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A PREDICTIVE MODEL OF FLIGHT CREW PERFORMANCE IN AUTOMATED AIR TRAFFIC CONTROL AND FLIGHT MANAGEMENT OPERATIONS*

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ABSTRACT

This paper describes Air-MIDAS, a model of pilot performance in interaction with varied levels of automation in flight management operations. The model was used to predict the performance of a two person flight crew responding to clearance information generated by the Center TRACON Automation System (CTAS). The model represents the information requirements, decision processes, communication processes, and motor performance required by the flight crew to integrate flight management automation and ground-side automation in clearance aiding. Stochastic variations in environment and flight crew interruption were entered into the model, which then generated predictions of flight crew decision-making and clearance enactment strategies. The model's predictions were then compared to full-mission LOFT-type simulation data in which CTAS clearances were systematically varied in performance requirements and timing at top-of-descent. The paper describes the model, its development and implementation, the simulation test of the model predictions, and the empirical validation process. The complex human performance model allows variations in CTAS design to be explored through predictive simulation. Procedures and performance criteria as well as situational variations can be controlled and tested. The model and its supporting data provide a generalizable tool that is being expanded to include air/ground compatibility and ATC crew interactions in air traffic management.

INTRODUCTION

In order to provide safer, faster, and more fuel efficient routing and operations in the terminal area, NASA and the FAA have undertaken a number of technology development efforts designed to effectively exploit advances in flight management system operation and automation developments in ATC aiding. The Advanced Air Traffic Technologies Initiative (AATT) and the Terminal Area Productivity (TAP) program have explicit research elements focused on the effective integration of flight deck, flight crew, ATC and ATC-aiding systems. This integration should produce optimized routing, sequencing, and scheduling in the terminal area while relaxing constraints in enroute environments to accommodate user-preferred routing and schedules. These goals are to be met by a shift in the character of operations in the National Airspace System and by closer links between flight and airspace control.

In order to explore the procedural implications of this change and to keep pace with the technological developments needed to support these goals, we have modified and applied a human performance analysis tool to provide a predictive flight crew performance model. The model focuses on the procedural integration of ATC automation with the flight management system (FMS) to carry out the required clearance operations.

The current paper describes the development and implementation of this model. The results from two computer simulation experiments that utilized this model are then presented. The first explored an optimal range of time for the issuance of a CTAS descent clearance. The goal was to identify a time prior to top of descent (TOD) when an aircrew would be likely to accept the clearance and enact it using flight deck automation. The second experiment was performed to evaluate the model's predictions against observed human performance. A single output dimension was chosen and evaluated to determine if it would predict the output of actual flight crews.

HUMAN PERFORMANCE MODEL

We have adapted the Man Machine Integration Design and Analysis System's (MIDAS) representation of a human operator to this top of descent clearance scenario (Corker & Smith, 1993). The MIDAS framework provides a collection of models that describe (within the limits of the accuracy of the constituent models) the responses that can be expected of human operators in several areas that are critical to safe and reliable operation of advanced aircraft systems. To provide a relatively complete and useful representation of the human operator in these systems, it is necessary to account for three aspects of the operator's behavior: perceptual processes, cognitive processes, and response processes. Each of the human operators modeled by MIDAS contains models and knowledge-base structures, the interaction of which will produce a stream of simulated operator activities in response to mission requirements, equipment design, and models of human performance capabilities and limits. Figure 1 illustrates the components of the full MIDAS model. Due to the modular nature of the MIDAS framework not all of the modules depicted need be active in any particular application. The model elements highlighted in the figure are the models that were used in this scenario and they are described in some further detail below. We refer to this application of MIDAS to the commercial aviation domain as Air-MIDAS.

Updatable World Representation (UWR): In MIDAS, the Symbolic Operator Model, or SOM, provides a mechanism whereby human agents representing individual and potentially cooperating teams of pilots and controllers access their own tailored or personalized information about the world. This internal representation of world knowledge is called an UWR (Updatable World Representation). The contents of an UWR are determined, first, by pre-simulation loading of required mission, procedural, and equipment information. Then data are updated into each operator’s UWR as a function of the perceptual mechanisms modeled in the operator. The data in each operator’s UWR are used to instantiate rules that guide behavior and are the sole basis for a given operator's activity.

