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Analysis of Advanced Airspace Concept Operations Using Human Performance Modeling

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The Advanced Airspace Concept (Erzberger, 2001) proposes to achieve increased capacity in both en route and terminal areas through the use of technologies that include air-ground datalink, automation generating 4-D trajectories, and an independent back-up system, intended to provide safe transition whenever there is a malfunction. An analysis of the concept's operations was performed using the human performance model Air Man Machine Integrated Design Analysis System (Air MIDAS) (Corker, 2000). For this research, three types of operations were modeled for an Air Traffic Control (ATC) agent – current operations, Automated Airspace Concept (AAC) operations, and Tactical Separation Assisted Flight Environment (T-SAFE) operations.. The results suggest that AAC operations decreased controller's workload when compared with current day operations. However, transition of the aircraft from AAC through T-SAFE to standard ATM control increased workload for the period of transition. This was marked with a high level of activity for the ATC-agent under the current and T-SAFE operations as the ATC agent sought to update its internal world representation with relevant aircraft trajectories to assume manual control.

Introduction

Various research efforts are focused on increasing the capacity of National Airspace (NAS). Advanced Airspace Concept (AAC) proposed by Erzberger (2001) is one such future concept, whose objective is to reduce Air Traffic Controller's (ATC) workload by automating the tactical functions of the ATC and by providing near term separation assurance. The key to safety is defined in the concept through the redundant system called Tactical Separation Assisted Flight Environment (T-SAFE).

The core ideas of the concept include segregation of the airspace into two categories, one is advanced operations airspace, and the other is standard or current practice airspace. The advanced airspace/sectors will combine several current sectors into a large single sector airspace, and this airspace configuration will be used during peak periods. Handoff between advanced airspace and standard airspace will be done using automation. Also, there are two kinds of aircraft anticipated in the concept, equipped and unequipped. The equipped aircraft are distinguished by their ability to exchange 4-D trajectories with the ground system and follow them accurately.

The ground automation called the Advanced Airspace Computer System (AACS) will generate 4D trajectories that will provide all the equipped aircraft with conflict free trajectories via data link. Flight crew reviews these trajectories before they are downloaded into the FMS. In the case that the aircraft does not accept a clearance issued by the ground system without cause, then that aircraft will be handed off to the manual system, i.e. to the ATC.

The concept has also has a fail-safe system , T-SAFE, which is an independent back up system that runs in parallel with the AACS, and is intended to provide a safe transition between automated and manual operations, in the case that AACS fails. Thus T-SAFE independently verifies that every trajectory provided by AACS is conflict free for the next 3 minutes before uplinking to the aircraft.

The present research effort hypothesized that workload levels for the ATC agent would be the highest in the T-Safe mode. This was based on previous research done on workload and mixed equipage. Several other studies (Corker, Gore, Flemming and Lane, 2001 or Jara & Corker, 2002) on mixed equipage operations have found that mixed operations can be challenging to the controllers. They found that highest subjective workload was reported by the operators in the mixed equipage mode. For example ATC reported higher subjective workload in the 80% free flight versus 100% free flight in the study by Corker, Gore, Flemming & Lane (2001). The human performance model used to analyze the impacts of the concept on human performance, particularly workload, is described in the next section.

Human Performance Model

Air Man Machine Integrated Design and Analysis System (Air MIDAS) is a computational human performance model used to predict human performance in joint cognitive systems. The system has been used in various environments ranging from aviation and emergency response systems to military systems (e.g., Corker & Smith, 1992). It has agent-based architecture and represents the physical world (e.g., equipment and terrain) and human perception – attention, and other cognitive functions – to varying degrees of fidelity. The system can represent a large number of human agents. Each human agent has, at its core, an internal representation of the physical world, a scheduler, and task demands. The dynamic interplay of all these components represents human interaction with automation. Some of the components or constructs represented in Air MIDAS are described in the next section.

Human Mental Constructs Represented – Activity: Activities define the behavior of the human agent. They are a part of the simulated operator's procedural knowledge contained in the Updateable World Representation (UWR) and form the backbone of the simulation. Activities are scheduled or queued before being executed. The human agent's scheduling behavior is based on Wicken's multiple resource theory (1999), where parallel activities can be performed, if resources (visual, auditory, cognitive and psychomotor) are available. If sufficient resource is not available for concurrent performance (using a simple additive model) then, these activities can be interrupted by a higher priority activity, and later resumed.

