THE MIDAS HUMAN PERFORMANCE MODEL

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A unique software tool for conducting human factors analyses of complex human-machine systems has been developed at NASA Ames Research Center. Called the Man-Machine Integration Design and Analysis System (MIDAS), this simulation system contains models of human performance that can be used to evaluate candidate procedures, controls, and displays prior to more expensive and time consuming hardware simulators and human subject experiments. While this tool has been successfully applied to research issues in several domains, particularly in aeronautics, a desire to expand its functionality and its ease of use has led to the construction of a new object-oriented system. This new version of MIDAS contains a substantially modified human performance model, one that is aimed at being more consistent with empirical data on human behavior and more natural for designers to apply to the analyses of complex new designs. This paper offers a summary of this new human performance model, together with justifications for some of its main components, and indicates plans for its subsequent verification and validation.

INTRODUCTION

For over ten years, the US Army, NASA, and Sterling Software have been involved in the development of a human factors tool to aid in the design and analysis of complex human-machine systems, such as aircraft cockpits. Called the Man-machine Integration Design and Analysis System, or MIDAS, the tool allows users to perform human factors analyses of new designs at an early stage, prior to the use of hardware simulators or even human-in-the-loop experiments. It does this through the use of a sophisticated human performance model that provides predictions of how expert operators, such as skilled pilots, would act in a typical mission within such a design (see Smith and Tyler, 1997, for an overview and A3I Report for further details).

While this tool has been successfully applied to research issues in a number of different domains - rotorcraft (Atencio, Shively, and Shankar, 1996), fixed-wing aircraft (Corker and Smith, 1993; Corker and Pisanich, 1995), nuclear power plant control rooms (Hoecker, Roth, Corker, Lipner, and Bunzo, 1994), emergency operations (911) consoles) - several factors drove the research team to undertake a major effort to rearchitect MIDAS. The general goals driving this redesign included: expanding the functionality of the system, especially in its modeling of human behavior; decreasing development time for new scenarios (from several months to one or two weeks); and increasing the efficiency of the running system (from around 50 times real-time to near real-time). For these reasons, a research phase was undertaken with the goal of redesigning MIDAS using object-oriented rapid prototyping techniques and implementing the system entirely in C++. Further significant improvements were planned for the human-computer interface of the system, as well as adding an explicit analysis environment for examining simulation results. The focus of this paper is detailing the human performance model of the new system.

Adequately modeling, in a closed loop fashion, skilled human behavior in order to predict performance in interacting with complex systems is a daunting challenge. However, if done successfully, such a model can offer substantial benefits to the human factors specialist, permitting early assessments of novel designs without the time and expense of building hardware simulators or conducting experiments with often scarce, skilled human subjects. Such a model also permits trying a wider range of ideas in order to increase the probability of creating a new system with fewer design flaws. Earlier papers presented the human performance model of the preceding version of MIDAS (Corker and Smith, 1993). This paper offers a new and enhanced model that can even better aid in human factors assessments. In particular, the new model encompasses more complete notions of attention and working memory, a more elaborate vision model to support a new situation awareness construct, a different technique for capturing skilled procedures, as well as support for representing multiple human operators and their interactions. This paper will review the major elements of this new human performance model and thereby

indicate its improved features as a human factors support tool.

TOP-LEVEL DESIGN ELEMENTS

Initial design efforts produced a high-level system architecture, with the following elements: a domain model supporting components necessary for running a simulation; a graphics system to enable simulation visualization; an interface for end user specification of the target domain models; a simulation system for controlling the simulation and collecting data; and a results analysis system for examining simulation data after it has been collected.

