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DESIGNING FOR JOINT HUMAN-AUTOMATION COGNITION THROUGH A SHARED REPRESENTATION OF 4D TRAJECTORY MANAGEMENT

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The current evolution of the ATM system, led by the SESAR programme in Europe and the NextGen programme in the US, is foreseen to bring a paradigm shift to the work domain of the air traffic controller. A focal point is the introduction of the 4D (space and time) trajectory as a means for strategic management rather than the current –hands on– method of control. In both programmes a central role is foreseen for the human operator, aided by higher levels of automation and advanced decision support tools. However, many other complex socio-technical domains have shown that the transition to higher levels of automation often introduces new problems, problems that are harder to resolve than the ones intended to solve in the first place. This paper presents one approach to the design of a shared representation for 4D trajectory management. The ultimate goal is to design a shared representation which forms the basis for both the design of the human-machine interfaces and the rationale that guides the automation. It is expected that such a shared representation will greatly benefit the joint cognition of humans and automated agents in ATM and will mitigate breakdowns in coordination by design. A preliminary version of a joint cognitive representation for 4D trajectory management has been developed and is introduced in this paper. Future work will focus on the further development and refinement of shared representations by means of human-in-the-loop experiments.

THE current evolution of the air traffic management (ATM)-system is expected to result in a situation where high-precision four-dimensional (4D, i.e., space and time) trajectories for aircraft, stored in automated support tools, will form the basis for the work of the human controller. A pull is provided by the increasing demand which is placed on the Air Traffic Management (ATM)-system (e.g., workload, capacity, efficiency, etc.). Conversely, technological advances on the air- and ground side of the ATM-system (e.g., advanced flight management systems, high precision trajectory prediction algorithms, domain-wide communication systems) provide a push facilitating a new form of Air Traffic Control (ATC).

A fundamental shift in the work domain of the human Air Traffic Controller (ATCo) is the introduction of *time* as an explicit control variable for defining *aircraft (4D-)trajectories*, rather than the current tactical –hands on– form of control. Whereas the current form of ATC mainly relies on the skill and experience of the human controller and is often performed with little help from automated tools, a shift towards 4D-based ATM will no longer be possible without the aid of advanced automated support- and decision-making tools (Parasuraman, Sheridan, & Wickens, 2000).

Although considerable research has been devoted to exploring this future approach of ATC with 4D trajectory support, a definite breakdown of the distribution of roles and coordination between the human operator and automation and the ‘central role’ of the human operator is not yet well defined.

From other complex socio-technical domains it has been shown that the transition towards higher levels of automation often introduces new problems, problems which are often harder to resolve than those intended to be solved in the first place (Bainbridge, 1983). Increasing the level of automation is –in itself– not good or bad. However, with increased automation a more extensive form of coordination between humans and automated systems will be required (Christoffersen & Woods, 2002).

Breakdowns in this coordination may result in humans having difficulty to getting the automation to do what they want, and conversely, a poor understanding of how the automation works (Rasmussen, 1986). To facilitate the coordination between human- and automated agents, it is imperative to create new forms of automation and to make the automated systems ‘team players’ *by design*.

This paper outlines an approach for designing shared human-automation cognition for ATM, based upon 4D trajectory management. The work presented is conducted in the context of SESAR WP-E project ‘C-SHARE’. Furthermore, a first prototype of a Joint Cognitive System (JCS) (Hollnagel & Woods, 2005) will be introduced, illustrating how this design approach can be used as a basis for ecological Human Machine Interface (HMI) design.

Designing for Shared Cognition

The introduction of higher levels of automation is essential in order to facilitate the shift towards a new form of 4D air traffic control. On one hand, advanced automated support tools are necessary to aid the human operator to cope with the increased complexity of 4D trajectory management. And on the other, as a systems designer there are many valid reasons to take advantage of modern computational technologies (e.g., data fusion and information processing, advanced algorithms). For example, to optimize the global use of airspace, reduce traffic complexity and minimize the cost for individual airspace users.

From other complex socio-technical domains however it is clear that the introduction of a higher level of automation in itself does not guarantee an improvement in overall system performance. There is an abundance of empirical, operational and theoretical evidence that breakdowns in human-automation coordination can introduce severe human and systems problems contributing to incidents and accidents, including transient workload peaks, ‘out-of-the-loop’ situation awareness and vigilance problems, overreliance (complacency), and skill degradation. Therefore, it is imperative to mitigate these breakdowns in coordination by design and make the automated systems ‘team players’.

