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Designing for shared cognition in air traffic management

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Abstract. It is to be expected that the task of an air traffic controller will change with the introduction of four-dimensional (space and time) trajectories for aircraft, as can be seen in ongoing developments in ATM systems in Europe (SESAR) and the US (NextGen). It is clear that higher levels of automation will need to be developed to support the management of four-dimensional trajectories, but a definite concept on a distribution of the roles of automation and human users has not yet been well defined. This paper presents one approach to the design of a shared representation for 4D trajectory management. The design is based on the Cognitive Systems Engineering framework and by using a formative approach in the analysis of the work domain, a step-wise refinement in the planning and execution of 4D trajectories is proposed. The design is described in three Abstraction Hierarchies, one for each phase in the refinement. The ultimate goal is to design a shared representation that underlies both the design of the human-machine interface and the rationale that guides the automation. It is foreseen that such a shared representation will greatly benefit the shared cognition in ATM and allows shifting back and forth across various levels of automation. A preliminary version of a joint cognitive system for 4D trajectory management has been developed and will be introduced in this paper. Further work will focus on the refinement of the shared representation by means of human-in-the-loop experiments.

Keywords: Ergonomics, interfaces, automation, air traffic management

1. Introduction

Currently, air traffic controllers (ATCo's) perform a sector-based, tactical form of control. They are responsible for planning and managing traffic within their assigned airspace, often with little help from automated tools [1]. In the coming decades, the task of an air traffic controller is predicted to undergo a large transformation. The pull for transformation comes from the increasing demands which are placed on the air traffic management (ATM)-system [2–4]. A push is provided by technological advances on the air and ground side of the ATM-system, which make a new form of air traffic control (ATC) possible [5, 6]. This is expected to result in a situation where aircraft four-dimensional (4D, i.e., space and time) trajectories stored in automated support tools form the basis for the ATCo's work [7–10].

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The explicit use of a 4D definition of the aircraft trajectory (4DT) as a shared representation between air and ground segments is a fundamental difference between current practice and future air traffic's management. In SESAR, this 4DT has been defined as a Reference Business Trajectory (RBT). Supported by a communications network, the System Wide Information Management (SWIM), the information on the 4DT is to be shared such that all parties involved have access to relevant and the most up-to-date flight information.

Given that the stakes are high, and that the ATM work domain inevitably has too many unforeseen situations to create a fully automated solution (i.e., the work domain can be characterized as "open", [11]), human users will have to remain involved in the system. The future air traffic controller will not, as he or she is doing currently, provide hands-on instructions to the aircraft, in essence creating the aircraft's 4D trajectory in real time. Rather, controllers will work on (refining) a definition of the aircraft 4D trajectory, using automated tools to visualize and represent this trajectory. Future or modernized aircraft will have the capability to receive this 4D trajectory update on the flight deck, and implement their flight according to this trajectory with a high degree of precision.

Although considerable research has been devoted to exploring this future approach to air traffic control with 4D trajectory support [12–16], a definite concept on a distribution of the roles of automation and human users has not yet been defined. It is clear that higher levels of automation will need to be developed, but the 'central role' of the human operator is not well defined yet. Many other complex socio-technical domains have shown that the introduction of higher levels of automation often introduce new problems, problems that are often harder to resolve than those intended to be solved in the first place [17]. Increasing the level of automation is not good or bad in itself, but with more automation greater coordination between people and technology will be required[18]. Breakdowns in coordination may result in humans having difficulty getting the automation to do what they want and, conversely, a poor understanding of the way automation works[19]. To mitigate breakdowns in coordination between human and automated agents, it is imperative to create new tools for coordination so as to make automated systems 'team players'.

This paper explores one possible design approach for facilitating a successful human-automation collaboration in a future 4DT-based ATM system. In the SESAR WP-E project 'C-SHARE' a Cognitive Systems Engineering (CSE) approach is adopted [11, 20, 21]. CSE starts from an analysis of the work domain, identifying goals and functions in this work domain, and in a design, it is possible to start top-down, initially independent of the chosen solutions for the system. The ultimate goal of the project is to find a "common ground" or shared representation for manipulating 4DTs that can be used to develop the automated tools as well as the human-machine interfaces. It is foreseen that a shared representation of automation and humans will greatly benefit the shared cognition in ATM.