Memory: The physical world is sampled regularly by the agent's perceptual and attention resources and the sampled data is stored in the UWR. Working Memory (WM) has been implemented in MIDAS based on postulates described by Baddeley and Hitch (1974). WM consists of a central control processor (with limited capacity), a "phonological loop" (temporary storage of speech-based information), and a "visuo-spatial scratch pad" (temporary storage of spatial information). Long Term Memory (LTM) is composed of both episodic and procedural archival structures. Both WM and LTM are susceptible to decay of information stored therein, caused by the passage of time since the information was last accessed, and to capacity overloads.

Goal Definition. Goals for every specific condition in the simulation world have to be defined. A goal is a statement of conditions (defined as "perceivable states of the simulation") that are to be met in its satisfaction. A goal is satisfied by decomposing the goal into "sub goals and activities"—these are defined by subsumption principles to provide a set of basic activities through which the human operator model interacts with other human agents in the simulation as well as with the equipment in the simulation. Basic (or leaf level) activities are defined as the point at which the action of the agents of the simulation are effected through an interface with the simulation world.

Activities. A set of goals and sub goals are decomposed into component parts that use an elementary information processing step in the human model and specific equipment. Activities are allocated resource loads associated with the elementary information processing aspects of human models. These loads are assigned in terms of visual, auditory, cognitive, and motor (VACM) requirements for an action to be performed. Activities also have duration estimates—and distributional variation around those estimates— used for scheduling the intended performance time of an activity. Each activity has a priority assignment that is inherited from the goal associated with it. They also have interruption specification (whether or not they can be interrupted once begun) and resumption specifications if interruptible. Activities and goals are the processes by which the human operator model interacts with the simulation world. Activities also have specification in their "goal decomposition" methods that assign logical processes (Boolean logic) to a task-type (e.g. activities that can be performed in a parallel fashion, activities that must be performed sequentially, do-while background or loop activities etc.).

Operators and Agents. Each operator (human or artifact) have software methods associated with it that track its interaction with other agents in the world. These "biographers" are used to collect the data of the transaction for agents in the simulation world. Human Operator Agents have several unique characteristics that are important to the functioning of the simulation.

Scheduler. The human agent has a scheduler that attempts to schedule activities for the human agent at each schedule cycle. As described earlier, he scheduler assumes that concurrent performance is desired unless otherwise specified. It attempts to schedule all activities possible in a given time frame until the human resource limit is reached. Priority determines which activities are scheduled first. Activities of the same priority are scheduled by a probabilistic coin flip.

Air MIDAS is able to provide a variety of outputs, e.g., operator workload, task performance timelines, and order of task completion, depending on the level of detail of model construction. The method section defines how the various characteristics of the concept were implemented in the model and data collected for the same.

Method

An informal cognitive walkthrough of the AAC was undertaken with the SMEs (retired ATC and AAC's concept developer) and comparisons drawn between this concept and current day operations. The concept was examined from the perspective of an air traffic controller working in the enlarged sector with traffic loads approximately double to those of current operations. At this preliminary stage of analysis, several simplifying assumptions were made to provide an initial implementation of the system that could be modified for further analyses.

Assumptions. It was assumed that there will be a single controller position (r-side) interacting with AACS with decision aids being provided through the set of tools usually used by the radar controller. All aircraft in the simulation are assumed to be equipped for AAC operation except for the current day operations condition.

The scenario provided that a single aircraft will transition from AACS through T-SAFE to ATC's manual control, and the controller will handle that particular aircraft until it leaves the sector. During the failure mode condition, the T-SAFE system provides a three-minute conflict free trajectory in the transition out of AAC mode and other controller tools provide support after that point. The T-SAFE system is not used after the transition. Communications are assumed to occur primarily through data link coordination between AAC and aircraft (and between controller and aircraft in standard/current day operations). Three scenarios were encoded - Current operations, AAC operations, and T-SAFE operations. The next section details the procedures for each kind of operation.

Procedure Definition

Three different kinds of procedures were simulated that focused on the en-route phase of the flight in this research effort. Also the role of r-side Air Traffic Controller was of prime focus. In the system, three kinds of agents were represented- Air Traffic Controller which was a Symbolic Operator Model (SOM) agent, AACS, and T-SAFE were represented as equipment agents. The main difference between a SOM agent and an equipment agent is that a SOM agent performs tasks specified by the task scheduler that uses estimates of human resources and priorities to schedule tasks, whereas the equipment agent has no such task scheduler.