The domain model is centered on a crew station, with the following models: the environment encompassing the crewstation; the vehicle containing the crewstation; the crewstation itself, particularly its contained equipment; and the crew, meaning the human operators together with their assigned missions and procedures. Figure 1 depicts these domain elements in object-oriented (Booch) notation.
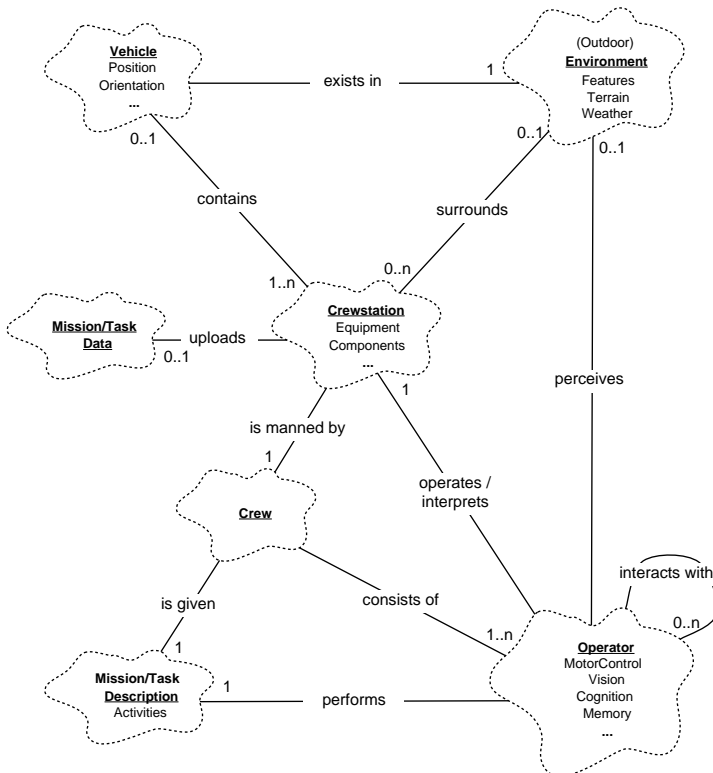

Figure 1. Domain Model Objects and Relationships

MIDAS HUMAN OPERATOR MODEL

In the redesign, the modeled human operator is both expanded in functionality and aligned more closely to typical information processing models of human cognition and perception. The model includes an anthropometric component, capturing physical aspects of human behavior, and used primarily for

visualizing the human operator's behavior during a simulation. The previous MIDAS anthropometric component was Jack® (Badler, Phillips and Webber, 1993). In the new design, a simple representation of the operator's hands and head was used, although this will later be replaced by a more complete model.

The processing architecture of the human operator model has input, memory and central cognition, output, and attentional components (see Figure 2). Operator input is received from the environment through the senses and then perceptually interpreted. The design includes visual, auditory, and proprioceptive input (previously, only visual input was modeled).
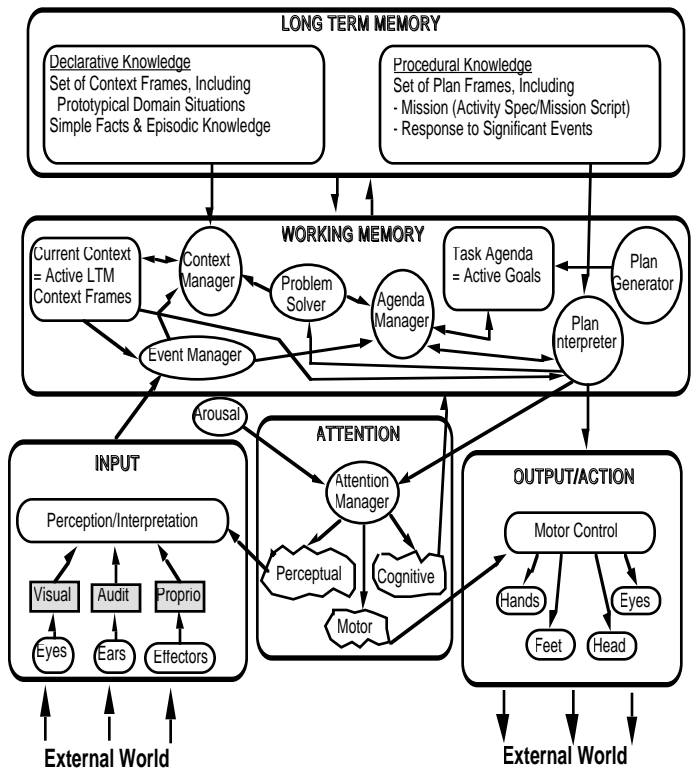

Figure 2. New MIDAS Operator Architecture

Visual Processing

The operator obtains visual information about his surroundings via an intermediate, the visual scene, which contains all potentially visible objects. An operator that participates in a scenario queries the visual scene and gets returned a visual field, containing the objects in view and the ambient conditions in the surrounding environment. The visual objects may have a geometric representation that allows visualization during a simulation, but no image processing is performed. Instead, the operator perceives the object through their symbolic representation, that is, the attributes that are attached to the objects.