The paper outlines a step-wise approach to the definition and refinement of 4DTs, discusses some of the implications of 4DTs on automation and display design and introduces a preliminary version of a 'joint cognitive system' for ATM.

2. The structure and function of airspace

The re-engineering of the air traffic management system is a design process, which will be approached here following the paradigm of Cognitive Systems Engineering (CSE). That means that the first step in CSE, the Work Domain Analysis (WDA), will be started in a top-down fashion. Part of the WDA will reflect the constraints innate in the work domain itself, for example the fact that aircraft need to have sufficient clearance from terrain and other aircraft (separation). However, other functions in the WDA are influenced by the design choices, both for the current system and for the envisaged new ATM systems.

2.1. Work domain analysis

The work domain analysis will be done by constructing an Abstraction Hierarchy (AH) [19]. In constructing an AH for a new domain, the main challenge is to select the proper choice for the abstract functions in this domain. In process technology and energy generation systems, where CSE originated, the abstract functions that describe the energy and mass balances in a system form an appropriate choice [11]. In the description of a single vehicle, the WDA at this level focuses on locomotion and on (potential and kinetic) energy balances [22]. For the case of ATM, the principal functions at this level are proposed to be identified as locomotion, localization, communication, separation, and a principle we refer to as "travel space".

Locomotion is a function of the moving elements in the ATM, realized by flight for aircraft, and drifting for weather. *Localization* is the function that determines the position of these moving elements, either on-board, by the navigation system, or on the ground, by the ATM surveillance systems. *Communication* supports localization and decision making in the system by sharing intentions, plans, and localization results. *Separation* is the principal means for safety in the ATM system: at all times a proper clearance to other aircraft, terrain and hazardous weather must be maintained.

The identification of *travel space* as a separate functionality in this analysis warrants additional explanation. We define travel space as the function offered by the air and infrastructure to the moving elements in the ATM system – the aircraft – to implement their locomotion. Other elements in the system, such as weather, terrain and including other aircraft, affect the possibility to use the available airspace in certain ways [23, 24]. That is, for a given aircraft fixed (terrain) and moving (other aircraft, weather) obstacles limit the maneuvering possibilities for that aircraft both in space and time. Travel space is by definition four-dimensional, and the way its constraints can be managed stands at the heart of (current and future) ATM.

2.2. Travel space function constraints

Identifying the possibilities for travel as a function in our analysis enables us to use a representation of the effect of the total of 4D trajectories in our design of new ATM systems. Many constraints in this function are unavoidable; removing them would require removing terrain or other traffic. However, the solutions chosen for our ATM system, such as the communication and navigation systems, the legal infrastructure and the way in which we plan and coordinate trajectories, affect the shape and characteristics of the travel space function.

Communication limitations. Current ATM mainly uses voice communication. To enable efficient use of this communication channel which is limited in bandwidth – on the other hand, it is extremely flexible – the actors taking part in this communication need to have agreed on extensive background information. This makes it possible to only use pre-defined and published way points and discrete altitude levels for defining tracks. The use of digital data-link communications means that the use of airspace can become more flexible.

Navigation systems. Traditionally, limitations of navigation systems provided constraints on where flight was possible. In the early days of commercial aviation, railroads and other landmarks formed the basis for the air structure. Later, radio navigation aids, such as the four-course radio range, VOR and NDB beacons largely determined the use of airspace. The navigation aids thus determined which parts of the airspace are usable as travel space, and how these can be used. Much of this restriction has been removed as aircraft are increasingly able to perform Area Navigation (RNAV), meaning that flight can be performed independently from the location of (ground) navigation beacons.

