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HUMAN PERFORMANCE SIMULATION IN THE ANALYSIS OF ADVANCED AIR TRAFFIC MANAGEMENT

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ABSTRACT

Models of human performance in large scale and complex systems have long served to engineers in prediction of system performance. They have also been used to identify performance shortfalls in the human-machine system under a range of anticipated scenarios. These shortfalls have then been used to predict requirements for aiding systems to augment human performance and assure safe system operation. Finally, human performance models have served the Human Factors and Cognitive Sciences by establishing a platform for the explicit instantiation of key theories of human performance. These require the stipulation of architectural and functional assumptions about the underlying process of human behavior.

1 INTRODUCTION

NASA, the FAA and Eurocontrol have initiated programs of research and development to provide flight crew, airline operations centers and air traffic managers with automation aids to increase capacity and safety in international airspace operations. The programs initiated propose sweeping changes in the process of operation of the system with shifts in the roles and responsibilities of the humans who manage and operate the system (RTCA 1996). The international aviation system is complex, and its subsystems are tightly coupled and interactive. The human-machine system encounters a huge diversity of factors in global operation. Analytic models of human performance coupled with empirical analysis hold promise in supporting the development of those aiding systems to meet international goals of safety and capacity. However, two challenges need to be addressed. First, the level of representation of human behavior must be sufficiently detailed to predict individual performance and to guide design for individual aiding and support systems while at the same time that behavioral representation must be able to provide input into large-scale analyses to predict global consequences of system modification. Second, the models of human-system performance must be sufficiently computational to support design specification in control theoretic terms, but also sufficiently flexible and robust to account for a range of human behavior influenced by cultural (corporate, professional and national) and environmental context. I will present a computational model that includes representation of multiple cognitive agents (both human operators and intelligent aiding systems), the Man-Machine Integrated Design and Analysis System (MIDAS). I will describe the use of the model in air traffic management analysis and provide a brief look at recent data that motivate a hybrid model structure to meet the challenges above.

The demands of this application require representation of many intelligent agents sharing world-models, and coordinating action/intention with cooperative scheduling of goals and actions in a potentially unpredictable world of operations. The operator model includes attention functions, action priority, and situation assessment functions. The cognitive includes working memory operations including retrieval from long-term store, and interference loss. The operator's activity structures have been developed to provide for anticipation (knowledge of the intention and action of remote operators), and to respond to failures of the system and other operators in the system in situation-specific paradigms. System stability and operator actions can be predicted by using the MIDAS model. Multiple operational concepts can be explored in this computational environment before committing to full mission simulation. The model's predictive accuracy was validated using the full-mission simulation data of commercial flight deck operations with advance data-link communications, sequencing (Corker and Pisanich, 1995).

2 MODEL DEVELOPMENT

Our goal is to develop human performance models that predict the consequences of the interaction between these advanced automation technologies and the human component in the air traffic management (ATM) system. In order to support these functions, we have developed a human/system model for advanced ATM operations that is a hybrid engineering control theoretic and cognitive performance model.

There is a long history of the use of human performance models based on a combination of engineering and psychological principles in dealing with complex aeronautical systems. Craik (1947) performed seminal work in human control of large inertial systems and characterization of that control through models. Craik's work advanced the study of human-machine significantly. First, he provides a methodology that describes human and machines in collaboration in the same mathematical terms in the same structural terms and in the same dynamical terms. This represented a fundamental paradigm shift in which man-machine systems could be conceptualized as a single entity linked/coupled to perform a specific task or set of tasks.

Second, the work supports an analytic capability to define what information should be display to the human operator in the human system as a consequence of his/her sensory/perceptual and cognitive characteristics in control.

In these developments a new level of abstraction was introduced and systematized by Craik and subsequent developers of operator control models. In this paradigm, the description the operator in the man-machine system could be used to guide the machine design. Further, the linked system could be used to explore the parameters of human performance, i.e., by changing the characteristics of the machine the scientist could observe the human's response and infer something about the characteristics of the human operator.