When looking at effective human-human interaction in productive team thinking and problem solving, its foundation for success is a shared understanding –or a ‘common ground’– of the task to be achieved and the paths by which this task can be achieved. Similarly, when looking at human-automation coordination, a common ground can be found in the properties, functions and constraints active on the work domain (or problem space) to which all actors must abide. It is to be expected that when these elements are somehow made visible to the human operator(s) and conversely act as a basis to guide the rationale of the automated agents, breakdowns in coordination can be mitigated and productive collaboration and team thinking can be achieved.

One systematic approach to identify this common ground for effective human-automation coordination is given by the framework of Cognitive Systems Engineering (CSE) (Hollnagel & Woods, 1999). Contrary to the user- and automation centred design approaches which take the needs, wants and limits of respectively the human operator(s) and automation as a starting point for design, CSE is based upon the global context in which the work takes place (i.e., the work domain), irrespective of any definite systems design or pre-determined task allocation.

As a first step in CSE, a functional breakdown is made of the work domain, identifying all relevant elements and functions on various levels of abstraction. As a subsequent step, and based upon the reasoning that knowledge of the entire system cannot be solely be built up from knowledge of the individual parts, the underlying relationships between the elements which define the global context are sketched using means-end links; basically asking the question of “how does it work?” and “why is it here?” for each element (Rasmussen, 1986).

When considering the work domain for air traffic control, various phases for the refinement of 4D trajectories are foreseen; from long term seasonal planning to the in-flight revision of trajectories during the tactical monitoring phase. It is foreseen that in each phase a unique form of coordination will exist between the human operator, their displays and support tools, and automated agents (Van Paassen et al., 2011).

For the scope of this research, focus has been put on designing a framework for shared cognition in the *tactical monitoring phase*, the in-flight management of 4D trajectories by ATC, as it provides the most challenging environment for human-automation coordination (e.g., time-critical, safety-critical, high dynamic complexity, and ‘open’ (Rasmussen & Pejtersen, 1990) work domain). Contrary to any prior planning phases which are deterministic in nature, the main task of the human operator in the tactical phase will be to identify and effectively cope with *any* unforeseen events.

Following the first step of CSE, an initial Work Domain Analysis (WDA) has been performed for the scope of the research by the construction of an Abstraction Hierarchy (AH) and is shown in *Figure 1*. Furthermore, a breakdown is given of the abstract functions in the work domain.

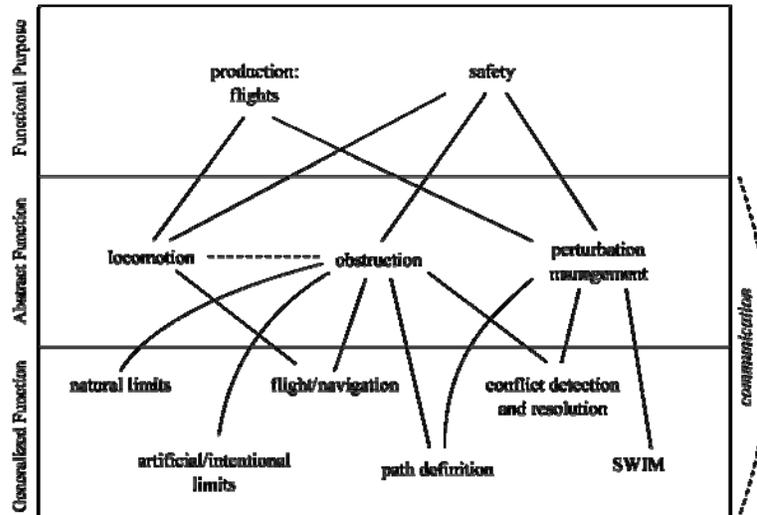


Figure 1. The top three levels of the Abstraction Hierarchy for the tactical monitoring phase.

Locomotion is realized within the constraints following from individual flights and their respective navigation within the environment. These constraints can be imposed by *internal* factors such as the aircraft performance envelope and the availability and fidelity of navigation systems, but also by *external* constraints such as airspace user preference and airspace regulations. The absolute locomotion of the moving agents can be captured in their resulting (4D-) path definition. The relative locomotion is then, in turn, realized by the dynamics of travel of all agents within the system.

Obstruction is realized by both static and dynamic constraints which limit the system from performing at a theoretical optimum. Such obstructions can be in the form natural limits (terrain, weather, ...) and artificial constraints (separation minima, airspace structure, ...). Furthermore, the relative locomotion of all moving agents and the current network status also impose obstructions on the operations.

Perturbation Management is realized by the awareness and integration of the intended-, current and projected state of the work domain. Here, the main source of the information (path definitions, Network Operations Plan (NOP) status, meteorological information, ...) for both the human and automated agent is foreseen to follow from a system wide information system. Furthermore, conflict detection algorithms are foreseen to provide more detailed information about safety critical perturbations.