Legal infrastructure. A further constraint on the locomotion is provided by the administrative organization of airspace. The (current) division in airspace sectors imposes restrictions on the paths of aircraft, basically because the handling and the transition of an aircraft from one sector to another requires a buffer zone between the sectors, and effort from the controllers and pilots. Aircraft trajectories are effectively constrained to transitions between sectors with more or less perpendicular angle to the sector boundaries. Short paths through sectors, such as the perpendicular traversal of narrow sectors, or passing through a corner of a sector, are difficult to manage and therefore uncommon.

Planning and coordination. Currently, the control of the traffic within an airspace sector is normally the job of a single ATCo, or of a small team of two to five. Support by tools is fairly limited, and the extent to which a 4D trajectory is known ahead of time is very limited. This forces an ATCo to impose additional structure on the use of airspace.

The technological advances in navigation systems and communications foreseen in SESAR and NextGen can remove part of the constraints on the travel space function, opening the way for more economical, and shorter – direct – routes.

3. Operational concept

3.1. Overview

This paper sketches an operational concept for the future ATM system that largely uses the functionality foreseen in the ATM master plan [2]. In particular, the functionalities provided by 4D trajectory management and information-exchange with a SWIM system are combined in a concept that assumes a central role for the human actors in the system.

A step-wise refinement of the 4D aircraft trajectories is proposed. Given the central role reserved for the human actors in this process, to enable them to contribute in defining 4D trajectories, proper support for visualizing, evaluating and modifying these trajectories is required. Also, the amount of work involved in defining 4DTs for all aircraft using the ATM system is expected to be very large, so human users have to be supported by automated systems in this task.

Task division between humans and automation is often approached as an ‘allocation problem’; either the human actor *or* the automation is selected for a task. Prime examples for this can be found within the aircraft themselves; the task of stabilizing the aircraft is normally allocated to the autopilot, and the navigation along a trajectory is performed by a combination of autopilot and Flight Management System.

The first guiding principles in task allocation have been laid out in what is now known as Fitts’ list [25]. In this concept, part of the tasks in the foreseen ATM concept are indeed *assigned* with these principles, such as the tactical monitoring for deviation between actual flights and the agreed 4D trajectories. However, other tasks are foreseen to be performed *jointly* by automation and humans, and some tasks can be done *in parallel* by automation and humans.

In most complex systems, however, many tasks are too ill-defined to be handled by automation. Such ‘fuzzy’ tasks are typically assigned to human operators. To support operators in those cases, a proper visualization of the problem space can help. Examples of such visualizations are the Ecological Interface Design for the example process system DURESS [26], or, more recently, visualizations for airborne traffic avoidance [27, 28], and 4D trajectory manipulations on the flight deck [29, 30] can be seen as automation support, where algorithms are used to visualize the work domain constraints in such a way that operators can implement appropriate control strategies. This leads to a task that can be performed jointly by automation and humans. The resulting cognition can be seen as a joint effort of the automation, and in particular the visualization of the problem, and the human user [31].

(a) short-term planning (b) pre-tactical planning (c) tactical monitoring

Fig. 1. Summary of the stages in refinement and implementation of 4DTs. Only for the tactical control the actual aircraft flight data is used (radar symbol). For the pre-tactical and tactical control, assistance from automated agents is foreseen.

Within the SESAR overall operational concept, several stages in the refinement of 4D trajectories are foreseen. The design presented in this paper focuses on three stages: (i) Short-term planning, performed 24 to 12 hours in advance of the flight; (ii) Pre-tactical planning, conducted several hours to 30 minutes in advance of the flight, and (iii) a Tactical monitoring phase (30 minutes to now). In contrast, the full SESAR design starts with seasonal planning. A summary of the foreseen phases is given in Fig. 1. The interaction foreseen in these three phases between users, their display and support tools and automated agents is discussed in the following subsections.

