysis will therefore be limited to an aircraft flying in an airspace with obstructive elements, for example, adverse weather cells or restricted airspace.

Abstraction Hierarchy. The abstraction hierarchy (AH) uses different levels, from abstract to concrete, to describe the same system in terms of means and ends. The highest level of abstraction provides insight in the system’s overall goals. The lower levels provide a more detailed representation of means and sub-goals. Four levels of abstraction were considered: 1. Functional purpose, i.e., what is the purpose of the work domain? 2. Abstract function, i.e., what are the underlying laws and principles? 3. Generalized function, i.e., what specific processes are involved? 4. Physical function. i.e., what tools are available to influence these processes?

Control Task Analysis

Decision ladder. The control task can be mapped as a sequence of subtasks (Vicente, 1999). The four dimensions of the trajectory to be defined are interdependent. For example, once a spatial trajectory has been defined, the time constraint at the meter fix, and the aircraft performance capabilities, limit the possibilities for temporal planning considerably. A distinction of the task in terms of temporal and spatial planning is therefore considered useful. Two decision ladders, with interactions, are shown in Figure 1.

Internal and external constraints. Assuming that the aircraft has the required navigation capability to execute user preferred routes in future ATM operations, the remaining internal constraints are: the flight envelope, the aircraft dynamics, and the fuel available. The constraints imposed on the aircraft are: first, obstructions of the flight path; second, operational regulations, and third, arrival requirements at a meter fix, which is typically near the destination and may designate the transition from user preferred routing airspace into airspace managed by air traffic control (ATC).

Strategies Analysis

Three experienced professional pilots, with backgrounds in civil aviation and research (see Table 1), were consulted for input on the interface design. After an introductory discussion of future ATM concepts and the implications on in-flight trajectory modification, the subjects were questioned on their preferences with regards to trajectory generation and interface content regarding a new FMS planning interface design.

Regarding trajectory alternatives in case of obstructions, three preferences were expressed: 1. To plan descents which are performed at constant throttle setting, 2. To separate speed changes from flight level changes, 3. To minimize fuel consumption resulting from the revision. Concerning the interaction with the automation, a preference for decoupled planning of the ground track and vertical profile was expressed. All pilots were in favor of direct manipulation of the flight plan geometry through a cursor control device. When asked to name display content that would be useful in performing a trajectory revision, the following answers were given: a visualization of time
constraints at the meter fix, a preview of throttle settings and speeds per planned trajectory segment, a preview of the maximum rate of descent, an estimate of the fuel consumption corresponding to the modified trajectory, and an outline of the original trajectory during the editing process.

Figure 1. Decision ladder of the 4D planning task, separated into spatial planning, which is allocated to the pilot, and temporal planning, which is allocated to the automation.

Table 1. Age, gender and experience of interview subjects.

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Gender</th>
<th>Age</th>
<th>Flight Hours</th>
<th>Aircraft Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Male</td>
<td>32</td>
<td>2,000</td>
<td>Cessna Citation II, Piper PA-31</td>
</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>64</td>
<td>9,000</td>
<td>Boeing 737-200/300, 757-200, 767-300 ER</td>
</tr>
<tr>
<td>C</td>
<td>Male</td>
<td>69</td>
<td>14,000</td>
<td>Boeing 747-300/400</td>
</tr>
</tbody>
</table>

Social Organization and Cooperation Analysis

The spatial trajectory planning task is left to the pilot. The temporal planning of the trajectory is allocated to the automation. Once the pilot has defined the new spatial trajectory, the automation completes it by suggesting speed and altitude profiles that satisfy the 4D constraints at the meter fix, that, additionally, optimize fuel efficiency. The interactions between the automation and pilot decision ladders in Figure 1 illustrate how the outcome of spatial planning affects temporal planning, and vice versa. To allow the pilot to quickly make a well informed decision on the spatial resolution, the effect of his actions on adherence to constraints can be previewed in a spatial affordance zone, which is realized through automated pre-evaluation of numerous spatial trajectories (Mulder, Winterberg, van Paassen, & Mulder, accepted). Upon definition of a new spatial trajectory by the pilot, the automation adds a corresponding temporal plan, so as to ultimately obtain a complete 4D trajectory.
Worker Competencies Analysis

The purpose of the worker competencies analysis is to identify the level of cognitive behavior required to perform the tasks allocated to the human. Using the skills, rules, knowledge taxonomy (Rasmussen, 1983) as a qualitative framework for assessment, the hypothetical benefits of the proposed planning interface can be explained. Through the proposed automation support, the pilot's task of choosing and implementing a satisfactory resolution strategy is reduced to applying expertise to the signs on the display. His cognitive behavior is thus supported on the rule based level. Since establishment of the waypoint geometry is achieved through direct manipulation with a cursor control device, it is now best categorized as skill based behavior. If the complexity of a situation requires knowledge based behavior, the automated representation of constraints supports the pilot in his tasks of interpretation and decision making. The resulting demands on pilot cognitive behavior are hypothesized to allow effective in-flight re-planning even under high workload.