In performing such experiments, data in tracking control studies led Craik to conclude the human operator behaves basically as an intermittent correction servo. This formulation was further refined by McRuer and Krendall (1957) and summarized by McRuer and Jex (1967). The resultant description of the human operator is a good servo with bandwidth constraints and a cross-over frequency response characteristic.

The human operator in tracking systems tasks can operate as a good servo because of their ability to identify consistent forcing functions and consistent response in control. The model of the human operator as servo guided the design of aiding systems for the operator in that servo task (Birmingham and Taylor, 1954).

As the human operator was served by automation that operated at remote sites in semi-autonomous modes a new set of model descriptors was developed, led by Sheridan's work in Supervisory Control (Sheridan and Ferrell, 1969). This view of human as supervisor has spawned a considerable body of research and development with the significant inclusion of an "internal model" of the system behavior and goals that needs to be shared by the human operator and the aiding autonomy in support of the operator.

2.1 ATM Model Development

In the context of air traffic management, such a representation needs to be expanded to include multiple operators in the system of control and to include the uniquely human contribution of adaptable, but potentially noisy control input. The "noise" in this view of the operator is not stationary Gaussian distributions, *but errors of specific types and with potentially significant consequence.* We have developed a hybrid model for multiple human operators in advanced ATM. Traditional transfer function models are adequate to the inclusion of the operator as optimal controller with lag and noise components. However, because of the monitoring and supervisory role of the operator in the advanced ATM, the specific cognitive transfer function that the human operator provides also must to be considered. A model of human operator performance with explicit representation of the perceptual and decision-making processes has been developed (Corker and Smith 1993). The Man-Machine Interactive Design and Analysis System (MIDAS) serves as the basis of the advanced ATM performance models addressed here.

2.2 MIDAS Model

In order to successfully predict human performance or to guide design in linked human/automation systems characteristics of cognitive function, both in its successful and flawed performance, must be modeled. Humans are included in (and are critical to the successful performance of) complex systems in order to exploit their adaptive and interpretative intelligence. Human performance profiles arise as a function of the dynamic interplay among the following:

- the task demands,
- the characteristics of the operator reacting to those demands,
- the functions of the equipment with which the operator interacts, and
- the operational environment, the time course of uncontrolled events

The MIDAS system has evolved over a period of 10 years of development. The basic structure of the core system is presented here based on the work of Tyler et al. (1998). This architectural version of MIDAS has through its development been used to evaluate helicopter crew stations, short-haul civil tiltrotor emergency handling operations and the impact of MOPP flight gear on crew performance (Atencio et al. 1996, Atencio et al. 1998, Shively et al. 1995). The specific development for analysis of air traffic management systems will be provided below.

The user enters the system through the Graphical User Interface (GUI) that provides the main interaction between the designer and the MIDAS system. The user selects among four functions in the system. Generally the sequence would require the user to establish (create and/or edit) a domain model (which includes establishment and selection of the parameters of performance for the human operator model(s) in the simulation. The user can then select the graphical animation or view to support that simulation or a set of simulations. The user can specify in the simulation module the parameters of execution and display for a given simulation set, and specify in the results analysis system the data to-be-collected and analyzed as a result of running the simulation. The results analysis system also provides for archival processes for various simulation sessions.

The domain model consists of descriptors and libraries supporting the creation of:

- Vehicle characteristics- (location space, aerodynamic models of arbitrarily detailed fidelity, and guidance models for vehicle (automatic) control.
- Environment characteristics- This provides the external interactions including terrain form selected data bases at varied levels of resolution, weather features in so far as they effect vehicle performance or operator sensory performance, and cultural features (towns, towers, wires etc.) In short, the analyst here specifies the world of action of the experiment/simulation.
- Crew-Station/Equipment characteristics- The crew station design module and library is a critical component in the MIDAS operation. Descriptions of discrete and continuous control operation of the equipment simulations are provided at several levels of functional detail. The system can provide discrete equipment operation in a stimulus-response (black-box) format, in a time-scripted/event driven format, or in a full discrete space model of the transition among equipment states. Similarly the simulated operator's knowledge of the system can be at the same varied levels of representation, or can be systematically modified to simulate various states of misunderstanding the equipment function.
- The Human Operator Model (HO)- The human performance model in MIDAS allows for the production of behavior and response for single and multiple operators in the scenarios.
- Mission and Activity Models- Describe in a hierarchic structure the goals and the available recovery activities from missions-not-as-planned that make up the human operators high level behavioral repertoire in the mission. The next level of decomposition of the action of the mission is a set of high level procedures (that can be stored as a fairly generic set of routines, e.g. look-at or fixate). Finally there are the specific actives in "active action packets" RAPS that are the process by which the human operator affects the simulation.