3.2. Short-term planning

Short-term planning – termed short-term here to correspond with SESAR terminology – takes place approximately 24 to 12 hours in advance. This phase starts with an inventory of intended flights, initially designed as the shortest and most economical route to the destination. A visualization will be used to show the use of airspace, including “hot spots”, with high concentration of traffic. The human planners use this representation to create a global structuring of the airspace (e.g., restricting the number of flights in certain areas, reserving altitudes for certain headings, making sure that there is ‘spare’ airspace to handle unforeseen disturbances or to re-structure the flows to be able to handle a change in runway at an airport, etc.). The function of the automation in this stage is mainly to provide visualization and identification of hot-spots.

The result of this stage is a planned airspace ‘structure’, i.e., the travel space will be partly pre-allocated. NextGen flow corridors [4] might be an example of this. The 4D trajectories are then modified by automated algorithms to conform to this structure resulting in an indirect de-confliction (e.g., to adhere to capacity limits defined for the airspace), but overlapping conflicts that may exist between the 4D trajectories are not identified or resolved, since the actual 4D trajectories are not yet sufficiently defined to perform this step.

Part of the work domain analysis is given in the Abstraction Hierarchy in Fig. 2. The work domain analysis describes the functionality and constraints of the work domain, in this case of Air Traffic Management. An Abstraction Hierarchy describes one and the same system or work domain at different levels of abstraction [19]. The top level is the *functional purpose* level, containing the goals identified for the system. The *abstract function* level describes the basic principles and processes in the work domain that enable the realization of these goals. In this case, the basic mechanisms at work are obstruction (e.g. by weather) and allocation of space. The *generalized function* level further specified this in terms of “systems solutions”. Normally, an AH has two further – more detailed – levels, that are not yet specified for this study [32].

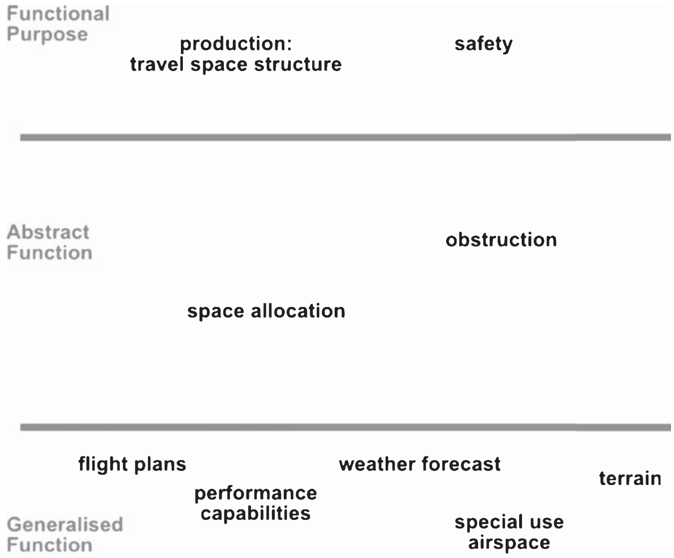


Fig. 2. Short-term planning stage, top three levels of Abstraction Hierarchy.

The product that comes out of the short-term planning step is a “structure” for the travel space; choices are made to reduce traffic at places where large volumes of traffic are expected, and additional capacity is reserved where needed, for example as a contingency for weather phenomena. This planned structure should achieve the goals identified at the top level in the AH.

3.3. Pre-tactical planning

This takes place from several hours up to approximately half an hour in advance of current time. Using adjustments to the 4D path, and taking into account aircraft performance and weather, the 4DTs are further defined to be “in principle” conflict free. The adjustments to 4DTs can be performed by human operators and automated agents in parallel. A proper visualization of the travel space functions are used as a template for the cognitive process; human operators can use this visualization to directly perceive the effects of path and speed manipulation. It also serves as a shared memory, offering a workspace to automation and human agents alike. The result of this stage is that the 4DTs are de-conflicted and in accordance with the airspace structure defined in the previous step.

Part of the work domain analysis for this stage is given in Fig. 3. The airspace structure generated in the previous stage is now a generalized function. It defines a rough plan for the generation and modification of trajectories for individual flights, and it acts as an additional constraint in this analysis, imposing limits on flights but providing an overall means to simplify the planning process, analogous to the way the current airway structure is used to shape air traffic. Observing the needed separation, possible obstruction by terrain, weather, etc. and the geometric constraints of each flight’s path, this stage results in refined definitions for the 4DTs.