Current Operations. The standard operations for the controller monitoring traffic, detecting conflicts, and resolving conflicts were encoded. Handoff procedures similar to the current day operations, where the controller via automation flashes the aircraft to be handed off on the ATC display. The controller in adjacent sector notes the flashing aircraft, prepares for handoff, and accepts the handoff. The previous sector controller notes that handoff has been accepted and accordingly requests aircraft to switch frequency to the next controller. Similarly conflict detection and resolution algorithms were formulated for this condition.

*AAC Operations***.** A conflict free scenario was encoded to depict conflict free trajectories created by the AACS. All aircraft in the simulation were considered equipped and under AACS control with just one controller handling them. The task of the controller was primarily to monitor traffic. Handoffs between sectors were handled by the automation (AACS).

*T-SAFE Operations***.** The operations using T-SAFE were procedures for transition between automated and manual / standard operations. This occurs when an equipped aircraft due to some reason (failure) changes status to unequipped aircraft. T-SAFE computes a 3 minutes conflict free trajectory for the failed aircraft before handing-off the aircraft to the ATC agent. After that the controller assumes manual control of the aircraft, T-SAFE has no role to play for that aircraft.

Procedures for the AAC & T-SAFE operations scenario and sequence of activities include the human operator agent monitoring the state of the airspace as a part of his/her standard goal of maintaining situation awareness. This monitoring for Situation Awareness (SA) goal is a background "do-while" activity. If an AAC T-SAFE alert is heard or seen, the operator agent ceases the standard SA scan and begins the goal of preparing to accept hand-off from T-SAFE. This handover occurs because the T-SAFE goal is a higher priority than the monitoring goal, and when interrupted the scheduler finds that the resource demand for the T-SAFE set of activities is high, therefore the activities cannot be performed in parallel. As will be discussed in the results section of this report, due to memory limits the information that the controller agent may have about the airspace into which the transition is occurring may be deficit. So a series of information seeking activities are initiated.

Airspace Definition

The airspace used to test the procedures was sector 47 and 49 in the Cleveland (ZOB) Center. The two sectors were combined to create “super sector” as described in the AAC concept. Only four major routes were simulated in the combined sector, and they all intersected close to the Cleveland airport at Dryer (DJB). The four routes represent traffic flows in the north-south, east-west, northeast to southwest and southeast to northwest directions and vice versa.

Aircraft and their trajectories were selected from the ETMS data for August 28, 2002. Aircraft that were enroute for the combined-sector were selected for the simulation, which meant that arrivals and departures out of the combined-sector were excluded for this phase of the simulation. The number of aircraft in the current ops was half the number of aircraft in the AAC and T-SAFE mode. The AAC and T-SAFE scenarios had 32 aircraft whereas the current operations had 15 aircraft.

Model Caveats and Constraints

As noted earlier and summarized here, several constraints need to be kept in mind while interpreting the results of this simulation. First, MIDAS does not have a complete efficiency and flow referenced set of air traffic procedures. So comparison of the performance of the model as a comment on the expected utility of the AAC to control and manage traffic is not appropriate.

Second, other support tools that would presumably be available to the controller have not been modeled, to assist the ATC in the management of traffic in the transition from T-SAFE.

Third, while the traffic sample is realistic (being taken from ETMS data files) however, there are no weather or other anomalous events to engage the controller even when AAC operation is nominal.

Fourth, the model lacks the implementation of the “critical maneuver” support techniques that are postulated to be part of T-SAFE, so the relative contribution of these to traffic control is not predicted.

Results and Discussion

The simulation focused on understanding the impact of the advanced airspace concept versus current operations on procedure, with respect to changes in workload, and status of goal completion for the controller agent.

Workload

The advanced airspace concept argues that a limiting factor to the capacity in the en route National Airspace is the workload experienced by the en route air traffic controller. Thus the analysis of estimated workload was performed for three different operational scenarios- Current operations, AAC operations, and T-SAFE operations. It was hypothesized that the estimated average workload for current operations would be the highest; it would decrease under AAC operations, and again increase for the T-SAFE operations. It is interesting to note that the workload estimated for the current operations and T-SAFE is the same (Figure 1), although there is a big difference in the number of aircraft. T-SAFE had 32 equipped aircraft with only one unequipped (due to unspecified failure), where as there were only 15 aircraft under ATC’s manual control in the current operation condition. Thus monitoring just one unequipped aircraft along with 31 equipped aircraft forces the controller to operate within narrow boundaries that increases the controller’s workload.