In addition to the model development environment, editors provide tools for the user to define, or modify extant domain models.

2.3 Human Operator Model

The human operator performance model is composed of a combination of a series of functionally integrated micro-models of specific cognitive capabilities within a human operator. The human operator model functions as a closed-loop control model with inputs coming from the world and action being taken in the world. The model provides psychological plausibility in the cognitive constructs of long-term, working memories (with articulation into spatial and verbal components of the theses models) and with sensory/perceptual and attentional components that focus, identify and filter simulation world information for the operator, action and control. The cognitive function is provided by the interaction of context and action. Context is a combination of declarative memory structures and incoming world information. Output of action in the world is effected through the models of the operator linked to the anthropometric representations (if they are invoked by the analyst). The action changes the external world and the cycle begins again. Figure 1. illustrates the structures and their interconnections.

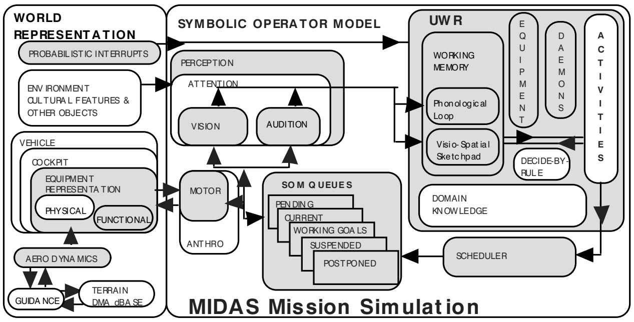

Figure 1: MIDAS Architecture for Human Representation in Complex Systems. Each of the modules represented in this figure is a functional model of human performance. They are linked together into a closed-loop simulation of operator performance. This basic structure is replicated to account for multiple crew member operations.

In order to capture the central role of schema and internal representation we have an elaborate representation of both declarative and procedural information in the

MIDAS model. In MIDAS, the internal updateable world representation (UWR) provides a structure whereby simulated operators access their own tailored or personalized information about the operational world. The structure and use of the UWR is akin to human working and long term memory and is one of the aspects of MIDAS unique from most human-system modeling tools. UWR contents are defined by pre-simulation loading of required mission, procedural, and equipment information. Data are then updated in each operator's UWR as a function of the mediating perceptual and attentional mechanisms previously described. These mechanisms function as activation filters, allowing more or less of the stimuli in the modeled environment to enter the simulated operator's memory. Knowledge of what is on each operator's mind is a key modeling feature that allows MIDAS to examine decision making and the information exchange that is critical to decision making.

2.3.2 Activity Representation

Tasks or activities available to an operator are contained in that operator's UWR and generate a majority of the simulation behavior. Within MIDAS, a hierarchical representation is used (similar to, but more flexible than the Mission-Phase-Segment-Function-Task decomposition employed by many task analysis systems). Each activity contains slots for attribute values, describing, e.g., preconditions, temporal or logical execution constraints, satisfaction conditions, estimated duration, priority, and resource requirements. The task network can complete successfully, be interrupted by other task networks or be aborted. The relationship among the actions in terms of logic of performance (e.g. sequential or concurrent tasks) is specified in the agenda structure.

2.3.3 Decision Making

Quick, skill-based, low effort responses to changes in values of information held in the UWR are captured by "daemons" when a triggering state or threshold value, sensed by perception, is reached. Daemons represent well-trained behaviors such as picking up a ringing phone or extinguishing a caution light. Classic production rule-based behavior is also available, and used when conditions in the simulation world match user-defined rule antecedent clauses active for the scenario modeled. Finally, more complex or optimization-oriented decision making is represented via a set of six prescriptive algorithms.