3.4. Tactical monitoring

At this stage the *planned* 4DTs of the different flights are conflict free. However, in the execution of flights, small deviations from these planned trajectories are expected to be unavoidable. Automated

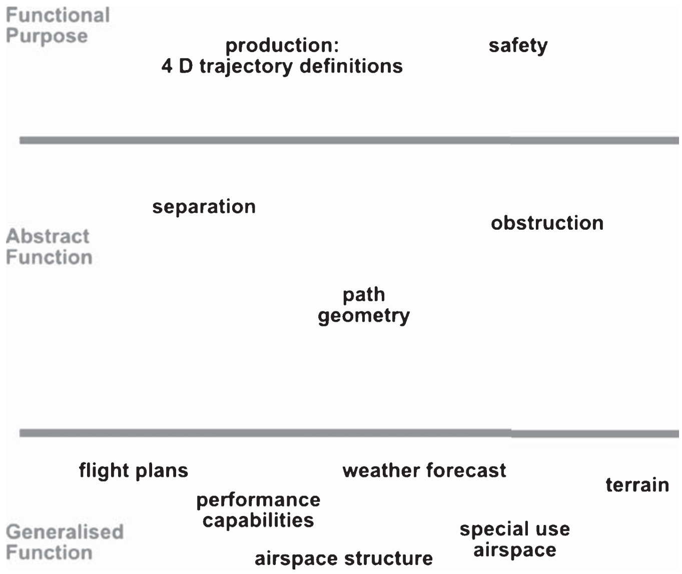


Fig. 3. Pre-tactical planning stage, top three levels of Abstraction Hierarchy.

agents monitor the execution of the trajectories and provide limited solutions (e.g., speed and minor path adjustments) to keep the flights conflict-free. The visualization now serves to inform the human users of the progress of the flights and of the actions of the automated monitoring agents. The situation awareness thus built up permits the human user to perform the higher – system – level monitoring, and to intervene when unforeseen circumstances make this necessary.

Part of the work domain analysis for this stage is given in Fig. 4. At this stage, the physical function level will be formed by the functionality related to the aircraft and physical devices in the ATM system. While the previous stages mainly involved planning flights (first globally, resulting in the travel space structure, then in more detail), the result from this stage are the actual flights. Real-time communication therefore becomes an important function at this stage.

3.5. Joint cognitive representation

The three stages differ in their nature of the joint cognition by human users and operation. In the short-term planning, the contribution by the automation is mainly the visualization. The human users are primarily responsible for the planning result. In the pre-tactical planning, the automation and human users contribute on a more or less equal basis. The visualization serves here as the representation of the commonly used (space) resources. The tactical monitoring situation most closely resembles current high levels of automation, with a large contribution of automated agents, utilizing a probabilistic road-map method, to the final solution.

The work domain analysis, which in current approaches to Ecological Interface Design (EID) serves as an input to the display design process only, will in this project C-SHARE be used for both the design of the automation and the displays. That is, the constraints on the 4D trajectories as identified in the WDA are transformed into a representation that underlies both the design of the human-machine interface as well as ground- and air-automated tools.