Activity Representation: Activities are MIDAS constructs that simulate actions performable by an agent in the system. Representations of activities available to an operator are contained in that operator’s UWR and are organized by flight-system and mission goals. Activities in this scenario are characterized by: *preconditions* that define the allowable conditions for their initiation; *satisfaction conditions* which define their successful completion; *spawning specifications* which detail the temporal and logical constraints on any “child activities” that might be needed for activity performance (child activities of the activity enter-descent-clearance might include: enter-FMS-speed-constraints, enter-FMS-bottom-of-descent-limit, enter-MCP-bottom-of-descent-limit); *decomposition methods* that describe in a context-sensitive way what children should be spawned to accomplish a higher-level activity’s goals; *interruption status and interruption specifications* which detail the interruption and resumption methods for that activity; and *duration* either estimated or calculated by an activity-specific function. These activities are the drivers for simulation action and are recorded as a function of simulation runs.

Decision Rules: The rules that the simulated flight crew apply to a decision for action at any point in the flight are a specialized form of activities. Decision activities include an added element of contingent behavior represented in a propositional structure. The data to decide the proposition are found in the UWR of the flight crew member or are sought by perceptual interrogation of the external simulation world. If conditions are appropriate, a rule may spawn activities in response to changes in the simulation world.

SIMULATION AND EXPERIMENTS

Experiment 1: Exploring an Optimum Time Range for Issuing a CTAS Descent Clearance.

Method

The MIDAS simulation architecture and editing tools were used to develop a model of the top of descent environment. The challenge was to explore an optimal range of time for the issuance of a CTAS descent clearance so that the aircrew would be likely to accept the clearance and enact it using flight deck automation (as opposed to manually commanding the descent). CTAS calculations tend to favor a late issuance (close to the TOD); while the flight crew tends to favor clearance information as early as possible to aid them in planning and configuring the aircraft. A full range of communication (Voice and Datalink) and automation implementation modalities (Autoload, CDU (Control Display Unit), and MCP (Mode Control Processor)) were modeled (Corker, Lozito, & Pisanich, 1995).

The basic simulation driver in MIDAS is time, using an increment length of 100 milliseconds. All simulation events (e.g., time of clearance issuance, interruptive activities, traffic events, and communication interrupts) were generated using probability distributions tailored to represent the stochastic models developed. These distributions were generated using expert opinion and human performance data from a prior full-mission flight simulation study, referred to as the Air/Ground Compatibility experiment (Corker et. al., 1995).

The Air/Ground Compatibility experiment was performed using the 757-class Advanced Concepts Flight Simulator (ACFS) located within the Crew-Vehicle Simulation Research Facility (CVSRF) at NASA Ames. Data used from this study involved the TOD portions from five CTAS flights, under both voice and datalink communication conditions. The human performance data used for model development were generated from analysis of the video recordings of flight crews in this manned simulation. These data were verified and resolved through computer output data of each flight in the experiment.

Activities: A sequential activity set was developed to describe the aircrew tasks associated with servicing the top of descent CTAS clearance. In the case of a nominal clearance those activities are to be performed as follows: Receive CTAS clearance from ATC; Determine if time is available to decide on the clearance; Determine whether the descent can safely be initiated; Communicate intent to accept or reject the clearance to ATC; Determine automation level for the descent procedure; Implement descent procedure.

Using this structure as a framework, the associated leaf-level activities, decision rules, and information requirements were investigated for each communication/automation combination. Leaf-level activities such as crew equipment accesses, data input, and monitoring tasks were defined and populated using video review and line pilot input. These were encoded using the MIDAS activity description language. Special attention was applied to differences in activities due to the automation and communication requirements. The completion times of these activities were represented as stochastic distributions of the performance exhibited by actual crews in the simulation experiment.