Interface Design

The interface design is a combination of conventional and novel display elements. There are several reasons for building on conventional displays, rather than designing 'from scratch'. First of all, the existing representations used for aircraft navigation, that is, the Horizontal and Vertical Situation Displays (HSD and VSD respectively), have already proven their value both in experiments (for example, Prevôt & Palmer, 2000) and practice. Second, it was not so much the navigation display that needed re-designing, but rather the way pilots could interact with it. Third, a practical advantage of extending conventional display functionality is that it may facilitate speedy implementation of the proposed re-planning interface in future systems. The proposed horizontal and vertical planning displays are shown in Figure 2.

Novel Display Elements.

**Horizontal Situation Display.** In the HSD, control action is equivalent to modification of the location of the selected waypoint. The constraints that bound the affordance zone, are the time available in which to reach waypoint FIX and the achievable ground speed range (Mulder et. al., accepted). Modification of the trajectory by means of waypoint relocation will generally result in a different distance-to-fly to waypoint FIX. By adjustment of the speed profile to the trajectory length resulting from waypoint relocation, the estimated time of arrival (ETA) of the new trajectory can be made close or equal to the required time of arrival (RTA) of the contracted trajectory. Since there is a tolerance window around the RTA, candidate trajectories may be classified in three types, according to the smallest possible difference between ETA and RTA at waypoint Fix: 1. The ETA equals the RTA. Candidate locations that would result in this type of a trajectory are represented by the light shade of the affordance zone (see (1) in Figure 2). 2. The ETA lies within tolerances, but the RTA itself cannot be achieved. Waypoint locations corresponding to such trajectories are represented by the dark shade of the affordance zone (2). 3. The ETA is outside RTA tolerances. Corresponding waypoint locations are not part of the affordance zone, as the resulting trajectory would require renegotiation of a slot in the landing queue. The HSD additionally includes a representation of the speed profile selected by the automation (3), and the location of the top and bottom of descent (4).

**Vertical Situation Display.** Since manipulation of waypoints in the HSD only results in a (re)definition of the ground track, the VSD is used to facilitate modification of the vertical profile. After manipulations to the ground track, the automation will present the corresponding optimal vertical profile on the VSD by default. Analogous to the ground track, the vertical profile can be modified by manipulation of its nodes, which are the top and bottom of descent. The affordance zone in the VSD consists of a horizontal band (5), which appears when either the top or bottom of descent is selected, and highlights the alternative locations for the selected waypoint that would result in a feasible vertical profile. Placing the top or bottom of descent within this band ensures that the resulting trajectory is not too steep to allow for descent with constant ground speed. The second element of the vertical affordance zone is an outline of the descent envelope (6), which is bounded by the steepest descent from the earliest and latest top of descent location, and of the initial and final altitudes. To assist the pilot in evaluating the vertical profile, a numeric representation of the maximum vertical speed is included (7). Finally, since it is important for pilots to form an accurate mental picture of the 4D flight plan during evaluation and re-planning, the trajectory edit display reveals the time dimension of the trajectory means of ground speed targets, along with predicted throttle settings (8).
Showing this information is hypothesized to increase situation awareness and reduce the risk of the crew being surprised by, for example, automatically executed speed changes.

Concluding Remarks

A new interface for modifying a 4D flight trajectory was introduced, which was designed using the principles of ecological interface design. The interface visualizes the constraints for the re-planning task to the pilot in a manner that is consistent with the constraints pilots have to take into consideration during this task (Mulder et al., accepted). It is expected that this interface will enable pilots to quickly generate alternative 4D trajectories when faced with the necessity of making route changes, allowing them to make efficient use of the powerful capabilities of the FMS. Furthermore, as was shown in the design rationale, the interface supports cognition on all levels of the skills, rules, and knowledge taxonomy of Rasmussen (1983). This display will be evaluated in a flight simulator in the near future.

References