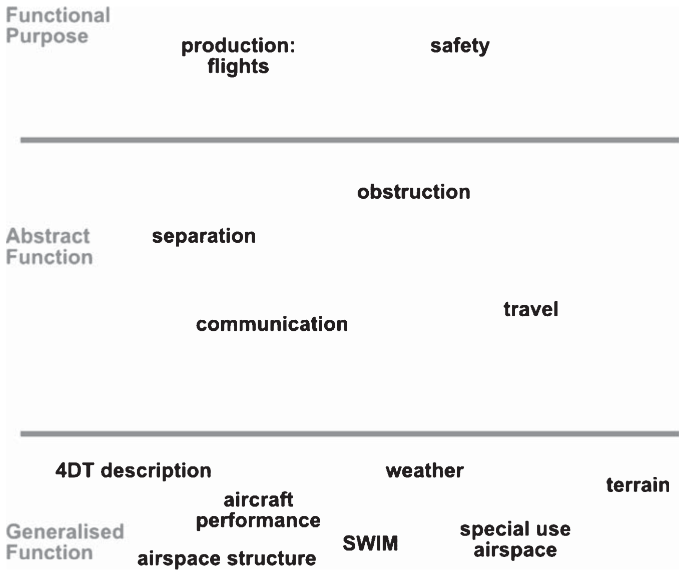


Fig. 4. Final tactical monitoring stage, top three levels of the Abstraction Hierarchy.

By virtue of being based on a ‘shared’ representation, the results of the work done by automated tools will be compatible with the human’s representation of the work domain, and can be visualized in a human-centric fashion. With automation and humans working on a shared cognitive representation, this also allows shifting back and forth across various levels of automation, from fully manual control to fully automated control, and in principle also supports the transition between SESAR’s unmanaged and managed airspace.

4. Implications for display design

In CSE, the analysis of the work domain is a primary input for the actual design of the display. However, the design of a display presentation is still a creative step, the WDA does not result in a “recipe” for how the display is to be created, it only provides guidance in determining what functions should somehow be made visible in the display [30]. The following first inventory of the important elements, and the way they might be visualized, is given here:

Short term For the short-term planning of the travel space structure, obstruction and space allocation are considered primary functions at the abstract function level (Fig. 2). The product of this stage should be the travel space structure for the next day, indicating how airspace will be allocated for flights, and where disruptions are expected and thus buffers are reserved. The input to this work is the set of flight plans as filed by airline companies. Important aspects of the visualization will be the obstruction, by weather cells, terrain, or temporary restricted airspace. A global visualization of the traffic flow (not per 4D trajectory, but as a whole), and a visualization of the means to modify this flow by structuring the travel space is needed.

Pre-tactical Pre-tactical planning should result in initial conflict-free 4DTs. The visualization should show the travel space structure created in the previous step. Since the planning is done in parallel by automated agents and human users, communication between the agents and humans on the ongoing