Interrupts are a second class of activities represented within the simulation which do not contribute directly to the completion of the clearance task (such as responding to traffic calls). These activities can suspend the current clearance activity, delaying its completion while the interrupt is serviced. The following interrupt activities were represented: TCAS traffic advisory (TA); Visual traffic call by crew; ATC messages to other aircraft; ATC message to own aircraft; ACARS message; Request to repeat message by crew member; Cabin crew request. An interrupt resumption method is assigned to all leaf level activities. If interrupted, activities can be defined to resume in a variety of ways, based on the behavior observed in the man in the loop simulation.

Decision Rules: The rulesets used to make decisions at top of descent were developed using expert opinion. These rulesets define decisions based on time available, safe descent, and automation usage. A pilot's "ruleset" was developed for each of these decision types, along with the data and ranges upon which they depended. For example, the rules associated with a safe descent involve weather, equipment-limitations, and passenger comfort considerations. The UWR data that the weather specific rules consult include: reported icing, high cloud tops (visible convection) ahead, and reported turbulence.

The rules were represented using a decide by algorithm (DBA) notation. Adapted from work by Payne, Bettman and Johnson (1988), the DBA allows the time required to make a decision to be estimated, depending on the strategy and the number of attributes considered. Elimination by aspects was the decision strategy applied in this model.

Updatable World Representation: An UWR structure was developed to represent the information that the aircrew understands about the top of descent world. This includes data that are known prior to beginning the clearance and information that is updated during the course of the scenario as perceived or determined by the aircrew. Categories of UWR information include the aircraft state and configuration, meteorology, descent information, traffic, and pilot operational knowledge.

<u>Model Runs</u>

A 3 X 2 X 5 full factorial experiment was run with 100 replicates for each factor-level combination. The factors manipulated were: automation implementation mode (autoload, CDU, and MCP), communications mode (datalink and voice) and time provided to implement the clearance (five times corresponding to increasing distances from the top of descent). The weather, altitude, and calculated descent rate were allowed to vary within a reasonable range. Whether or not the flight crew was successful in completing the clearance within the time given, and the automation mode ultimately used in that process, were the dependent variables in this experiment.

<u>Analysis</u>

In examining a portion of the data output from the MIDAS model (Figure 2) we see that as the TOD point is approached the aircrew model tends to select a flight mode that involves less automation (MCP operations). Further, the time (distance) from TOD that the crew selects that less automated operation is sensitive to the medium through which the clearance is presented; voice presentation of the data provides a more pronounced use of nonautomated modes. This mode switch interaction with medium of exchange is also reflected in the human performance data provided.

A comparison of the model output behavior with that of the video taped crews indicates that the model “behaves” in a way that is consistent with observed human crew operation in the mode selection process. The model also confirms the hypothesis that as the TOD point is closer the aircrew will select the less automated alternative mode of control. Finally, as the aircraft approaches within 5 to 8 miles from the CTAS required TOD point, the number of successes in any clearance compliance is reduced significantly.

Experiment 2: Evaluating Model Predictions .vs. Human Performance

Method

A follow-on experiment was performed to evaluate the predictive nature of the model. The basic activity framework and conditions developed for the first experiment were also used for the second. Human performance data (activity durations, interrupt durations and frequencies) were gathered from video and computer analysis of a recent man in the loop study, referred to as the CTAS/DA experiment (Corker & Pisanich, in press).

The CTAS/DA study was performed in a full mission simulator (Boeing 747-400), also at the NASA Ames CVSRF. In the CTAS/DA study, four two-pilot crews participated with each of the pilots making two approaches and one landing in the experiment. The result was four runs per flight crew across the experimental manipulations and sixteen runs for the human pilots overall. Important to the model being developed was that the distance before the TOD at which the clearance was provided was varied between 15 and 20 nautical miles prior to TOD. Only the flights that utilized FMS automation were used in the model evaluation process.

In order to compare the performance of the predictive model of flight crew behavior with that of the human flight crew, the model was initialized with the same information as the human flight crew. The model flight crew was then directed to fly descent profiles with the same conditions of speed, crossing restriction, and distance to top of descent as experienced by the human flight crews. A split-halves method was used in which the model’s activity times (e.g. FMS operation and “button-push” time) were derived from one half of the human performance data and the model was tested to see if it could predict the behavior of the remaining half of the human performance data.