Although the AH highlights the underlying functions which govern the work domain, it does not provide a final recipe for how shared cognition can be obtained through a specific human-machine automation design. Determining which form of representation including its interaction with both the human user and automated agents is suitable is still a creative step and depends on the (sub-) task for which it is designed. However, the functional breakdown in the AH provides guidance in determining which functions, constraints and relationships should somehow be made visible in a shared representation.

Travel Space Representation

As a starting point for the design of a joint cognitive system, a prototype of a constraint-based shared representation has been designed for the task of the in-flight manipulation and revision of 4D trajectory by ATC. According to definition a 4D trajectory consists of a set of consecutive segments linking 4D points (waypoints), at which the indicated times are estimates in the form of target times or times subject to constraints (Eurocontrol, 2007). The manipulation and placement (position and timing) of such waypoints is taken as the task to be shared between the human users and automated agents. Re-planning of waypoints is necessary in case one or more inherent (other traffic, terrain, weather, ...) or intentional (restricted airspace, procedures, ...) constraints active on the aircraft trajectory, cannot be satisfied due to any number of unforeseen events.

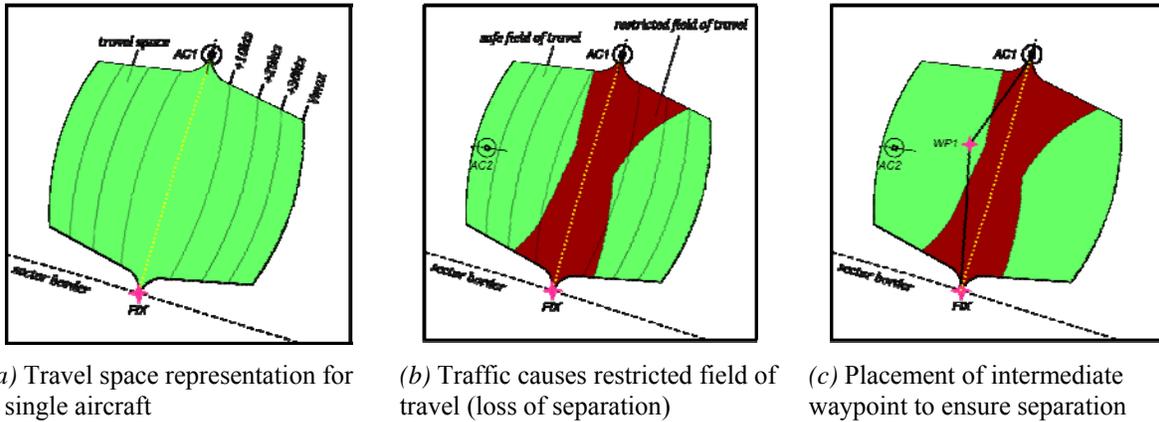


Figure 2. Conflict resolution by trajectory re-planning with the travel space representation

For the design of a shared representation the Ecological Interface Design (EID-) (Vicente & Rasmussen, 1992) approach has been adopted. EID closely follows the line of CSE, and argues that for effective human-machine interface design the constraints and underlying relationships governing the work domain (or ecology) should be somehow made visible to the human operator. It is hypothesized that, by visualizing the task-relevant functional constraints that arise from the work-domain, the *same* constraints that guide automated actions, humans will get a deeper understanding of why automation proposes a particular action. This may benefit the operator's trust and acceptance of the automation, and facilitate the transition back and forth from higher levels of automation.

Safe field of travel

When considering the task of in-flight re-planning of a 4D trajectory by ATC the relevant functions and constraints which govern the work domain can be derived from the AH. The overall goal of the aircraft is to execute its subsequent trajectory segments and pass all waypoints within the timing constraints in agreement with ATC. Now consider that either the aircrew or air traffic controller intends to introduce an intermediate waypoint into a trajectory segment. Any arbitrary (4D-)placement of that waypoint will lead to a new definition of the trajectory. The feasibility of such a trajectory can be tested against the relevant constraints which govern the work domain (e.g., adherence to *locomotion*, *obstruction* and *perturbation management*). Then, the subset of all trajectories which adhere to these constraints are feasible solutions and, by definition, form a so called 'safe field of travel'. By means of one-to-one mapping, a correspondence-driven (Vicente, 1990) translation of this safe field of travel can be made on the air traffic controllers' plan view display, indicating the real-world spatial locations of feasible waypoint placements and their timing implications.