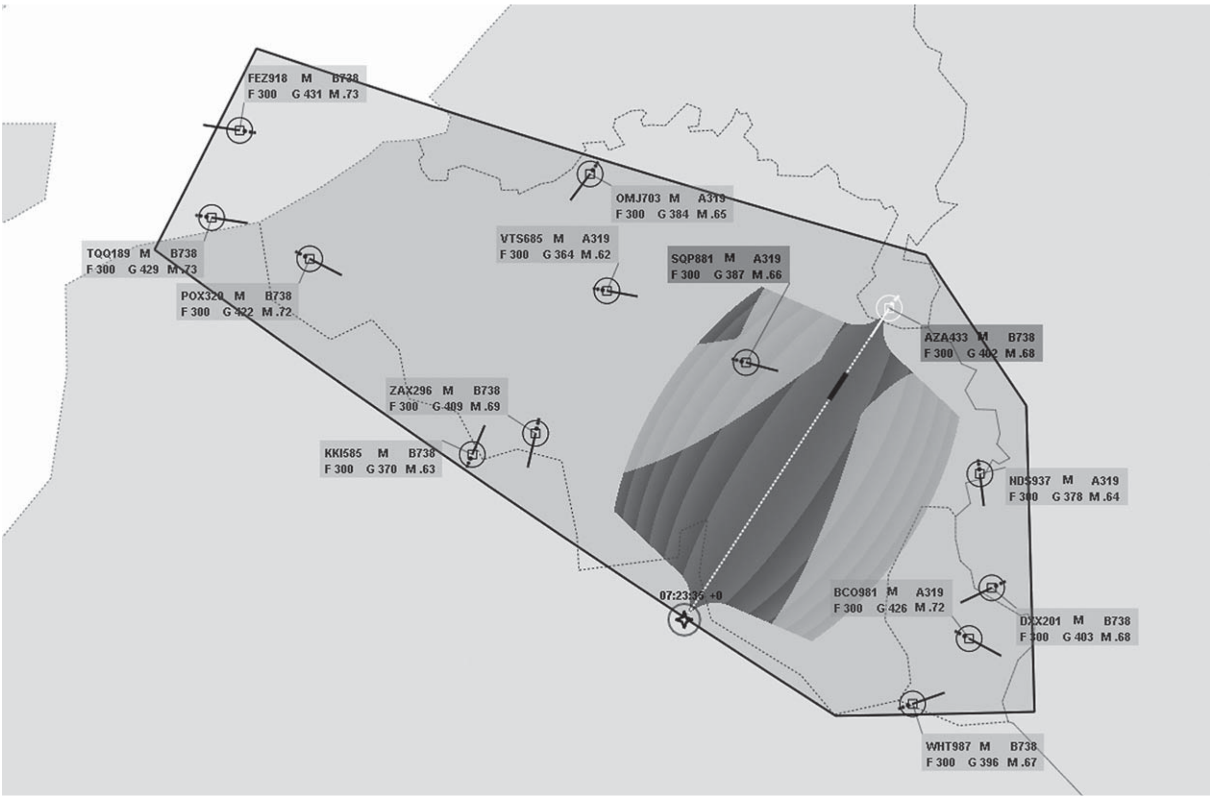


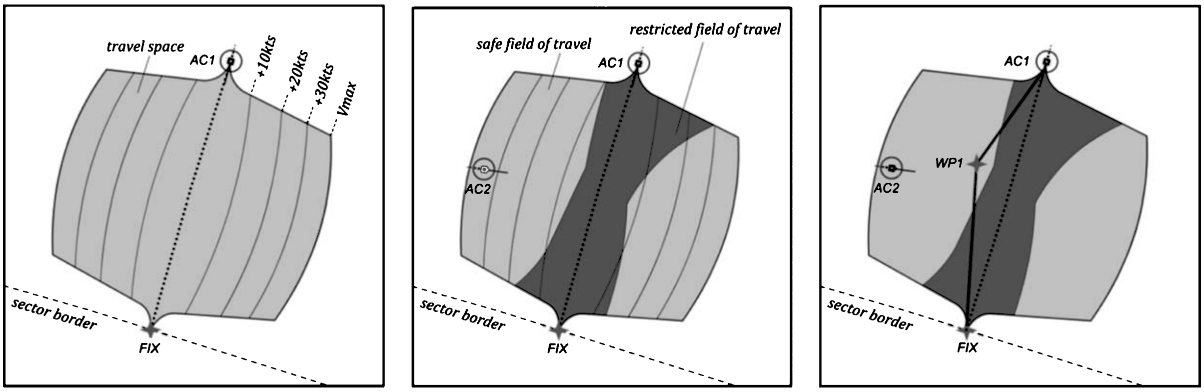
Fig. 5. Prototype of the travel space representation.

work, and allocation of (space) resources is important (Fig. 3). The result is mainly the path geometry of the 4DTs. At this stage, the constraints by the aircraft performance capabilities, and the separation should be visible. An important feature of the display is the visualization of the relation between the possible modifications to the 4DTs and the effect on separation and performance.

Tactical In the tactical planning, much of the actual work should be performed by automated agents. Flights that are operating on or near the 4DT defined in the previous stage can be monitored automatically. The visualization for the human user should enable checking of conformance to the 4DT at a glance. At this stage the detection of anomalies is important. Since the actual implementation depends on real-time communication, an indication of communication health for all flights should be given (Fig. 4). Handling flights with problems, that need to be diverted from their route, needs a visualization of separation from other flights and of buffer zones that can be used to safely divert the flight.

5. Travel space representation

As a starting point, an initial prototype for a shared representation has been designed for the task of re-planning an RBT during the tactical monitoring phase (Fig. 5). Re-planning is necessary in case one or more inherent (other traffic, weather, ...) or intentional (restricted airspace, procedures, ...) constraints, active on the aircraft RBT, cannot be met due to any number unforeseen events.