Several other studies (Corker, Gore, Flemming and Lane, 2001 or Jara & Corker, 2002) on mixed equipage operations have found that mixed operations can be challenging to the controllers. Corker, Gore, Flemming & Lane (2001) studied the impact of mixed equipage by changing the percentage of aircraft in free flight (standard ops, direct routing, 20% aircraft in free flight and 80% aircraft in free flight), and found that controllers reported highest subjective workload for the condition with 80% free flight aircraft.

Jara & Corker (2002) conducted a part task simulation study on controllers with varied control modes and also manipulated the presence or absence of a secondary task. The conditions designed with respect to the secondary task were referred to as shared and traded supervisory control. Shared control is the performance of a task by a human operator with the concurrent assistance of automation. In the shared supervisory control, the specialists monitored the airspace with no distractions from a secondary task. The traded condition represents a control style where either automation or human is in complete control, thus a secondary task was introduced in this condition. The researchers also found that controllers experienced significantly higher workload in the traded condition. Traded condition is somewhat analogous to the T-SAFE condition because it involves an unequipped aircraft, which is equivalent to the secondary task in the part task simulation.

In looking at the averaged workload in some detail (Figure 2), we have selected three sequences associated with conflict detection and resolution in current operations or baseline, T-SAFE handoff and normal AAC operations. These are represented in the following figures. The time scale for these graphs is the completion time for each activity (roughly a time line or an event line).

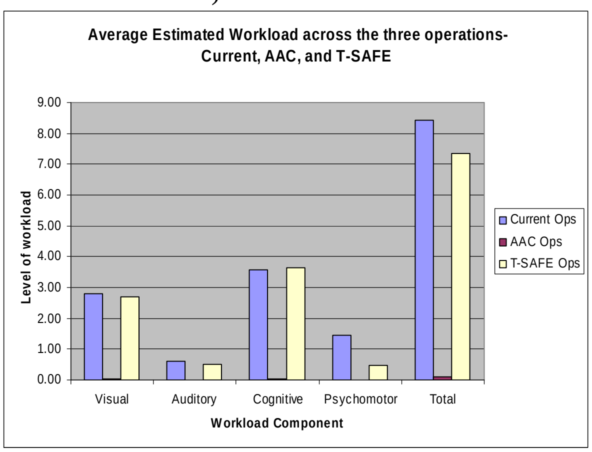

Figure 1. *Average Estimated Workload in the three operations – Current Day, AAC normal and T-SAFE. The workload scale ranges from 0 to 7 on every workload component.*

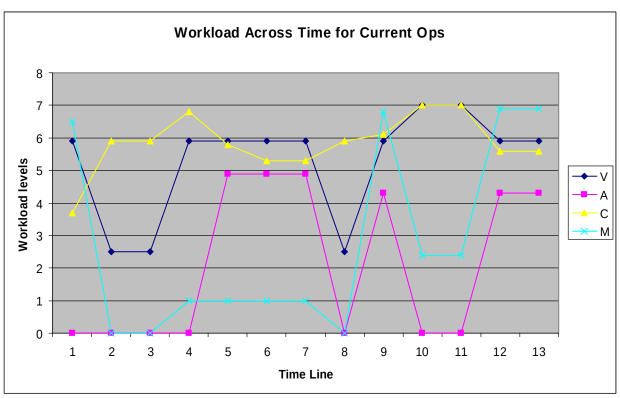

Figure 2. *Workload in visual, auditory, cognitive and motor (V,A,C,M) terms for activities associated with managing and separating approximately 15 aircraft in a sector in the current operations condition.*

Figure 3 shows the workload associated with managing a single aircraft in transition through T-Safe to manual control while managing approximately 31 other aircraft. It is clear from examining this workload trace that the predominant workload in this process is that associated with regaining awareness of the airspace into which the transitioning aircraft enters. This update is based on the requirement in the model to have current information in working memory to carry out the goals associated with aircraft conflict detection and resolution. Cognitive and visual load is high associated with tasks required for situation update.

