Joint Human-Automation Cognition through a Shared Representation of 4D Trajectory Management

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***Abstract*—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 large changes to the work domain of the air traffic controller. In both programmes, a key element is the introduction of the 4D (space and time) trajectory as a means for strategic management, rather than the current tactical –hands-on– method of control. A central role is foreseen for the human operator, aided by higher levels of automation and advanced decision support tools. However, a definite breakdown of this co-operation is not yet well defined. 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 also allow shifting back and forth across various levels of automation. A preliminary version of a joint cognitive representation for 4D trajectory management has been developed and is introduced in this paper. The results of a first conceptual evaluation will be discussed that aimed at validating the concept and usability of the representation. Future work will focus on the further development and refinement of shared representations by means of human-in-the-loop experiments. *Foreword*—This paper describes a project that is part of SESAR Work Package E, which is addressing long-term and innovative research.**

Index Terms*—Ergonomics, human factors, interfaces, automation, travel space , Air Traffic Management

I. Introduction

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 [1–4]. The pull for this evolution comes from the increasing demand which is placed on the air traffic management (ATM)-system (e.g., on workload, capacity, efficiency, etc.). A push is provided by technological advances on the air- and ground side of the ATM-system (e.g., advanced flight management systems, high-precision trajectory prediction algorithms, System Wide Information Management (SWIM) environment, etc.), which facilitate this new form of air traffic control (ATC) [5], [6].

The introduction of *time* as an explicit control variable in the definition of trajectories implies a fundamental change in the work domain of the human air traffic controller (ATCo). Where currently ATCo's perform hands-on tactical control of aircraft, often with little help from automated tools [7], the shift towards 4D-based ATM will no longer be possible without the aid of automated support- and decision-making tools. Considerable research has been devoted to exploring this future approach to air traffic control with 4D trajectory support. The need for the development of higher levels of automation [8] to enable such an approach is clear. However a definite concept on a distribution of roles and coordination between automation and the 'central role' of the human operator is not defined yet.

Many other complex socio-technical domains have shown that the transition towards higher levels of automation often introduces new problems, problems that are often harder to resolve than those intended to be solved in the first place [9]. Increasing the level of automation is not good or bad in itself, but with more automation more extensive coordination between humans and computers will be required [10]. Breakdowns in 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 [11]. To facilitate the coordination between human and automated agents, it is imperative to create new tools and to make the automated systems 'team players'.

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'. A first prototype of a Joint Cognitive System (JCS) [12] will be introduced, together with the results and conclusions from an initial conceptual evaluation.

II. Designing for Shared Cognition

In the SESAR overall concept of operations, various phases for the refinement of 4D trajectories are foreseen [13], [14].

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 [15].

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' [16] 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.

A. Pertubations in ATM

In order to bound the work domain of the tactical monitoring phase, a literature study of the origins and impact of such unforeseen events (e.g., *perturbations* with respect to nominal operations) has been done. If flight time delay is taken as a manifestation of perturbations, then in the US in the early 2000's only 16% of all delayed flights incurred the delay whilst the aircraft was in the air [17]; the remainder of delays happened at the gate (50%) or during taxi-in/out (34%). The majority of delays (~70%), both on the ground and in the air, are reported to be weather related [17–20].

A second consideration is the *impact* of a perturbation. By scaling up, a distinction can be made between *local* (affects a single flight), *regional* (propagates across several flights), *extended* (affects a large number of flights and takes a long time to restore the Network Operations Plan (NOP)), and *disruptive* (can only be solved by removing a number of planned flights) perturbations. The fact that there are different extents to the impact of a perturbation implies a different approach to managing them within the ATM system; a local perturbation can be resolved within the discretion of a single controller whilst an extended or disruptive perturbation will require input and action from multiple stakeholders.

In the gate-to-gate 4D trajectory management concept it is expected that a number of perturbation sources can be mitigated by adopting a more precise planning (e.g., taxiway congestion, runway capacity, airspace bottlenecks, etc.). However, other sources of perturbations will remain unavoidable (e.g., hazardous weather, not meeting planned constraints by flights, technical failure or equipment damage, etc.). Therefore, although the planned 4D trajectories of all flights are –per definition– perturbation free at push-back [13], deviations on various scales from the intended paths will be unavoidable [21].

B. Foreseen human-automation coordination

In the tactical monitoring phase it is foreseen that automated agents will monitor the execution of trajectories and provide limited actions (e.g., speed updates [13]) to constantly realign the system with respect to the overall NOP. Shared representations will provide the human users with information about the state and intent of the system and the actions and reasoning governing the automated agents. This will allow the user to perform higher level (system wide) monitoring tasks, and ensures that the they can step in as creative problem solvers in case of any unforeseen events.