Representation breakdown

In *Figure 2(a)* the basic composition of the travel space representation is shown. Aircraft *AC1* is flying along a pre-agreed 4D trajectory towards a certain metering fix (point *FIX*) at the sector border. The Controlled Time Over (CTO) at the fix is taken as a hard constraint (i.e., it must be met). When considering constraints which follow from the aircraft performance envelope (in combination with the time constraint at the fix), an area can be bounded in which intermediate waypoint placement is feasible. The aircraft turn characteristics determine the rounded shape of the travel space close to the current aircraft position and the metering fix. Furthermore, any intermediate waypoint that does not lie directly on the current trajectory segment implies an increase in track length, and thus an increase in required ground speed. The outer edges of the travel space are therefore bounded by the maximum achievable speed within the aircraft performance envelope.

In *Figure 2(b)* other traffic has been introduced in the form of a single second aircraft (*AC2*). When taking the separation constraints for *both* aircraft into account, an area within the travel space for *AC1* becomes restricted (i.e., an intermediate waypoint in that area will result in a 4D trajectory which is in conflict with the other aircraft at a certain point in time). This area is indicated in the figure as the *restricted field of travel*. The restrictive area visualizes the locations where an intermediate waypoint would not lead to the resolution of the conflict. Note that these same constraints on waypoint placement *also* hold for an automated agent. It is essential to understand that these constraints arise from the work domain, *independent* of who will act on the task of resolving the conflict, the human, the automation, or both.



Figure 3. Interactive software based implementation of the travel space representation

Figure 2(c) shows how the travel space representation can be used by the human- or automated controller to select an appropriate position for an intermediate waypoint in a conflict situation. By placing the waypoint (*WP1*) inside the safe field of travel within the travel space, the constraints following from aircraft performance, separation, and timing are all met. Note that here, the timing of the introduced waypoint is set such that it corresponds with the constraints visualized by the representation (e.g., constant speed along both segments and fixed timing at the final waypoint).

This visualization of the work domain constraints and their relationships allows a human controller to reason about, and directly act upon the airspace environment. To emphasize once again, note that this same representation can be used to guide the rationale of an automated agent or, equivalently, a team of human operators and automated agents to achieve productive collaboration and team thinking. For example, an automated agent could propose a resolution and map this resolution within the safe field of travel. By carefully observing the machine's advisory, the human agent could either 'accept' or 'veto' the advisory warranted by the demands of the situation at hand.

In other words, users are not only able to see the intentions of the automated agents, but they are also able to re-direct machine activities easily in occasions where they see a need to intervene. By visualizing the task-relevant functional constraints that arise from the work-domain, the *same* constraints that limit automated actions, it is hypothesized that humans will get a deeper understanding of why automation proposes a particular solution. This may benefit the operator's trust and acceptance of the automation, and facilitate the transition back and from higher levels of automation.

Discussion

Perhaps the largest change for an ATCo in future ATM operations will be to step away from the current hands-on tactical control of aircraft to an operation in which traffic is planned in detail beforehand. For individual flights, it has proven possible to implement, monitor and manipulate 4D trajectories, usually in the context of all other aircraft being controlled traditionally. The case when all aircraft are to be controlled based on their 4D trajectory means a tremendous step, and a real-time visualization of how all trajectories will evolve in time is a big challenge for display designers. Whereas the dimensionality of the control problem explodes, the visualization and display techniques remain limited by, among others, clutter issues, and physical constraints such as screen size and resolution.

The prototype of the travel space representation has shown to be a good starting point; this framework for 'joint cognition' can act as a basis for designing both the automation support and the human-machine interfaces, in the air and on the ground, from one and the same perspective. A qualitative evaluation with an initial interactive software based implementation of the travel space representation (Figure 3) has shown that this type of representation is indeed suitable as a common ground for reasoning between the human operator and automated agents in resolving *local* perturbations (e.g., re-plan the trajectory of individual aircraft). However, one can argue that in case of larger scale perturbations (i.e., regional or network-disruptive) the complexity and temporal load of focussing on the constraints of

individual aircraft could exceed the cognitive limits of the human controller. In that case perhaps, a common ground should be found in the higher level properties of the airspace such as intrinsic complexity, robustness to perturbations, flexibility and the flow of traffic. It is hypothesized that the controller could then –by means of a more heuristic approach– structure the global use of the airspace and traffic, and zoom in for detailed refinement where necessary. This is foreseen to result in a situation where humans will have a deeper understanding of the actions and reasoning governing the automated agents, and will facilitate the transition back and from higher levels of automation.

During the further development and testing of prototypes, it is likely that the Work Domain Analysis will need to be augmented and/or partially revised. A number of human-in-the-loop experiments are foreseen that will show to be crucial in converging the design and analysis iterations to a representation of 4DT management and that can indeed be used for both automation and human-machine interface design.

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