The model uses a stochastic element of interruption in communication to replicate communication with ATC. The interruption data were also generated using the split halves method so that the frequency and length of interruption that the model provides are based on a reasonable set of actual ATC operations. The model invokes a contingent decision activity in which it considers, through its rules, whether or not a clearance is acceptable and when and how to enact it using the variety of methods within its activity set.

Model Runs

The model was run eight times to match the number of human performance runs used in the split-halves method, and its variability was tested by performing four sets of eight runs. The model generated activity data comparable to that generated by the human operators. For example, data collected for the human flight crew included time to complete access and to enter the clearance, time to receive the clearance, time to decide on clearance acceptability, ATC communication times, and FMS operation times. The model similarly generated activity times for that sequence of behaviors that can be used in direct comparison. It should be noted that at the present time the model represents the activity of one crew member performing an amalgam of the pilot-flying and pilot-not-flying duties.

The hypothesis tested in this study was that the model performance across the manipulations of CTAS would not be significantly different from that of the flight crew in the same performance regimen. There are multiple measures available to test flight crew versus model performance. We compared model performance in the critical flight phase of receiving the CTAS TOD clearance, deciding whether and how to enact it and preparing the aircraft systems for the required TOD. The variable reported was the time remaining between the aircraft being fully configured for descent and the TOD point. This is a measure of the “spare time” the crew has between receiving and enacting a clearance and its required time of completion, i. e., the TOD point. This measure is applied across the conditions of the experiment for comparison of model and human behavior.

Analysis

Three comparisons were made and *t* tests were applied. First a comparison was made between the behavior of the model across the experimental conditions and the performance of the flight crew across those conditions (split-halves comparison). Second a comparison was made between the one model run and cumulative data from the four simulation model runs to check for internal consistency in the model (cumulative model data versus single run). Finally, the accumulated human data were compared to a single model run, chosen at random, to see if there was an effect on the model variance encountered by summing across model runs (flight crews versus simulation run.) In all cases the *t* test (df = 14) revealed no significant differences between the data sets compared. The comparisons are presented in Table 1.

	t	p (T<t) two-tailed
split-halves	1.286	0.23
cum. model /single run	1.088	0.29
flight crew /single run	1.017	0.33

Table 1. Three comparisons of model vs. human performance data.

The data suggest that the model performance is predictive of the flight crew performance across the conditions of this experiment. The lack of significant difference between the model and the cumulative human performance and the check for internal consistency in this model are encouraging to our effort. The simulation model produced a stream of activity that included decision and interaction with varied levels of flight management automation. In the time-stressed operation at TOD, the model behavior is predictive of the flight crew's behavior in terms of the time taken to meet an ATC profile descent clearance.

CONCLUSION

An effort to produce a model that predicts human flight crew behavior was undertaken. The goal was to provide an analytic tool to answer questions about human/automation interaction in advanced airspace management. Preliminary results indicate that the MIDAS model structure serves the purpose of this analysis. The initial success with limited parameters suggests that the model parameters be further manipulated and the model coverage be expanded to other flight phases.

A split-half reliability experiment was performed to evaluate the predictive nature of the model. The results indicate that this model of human behavior in its coarse level of predictability provides a tool for efficient and effective examination of these issues. Verification of the model's micro-behavior accuracy is required before the model-based analysis can be considered as a fully credible design-analysis tool.

Research into emerging TAP and AATT concepts such as CTAS-FMS integration, free-flight, and Air Traffic Management (ATM) will require a deeper understanding of how changes in automation, communication, operator roles, and procedures will impact the combined flight deck and air traffic control environment. Further enhancements to the simulation and model are underway to support these and other investigations.