2.4 ATM Applications

We have focused our early investigation on critical issues in air ground coordination and in distributed decision making. These interactions are focussed on a process whereby appropriately equipped aircraft can maintain their own separation from other aircraft through onboard instrumentation; thus reducing the air traffic controllers burden of control and affording the participating aircraft flexibility in route selection etc. The interaction among aircraft and controllers is proposed to occur at points in space around each aircraft called alert and protected zones (see Figure 2).

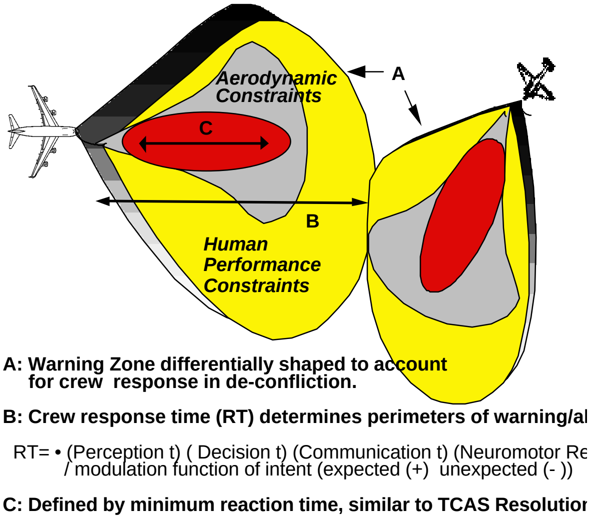

Figure 2: Alert and Protected Zones calibrated to human performance parameters, aircraft performance parameters, and communication systems parameters.

These zones are to be used by an alerting system to monitor and advise the flight crew and air traffic controllers (ATC) on conflicting traffic flying within these areas. In a cockpit-based system, the alerting system would warn the flight crew of any aircraft entering the alert zone. The crew could evaluate the situation and choose or negotiate a preferred deviation. If the intruding aircraft continued into the smaller warning zone, the crew would be advised to take evasive action, and the air traffic controller would be alerted as to a pending conflict.

2.4.1 Air Craft Self-Separation

The goal of this study was to develop a better understanding of the impact of joint and distributed decision making on the size and shape of the alert zones. This was accomplished by first analyzing and modeling the cognitive and procedural requirements of several candidate encounter scenarios. These models were then populated with performance data derived from human in the loop experiments. The specified scenarios were then represented within the MIDAS computational modeling and simulation system.

Using Monte Carlo simulation techniques, each scenario could be exercised many times, eventually establishing a statistical distribution for the human-machine performance of that configuration. By combining this with the aerodynamic performance of the system (in this case, the closing speed of conflicting aircraft at differing encounter angles) the differences in warning requirements between the different scenarios should emerge. All encounters were assumed to be two-ship interactions.

The result was a sequential model identifying the high level processes (or activities) performed the operators. In scenario two and three, the activities that were to be performed in parallel by the other flight crew and ATC were also defined. Falling out of this analysis was a recognizable cycle of Alert, Recognition, Communication, Decision, then Communication, & Action by the crews. This process is replicated throughout the scenarios for each flight crew interaction.

A standard set of descriptive statistics was generated based on the set of fifty Monte Carlo runs across a range of control scenarios, which are shown in Figure 3. The goal was to determine, for each scenario and encounter angle, how much alerting distance would be required to provide at least a 5-mile warning zone around the aircraft. In other words, for each scenario, when should the initial alert be made so that the flight crew could begin to move away from each other before entering the 5 mile warning zone?