C. Cognitive Work Analysis

The approach taken for the design of a framework for 'joint cognition' in 4D trajectory management is based upon the framework of Cognitive Systems Engineering (CSE) [12], [22]. This approach takes the global context in which the work takes place (i.e., the work domain) as a starting point, based upon the reasoning that knowledge of the entire system cannot be solely built up from knowledge of the individual parts. The first step in CSE is to perform a functional breakdown of the work domain, identifying all relevant elements and functions on various levels of abstraction. The underlying relationships between 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 [23]. Such an initial Work Domain Analysis (WDA) has been performed by the construction of an Abstraction Hierarchy (AH) [11] for three of the stages in 4D trajectory refinement (*short-term planning*, *pre-tactical planning* and *tactical management*) foreseen in the SESAR operational concept [15].

When designing for shared cognition, a distinction can be made in the analysis of the work domain between a *correspondence-driven*- and a *coherence-driven* environment [24]. In a coherence-driven work domain, time for completion of the task is of relatively minor importance, and the emphasis is put on the coherence of the work (*planning* phases). If the work domain is governed by goal-relevant, dynamic (i.e., time-varying) external constraints, then the work domain is correspondence driven (*tactical monitoring phase*). Clearly, the work domain in the tactical monitoring phase is highly correspondence-driven. In terms of design implications for a shared cognitive system, this requires that the mental model of the human user not only corresponds to a system representation (or engineering model) of the environment, but also that both the human user and system have a strong correspondence to the objective state of the world itself. In order to assess the fundamental functions which build up this objective world state, the top three levels of the abstraction hierarchy for the tactical phase which are proposed are given in Figure 1. Means-end links between the various levels of abstraction are shown to indicate the underlying relationships. A short breakdown is given of the abstract functions of the work domain.

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, NOP status, meteorological information, …) for both the human and automated agent is foreseen to be the SWIM environment. Furthermore, conflict detection algorithms are foreseen to provide more detailed information about safety critical perturbations.

It should be noted that the function of *communication* itself is not stated explicitly in the AH, but forms the basis of network-wide information sharing and awareness between all agents in the environment. Communication can be seen as an intermediate (enabling) function for integrating information throughout the system to achieve the overall system goals.

Although the AH highlights the underlying functions which govern the work domain in the tactical monitoring phase, 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, and 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 joint representation.

III. Travel Space Representation

As a starting point, an interactive prototype of a constraint-based shared representation has been designed for the task of manipulating and revising a Reference Business Trajectory (RBT, SESAR terminology for an agreed 4D trajectory) in the tactical monitoring phase. For clarification, according to definition [13] an RBT 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. 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

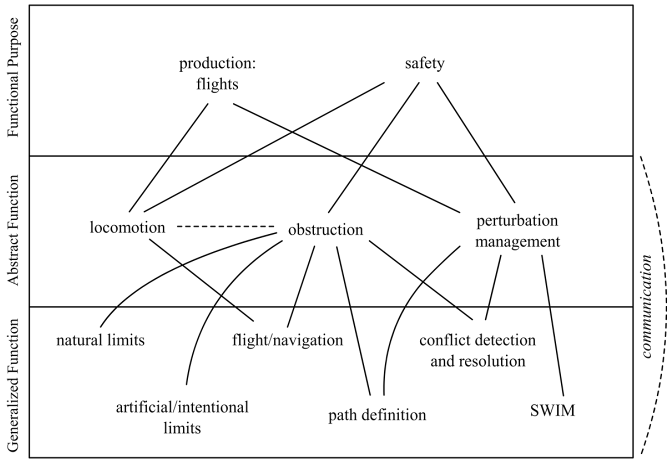


Figure 1. tactical monitoring phase, top three levels of the Abstraction Hierarchy.