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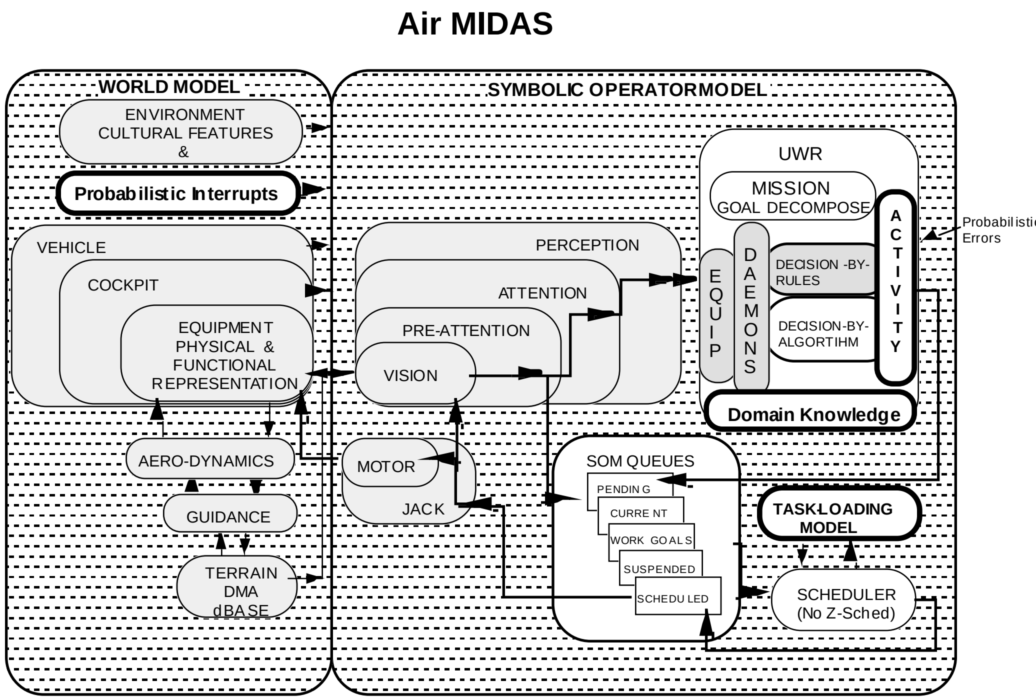

Figure 1. Full MIDAS closed loop model with all modules represented. Modules active in this simulation are shown in white.

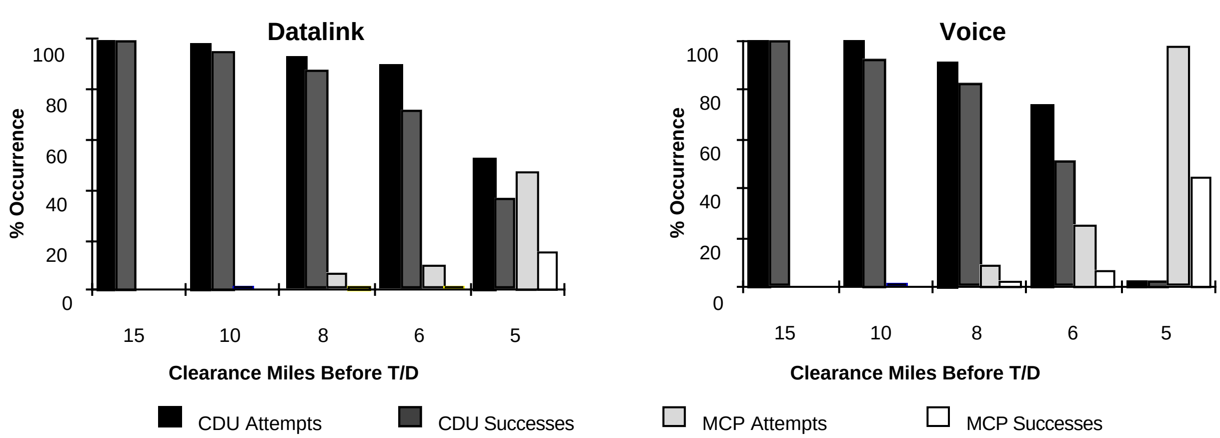

Figure 2. The effect of communication medium on automation selection and success rate.