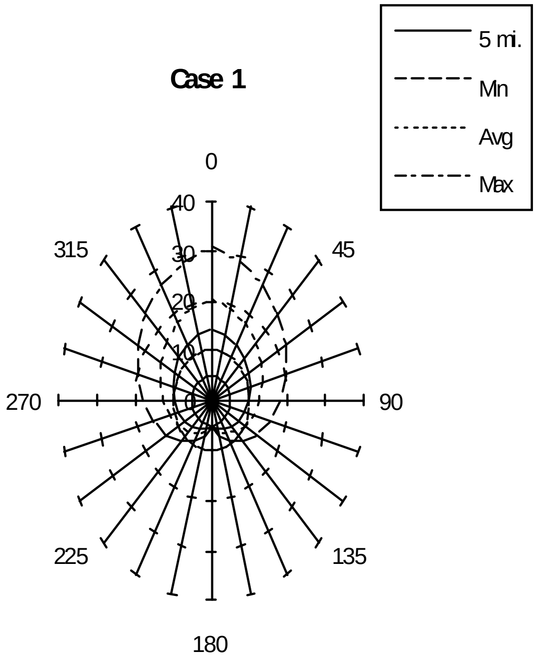

Figure 3: Carotid Shaped Minimum Average and Maximum Response Distances as a Function of Encounter Geometry.

Calculations were made with both aircraft maintaining a speed of mach .82. For each 15 degree angle around the aircraft, the resulting closing speed was calculated. Combining that speed and the performance distribution of each scenario resulted in a distance traveled for that angle. When plotted, these points create a heart shaped rosette shown an example of which is provided in Figure 3.

2.4.2 Air Traffic Control

I will report the results of recent study undertaken at the Embry Riddle University [1]. In this research, fully qualified transition sector controllers managed traffic in their home sector (Ocala Sector) in series of experiments that moved from current operations, to direct routing (user preference), to a condition in which twenty percent of the aircraft are self-separating, and finally the condition in which eighty percent of the aircraft are self-separating. The controllers were instructed that they were responsible for safe operation of the airspace, but that they could grant the authority of separation to the flight crew of equipped aircraft. They received the aircraft as self-separating into the sector in the proportions noted above. They were instructed to allow the continued self-separation except when they made a judgment that allowing self-separation violated certain conditions. These criteria were if the controller felt there was a potential threat to safety; if they anticipated that their workload was going to increase unacceptably; or if special use airspace was going to be violated. The controllers reported subjective workload during the experiment and in a post-experiment questionnaire. The subjective estimates of workload associated with each condition are: Condition 1: Standard Control, Condition 2: direct routing, Condition 3: 20 % self-separation, Condition 4: 80 % self-separation.

Ostensibly, the controller is being given less to do as we move from full active control to 80 % free flight operations with pilots maintaining their own separation from other aircraft. However, they clearly and consistently report mode workload associated with conflict detection and resolution.

It appears the data are consistent with a model of control provided by Hollnagel (1993). He has developed a model in which the context of the control is considered to be a determinant of the type of control that can be effected. In this view, the inherent human information processing components of cognitive and perceptuo-motor activity are modified by the context in which those activities are taking

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[1] The study conducted at the Embry Riddle Aeronautical University was supported by a grant from the NASA Advanced Air Transportation Technology project to the National Aviation Research Institute (Fleming, 1999).

Figure 4: Subjective workload associated with conflict detection and resolution under conditions of active control.

place. The types of control that have been postulated by Hollnagel are:

- Scrambled Control: In which the choice of the next action is unpredictable or random. The operator seemingly does not have any internal model of the world in which they are taking action. This is an extreme case. The process may occur in a panic situation or where other is no feedback as a result of action or no selection of a goals available.
- Opportunistic Control: Control corresponds to the case where action is taken based on the current context. The current context in these terms is perceptually salient features or patterns as opposed to more fundamental constructs such as intentions or goals.
- Tactical Control: Tactical control is characteristic of situation where operator performance is based on some kind of planning.
- Strategic Control: Strategic control is that condition under which the operator has a sufficiently accurate model of the controlled process and the environment in which that control is undertaken to support planning and prediction in support of high level goals that can be managed across a system of interruption.