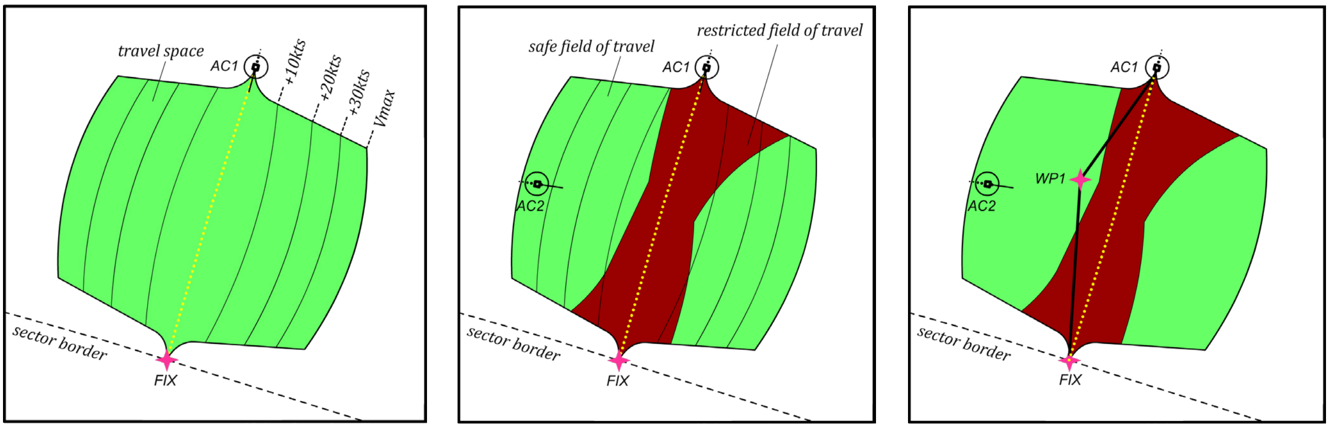
of waypoints is necessary in case one or more inherent (other traffic, terrain, weather, …) or intentional (restricted airspace, procedures, …) constraints active on the aircraft RBT, cannot be satisfied due to any number of unforeseen events.

A. *Safe field of travel*

Consider an aircraft flying along a certain segment of its RBT, from one 4D waypoint to the next. The overall goal of the aircraft is to reach the subsequent waypoint within the constraints following its agreed RBT. Now consider that either the aircrew or air traffic controller intend to introduce an intermediate waypoint into that segment. For any arbitrary (4D-)placement of that waypoint, a check can be made whether the resulting RBT abides to the relevant constraints which govern the airspace. The subset of RBTs which fall within these constraints are all feasible solutions and form a so called 'safe field of travel'. When translating this safe field of travel to a correspondence-driven representation, a one-to-one mapping can be made on the air traffic controller's plan view display, indicating the real-world spatial locations and time-implications of the solutions.

B. *Representation breakdown*

In Figure 2(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 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 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



(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

Figure 2. Conflict resolution with the travel space representation

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*. Note that if the observed aircraft is in conflict with other traffic, its complete segment lies within the restricted field of travel. The restrictive area shows the operator the set of all possible intermediate waypoints that will not lead to a resolution of the conflict. Note that these same constraints on where to put the waypoints *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 2(c) shows how the travel space representation can be used by the human 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 working principles of the representation.

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.

IV. Conceptual Evaluation

A conceptual evaluation of the prototype travel space representation has been conducted in this early design phase. The evaluation allowed for the validation of the underlying principles of the representation and forms the basis for further design decisions in the following development phase. Besides suggestions for improvement to the presented concept, the feedback of participants also provided input for generating new directions and insights. At this stage, the obtained results are qualitative.

A. Method

An interactive computer-based implementation of the travel space representation formed the basis of the evaluation. For this purpose, several traffic situations have been constructed, based upon real world data. From the EUROCONTROL Dynamic Data Repository (DDR), the flight plans (supplemented with radar-corrected timing information at the waypoints) of all IFR flights within the European airspace were obtained for a single day with a high volume of traffic (33.617 flight movements). From the analysis of a 4D-playback of the traffic sample, a section of airspace was selected which contained a high number of en-route crossing traffic. The shape of this airspace (or sector) is based upon the southern part of the Maastricht Upper Area Control (MUAC) airspace, the Brussels Upper Information Region (UIR). Subsequently, all flights passing through this section of airspace were filtered (2.272 flights), and their route straightened (reduced to one