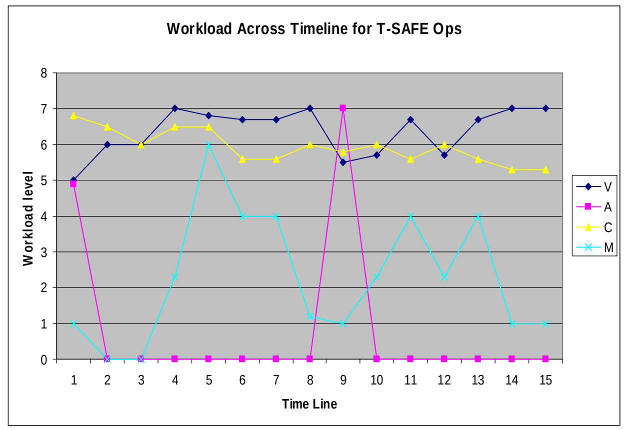

Figure 3. *Workload components (V,A,C,M) in the T-SAFE operations with one unequipped and 31 equipped aircraft.*

Status of Goals

The number of goals completed is an index of "how busy" the controller is, and number of aborted goals provides a sense of resource constraints experienced by the controller agent. The status of goals (completed and aborted) has a trend similar (Figure 4) to the average workload data. The number of goals completed is the highest in the current day operation because the controller is manually managing the traffic. It is interesting to note that number of goals handled under T-SAFE operations is high, where the controller agent is handling only one unequipped aircraft with rest of the traffic being handled by automation. These data are similar to the communication time data explored in the study by Corker et al. (2001). They found that although the controllers reported highest workload in the highest mixed equipage condition (80% free flight), they actually experienced highest communication load in the 20% free flight condition. Thus it is possible that increase in communication with a small percentage of mixed equipage (one failed or unequipped aircraft in the T-SAFE operations) can increase the number of tasks (mostly communications tasks) handled by the controller.

In terms of number of aborted goals, Figure 4 shows that about equal number of tasks/goals were aborted in the current and T-SAFE operations. Task shedding is a common response to information overload. Aborted tasks correspond to slips identified by Reason and Mycielska (1982) as causes of errors. They explain that slips occur when well formed plans are poorly executed due to omission of tasks, or intrusion of unwanted tasks.

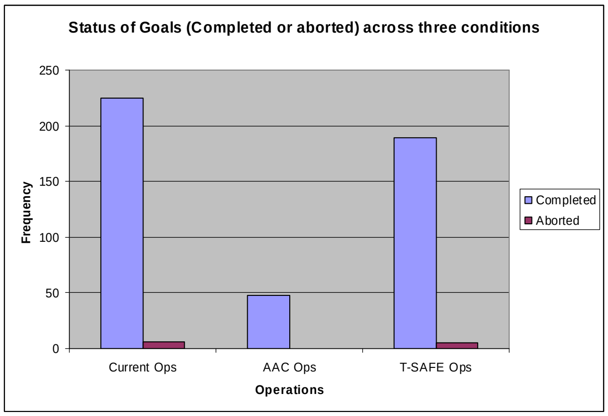

Figure 4. *Number of Goals completed and aborted across three conditions* **-** *Current Day, AAC normal and T-SAFE*

Conclusion

The purpose of this research effort was to model & analyze the current state of development and definition of the Advanced Airspace Concept Operations and using human-system performance model (Air MIDAS) to probe its impact on air traffic controller behavior. In order to examine the capacity benefits of AAC, current day standard operations, but with high traffic load were also modeled. It is clear that under normal conditions AAC operations significantly reduce workload for the controller. In this simulation twice the airspace and twice the traffic were handled in AAC operations by a single controller as compared with a controller team in current operations. However, one unequipped aircraft handled under T-SAFE operations can potentially increase workload to levels that approximate current day high load operations. The constraints, under which the current analysis was performed, have been explicitly stated. These constraints on assumed equipage and procedure can be relaxed to explore more refined representations of the operational concept. Future recommendations for research include examining any vigilance decrements under AAC operational mode due to extremely low levels of workload. Another recommendation would be to test more than one unequipped aircraft in the T-SAFE operational mode. It will be interesting to investigate the impact of the position of the failed or unequipped aircraft on workload. The position of the failure of aircraft will determine the cognitive resources required by the controller-agent to reconstruct her situation awareness.

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