The availability of multiple control modes requires a process of selection among those modes. (Assuming rules of operation allow for selection by the operators.) Two determining factors that have been explored by Hollnagel are the subjectively available time, and determination of the outcome of previous actions under a given control model. (Assuming that feedback is available that can be evaluated in the control mode under which the action was taken.) The process of feedback evaluation differs among control modes as well. Feedback under a scrambled control mode is may be fairly rudimentary in the observation of an effect in a desired direction. Feedback evaluation in a strategic mode may be fairly extensive. The relative impact of a given control action can be evaluated against current contexts and with reference to prior contexts and other control modes.

In the study cited above, there were other additional factors influencing the control mode selection. The selection of control modes was subject to external manipulation, i.e., and rules of operation. The use of self-separation operation, such as those imposed in this study can determine the number of simultaneous goals that are being, or can be, simultaneously maintained. Managing multiple goals implies that multiple parallel operations are being serviced by multiple streams of behavior either actually being undertaken by the operator, or being undertaken by agents under the control agent's influence. A large number of simultaneously active plans suggest the requirement of a control mode that has some future projection, i.e., and event horizon beyond immediate reactive operation. The process of self-separation, as currently implemented, did not provide future or aircraft "intent" information to the controller. In that mode, the amount of past or future information that can be taken into account by the controller is minimal.

The conclusion we reach is that under the conditions of this experiment, we have moved the controller from a situation in which they have strategic management and information (full positive control), to one in which they are fundamentally reactive, or opportunistic. However, the operational concept imposed still maintained a requirement that they make decisions based on a strategic management paradigm. Most controllers reported that this type of control was unacceptably difficult. In fact, reporting almost twice the workload in the 80% free flight paradigm as compared with the same scenarios under full positive control.

3.0 CONCLUSION AND DISCUSSION

The studies discussed provide evidence that the transition to free flight operations is likely to require the provision of additional information to the controllers and flight decks in order to support their tasks. However, the provision of information must be undertaken with an analytic capability to predict the consequences, both those anticipated (e.g., shared information supporting shared information awareness) and the unanticipated, (e.g., timing interaction in predictive alerting systems and human adaptation in the management of their control contexts to suite the available information.

As the potential for mixing control strategies (hence a mixing control contexts) is explored, predictive computational models that are sensitive to the contribution of context need to be developed and validated. In this development the model provides for the dual impact of action and communication. The primary effect is a change in the simulation world, the secondary effect is the establishment of internal expectations on the part of the actor that a reciprocal and propagated action may take place as a result of their initial action, e.g., an expectation of response from the initiation of a request for information.

Human performance models of sufficient complexity to predict human interaction with automation in complex and dynamic operations have a number of shortfalls in the state-of-knowledge relative to their development and application. System performance modeling (in which the operators and the system function are modeling in the same formalism and support allocation of function) leads to issues as follows:

- When system goals are accessed and the human performance is characterized relative to that system at a given point in time, or over a time, explanatory or normative system models are developed in which data or phenomena are observed and structure or process is asserted to produce such behavior. The model-basis is ad hoc and data driven. Various researchers would maintain that this kind of model development is in fact what is called for (Moray, 1998).
- Analytic models assert a required performance for system operation. They then assert a method or structure/process for its achievement and then test model outcomes against data ranges of system operation. These model development techniques tend to produce specific models that adequately represent a specific task with a specific formulation and may have a very highly predictive accurate performance profile (e.g. OCM and other manual models). However, attempts to cover a broader range of behaviors (e.g. decision making (Govindaraj et al. 1985)) find the accuracy diminished as the characteristics of the behavior moves away from the fundamental assumptions of the model.

We have attempted to capture the accuracy and avoid the pitfalls in the processes discussed above by establishing a framework wherein models based on multiple architectural assumptions can be established and interact with other models of hybrid formulation. The hybrid and linked framework also supports emergent behaviors from the interaction of the individual models in the framework.. Properly interpreted the emergent behavior provides potential for generation of unanticipated (n+1) event behaviors, useful in studies of the propagated effect of error.

It is an interesting irony that the utility of human performance models (in terms of effective cost-efficient methods to support system design) is derived form the complexity of the simulation required. However, the complexity of the required simulation may stress the current generation of human performance representations to such an extent that we must evolve a new paradigm for human performance and cognitive engineering modeling.

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