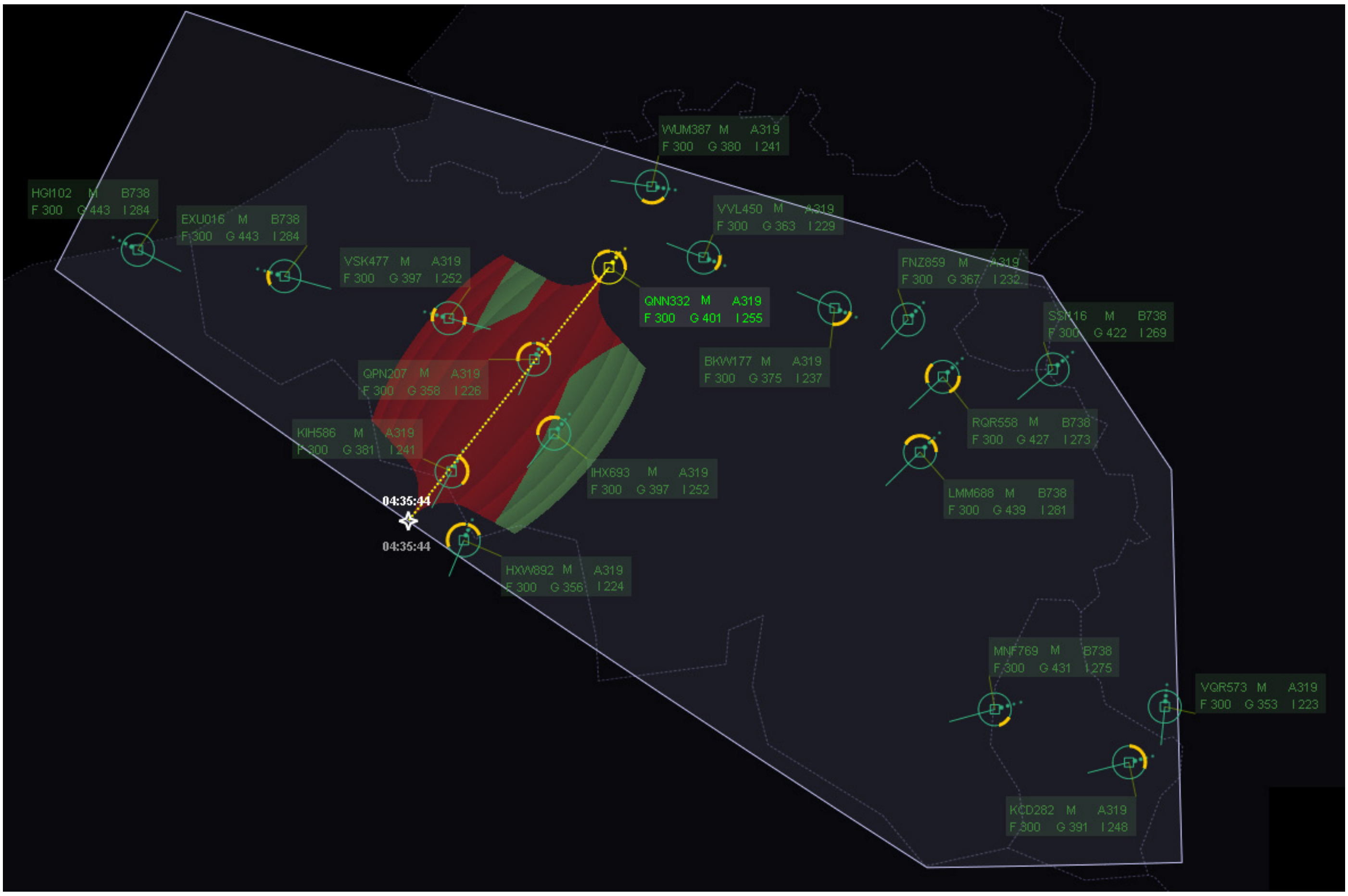


Figure 3. Prototype of the travel space representation

segment) from sector entry to sector exit point; flight plans will no longer be subject to fixed airways. For the scope of the conceptual evaluation the vertical dimension was flattened to a single flight level (FL)300 for all aircraft, in effect reducing the control space to 2D + time.

In a next step, the timing of all aircraft at the sector exit point was adjusted to create a constant segment speed of .62 Mach (~230kts CAS), and the aircraft type randomly set to a Boeing 737-800 or an Airbus A319. At this point numerous conflicts had been introduced in the traffic sample resulting from the previous modification steps. In order to create a conflict-free baseline scenario, an algorithm was developed which attempted to re-arrange the timing of trajectories to adhere to a minimum separation distance with respect to all other traffic. This resulted in three conflict-free baseline traffic samples with a minimum horizontal separation of 5NM (2.024 flights, ~85 flights/hour), 10NM (1.292 flights, ~55 flights/hour), and 20NM (674 flights, ~30 flights/hour).

The traffic sample with a minimum separation of 10NM was selected for the conceptual evaluation. In a final step, three conflicts between flights were introduced at certain times, and under varying geometry (head-on, crossing, and take-over situation).