(a) Travel space representation for a single aircraft

(b) Traffic causes restricted field of travel (loss of separation)

(c) Placement of intermediate waypoint to ensure separation

Fig. 6. Conflict resolution with the travel space representation.

The prototype is based on the principles of CSE and EID [11], and built upon on the results of a more elaborated WDA for the tactical monitoring phase (Fig. 4). It aims at visualizing the underlying relationships and constraints of the work domain, linking low-level functions (primarily the 4DT descriptions) and information to the more abstract higher levels of the AH (primarily separation and timeliness). The constraints inherent to the task of RBT re-planning are identified from the AH of the tactical phase; separation, obstruction, communication and travel. Any resulting RBT which abides to this set of constraints forms part of a so called 'safe field of travel'.

For the initial travel space representation in Fig. 5, the task of re-planning the *horizontal route* of an RBT is considered. More specific, an attempt is made to visualize the safe field of travel when introducing a new 4D-waypoint in a certain segment of the RBT. A similar representation has been designed for re-planning a 4D trajectory on the flight deck [29, 30], however, here also the separation from other *dynamic* obstacles (the other airspace users) had to be taken into account.

In Fig. 6(a) the basic composition of the travel space representation is shown. Aircraft `AC1` is flying along a pre-agreed RBT 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 not considering obstructions and other traffic, the constraints that bound the area within which an intermediate waypoint can be placed result from that particular aircraft's performance. 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 on the current trajectory segment implies an increase in track length, and thus an increase in required groundspeed. The outer edges of the travel space are therefore bounded by the maximum speed of the aircraft.

In Fig. 6(b) other traffic has been introduced in the form of a single second aircraft (`AC2`). When taking the separation constraints between both aircraft into account, an area within the travel space for `AC1` becomes restricted (i.e., a waypoint placement will result in a new RBT that is in conflict with the other aircraft). This area is indicated in the figure as the restricted field of travel. In this case both aircraft will be in conflict at a certain point in time as the current route of `AC1` passes through the restricted area.

Figure 6(c) shows how the travel space representation can be used by a human controller to select an appropriate position for an intermediate waypoint. By placing the waypoint (`WP1`) inside the safe field of travel within the travel space bounded by the aircraft's performance, timing and separation constraints are all met.

This visualization of the work domain constraints and their relationships allows the controller to reason about and directly act upon the airspace environment. But this same representation could 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 are also able to re-direct machine activities easily in occasions where they recognize a need to intervene.

6. Discussion

The largest change for an ATCo will be to step away from hands-on modification of aircraft trajectories to implement the desired traffic flow in real time, 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 4DT means a tremendous step, and a real-time visualization of how all trajectories will evolve *in time* is a tremendous challenge for display designers. Whereas dimensionality of the control problem explodes, the visualization and display techniques remain limited by, among others, clutter issues, and physical constraints like screen size and resolution.

The main outcome of the project will be a representation for the tactical and strategic manipulation of 4D trajectories. This framework for 'joint cognition' can act as a basis for designing both the automation support and human-machine interfaces, in the air and on the ground, from one and the same perspective. It is very likely that during the development and testing of prototypes, the Work Domain Analysis will need to be augmented and/or partly changed. Several 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 that can indeed be used for both automation and human-machine interface design.

7. Conclusions and future work

This paper outlines a possible approach for the creation of the new work domain in Air Traffic Management. The envisaged future situation in SESAR and NextGen, in which aircraft will be able to fly four-dimensional (space and time) trajectories, requires planning, monitoring, and if necessary modification of these trajectories. The approach proposed in this paper is based on Cognitive Systems Engineering, and assumes three successive steps in the refining and final implementation of the four-dimensional trajectories. Automation support comes in the form of visualization of the constraints in the planning phase, and collaborating agents in the execution phase. An initial Work Domain Analysis has been done for these three phases, and critical functions for each of the phases have been identified. A preliminary prototype for one of these phases, the Tactical monitoring phase, has been presented and discussed. Further work will focus on the refinement of the WDA, the creation of actual interfaces and the evaluation of the design.

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