Each participant was positioned in the role of the ATCo during the tactical management phase in the post-SESAR context and narrated through the traffic situations by means of a cognitive walk-through. The scenario was presented to the participant in a plan view display showing the geographical borders and sector lay-out. Flights were visualized including speed vector, protected zone, history dots, solution space heading band overlay and label.

At the different key-phases during the scenario (e.g., conflict free situation and the conflicts with varying geometry) the simulation was paused and the travel space representation visualized to the subject. Subsequently, the participants were free to provide feedback and comments. In addition, an early implementation of the Rapid Random Tree (RRT) conflict resolution algorithm (automated agent) [25] provided five optimized automated resolutions for review. Goal of this set-up was to assess whether the travel space representation lends itself for effective human-automation coordination.

Figure 3 shows a screen capture of the plan view display used in the evaluation. Flight QNN332 is selected, and its active RBT indicated by the yellow dotted line. The metering fix at the sector exit point is indicated by a star, together with its relevant time information (CTO and expected time, both 04:35:44 UTC+0). The travel space representation of the selected aircraft is visualized and shows that a conflict will occur somewhere along the RBT segment; the segment traverses through the red-coloured restricted field of travel. The safe fields of travel (coloured green) visualize the travel space in which the addition of a single intermediate waypoint into the RBT segment of the selected aircraft will resolve future separation conflicts with *all* other flights and will maintain timeliness at the fix.

Prior to the cognitive work-through, participants were given a questionnaire to complete classifying their background and knowledge of ATM, 4D operations and human machine interface design. Furthermore, a short introduction was given to the foreseen work domain of 4D trajectory management and the objectives of the current research. Next, for each evaluation, two experimenters provided the explanations of the concepts, narrative of the situations, and operated the demonstrations. In total, an individual session lasted between 1½ and 2 hours.

B. Participants

Seven professionals in the field of aviation and air traffic control – six males and one female – participated in the evaluation, their age ranging between 29 and 58 years. Five participants had basic to good background knowledge due to their profession in the field of aviation human factors and operations. The two other evaluators had in-depth knowledge because of their (previous) profession in the field of ATM research and development. Furthermore, one of the latter participants also had operational experience as a former assistant Area Control (ACC) controller for Air Traffic Control the Netherlands (LVNL) for a period of one year.

C. Results

Participants had the opinion that the travel space representation was visualized in a clear and intuitive manner, although required some initial explanation. As a point for improvement it was mentioned that more contextual information was necessary in order to interpret the restricted field of travel zones, especially with multiple complex shaped zones; for instance, by providing information on how the restricted zones are associated and linked with other active flights. One participant commented that this approach is scalable and that other obstructions such as special use airspace, restricted zones and weather could be taken into account in the representation.

In terms of current operational considerations it was mentioned by the former assistant controller that a solution involving both speed and route changes (to fix the time-over at the sector exit) as visualized seemed very costly. He mentioned that in addition it may be useful to fix the speed and show the time deviation with respect to the sector exit fix. Furthermore, one participant noted that in the current form of operations, this type of representation could be very useful for novice controllers, providing them with a quick overview of the type of speed and heading changed necessary for a certain deviation from the planned path (e.g., as a training tool), but that experienced controllers (again, in *current* operations) would not so much benefit from this representation.

The feedback from the participants on the trajectory resolutions provided by the RRT algorithm suggested that the number of resolutions should be limited, preferably to between one and three, especially in case of situations with a high workload or a high temporal demand. One suggestion was that the focus should not lie on the most ‘optimal’ resolution in terms of cost and efficiency, but rather on the *robustness* of the resolutions. It was suggested to use conflict probability as a metric for assessing routing alternatives, and that the routes with lower conflict probabilities are favored over the ones that have a higher probability. About half of the participants mentioned that the possibility of adjusting a proposed resolution (e.g., by means of post-hoc manipulation of a waypoint or trajectory) would be a valuable addition. Furthermore, the early RRT algorithm used slightly different rules and constraints than the underlying working principle of the travel space representation. This required some explanation to the participants and it was concluded that ideally both approaches would use the same set of rules. Overall, the participants agreed that the combination of the travel space representation and the automated resolutions provide a viable and useful coordination between the actions of the human controller and the automated agents alike.

V. Discussion and Conclusions

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 4DT 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 main outcome of the SESAR WP-E C-SHARE project will be a common representation for the tactical and strategic manipulation of 4D trajectories. 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. 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 that can indeed be used for both automation and human-machine interface design.

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