The vision model differentiates between peripheral and foveal vision, which typically enclose angles of 160 and 2.5 degrees, respectively. The purpose of peripheral vision is the capturing of salient, non-foveal visual events, for example, a flashing warning light or a fast moving exterior object. During a simulation, such events could either be triggered by a certain condition or be initiated at a prescribed time (timed event). When perception detects a visual event, it informs the central executive. The usual response is a fixation on the object that caused the event but under high workload, an event with a low priority could get lost. A user of MIDAS declares potential events as part of the scenario. Foveal vision is used exclusively for fixating on a specific object and involves focusing the operator's attention on a single target.

MIDAS conceptually differentiates interior (within the crewstation) and exterior (outside the crewstation) vision. For interior vision, the operator is assumed to have a mental representation of the equipment he interacts with including its location and function. Therefore, he does not have to go through the process of identifying the piece of equipment before he can take a reading from it or operate it. In contrast, an operator must recognize or identify an exterior object before he can reason about it.

Interior vision is mainly concerned with reading states, values, and messages off instruments, which usually involves a single attribute. The time for getting an instrument reading is dependent on the type of attribute, which can be symbolic (analog clock), digital (digital display) or text (message on screen). Instrument readings are forwarded to the central executive in two stages: approximate and exact. The stage of reading depends on how long the object is foveated and is indicated by an additional attribute.

Perception of exterior vision takes place in three stages: detection, recognition and identification. This perception level is dependent on two factors: 1) the dwell time and 2) the "perceivability" of the object. The perceivability of an object is dependent on a number of factors, including visibility, size and distance of object, object to background contrast ratio, and lighting. For each object that falls in the view of the operator, the perceivability factor is computed. This factor indicates the probability of an object being detected, recognized or identified if the object is foveated for the requisite time. At each stage, only the attributes pertaining to that stage are made available to the central executive. This allows the central executive to change fixation when enough information about an object has been obtained.

Auditory Processing

Analogous to vision, auditory input occurs through the intermediary object called the Auditory Scene, containing all signals and messages emitted by the crewstation equipment and operators. The requirements for MIDAS do not call for auditory perception exterior to the crewstation but operators in different crewstations may communicate with each other if they are connected to auditory equipment. The user can define such connections during the simulation setup. Auditory signals and speech messages are first perceived through pre-perception. The central executive is informed that an auditory source is emitting at a certain location and it responds by creating a listening task, after securing the necessary attentional resources.

An auditory signal is perceived in two stages, detection and comprehension, and is dependent on the perceivability of the emitted signal as well as the time the operator spends attending to it. At the detection stage, the location of the source is passed to the central executive, and at the comprehension stage, the remaining attributes are revealed. A verbal message consists of the message string and a number of attribute-value pairs that are used to represent the content of the message in the operator's memory. Currently, the model does not allow comprehension of partial messages, so if a listening task is interrupted, the entire content will be lost.

Central Processing and Memory

Memory now consists of long-term and working memory components. The long-term memory contains both declarative and procedural knowledge. Declarative knowledge includes facts the human operator may know (e.g., current vehicle location), as well as context frames capturing typical situations an operator might encounter in the target domain (e.g., processing a pre-flight checklist, flying through turbulence). Procedural knowledge is represented as Reactive Action Packages or RAPs, after the work in robotic planning by Firby (1989). RAPS describe how to accomplish a given goal and consist of the methods possible for achieving that goal, when each is most appropriate (according to the current context), and how it is known that the goal is satisfied. RAP methods can be either further subgoals, decisions which require reasoning, or motor primitives which can be directly executed by the motor output processes (see Figure 3). In earlier versions of MIDAS, human activities had to be specified completely for the entire scenario down to the activity primitive level. The reason for changing to the RAPs approach was to allow users to work with more abstract activities in describing human operator behavior and to allow more emergent behavior from a simulation, driven by context changes during the scenario.

The other, active portion of memory, working memory, has two main contents. One captures the current context (retrieved from long-term memory and instantiated from sensory input) and the other, the

task agenda, indicates the currently active goals. The types of central processing that occur related to the working memory contents include the following: 1) event management - new inputs are assessed to determine whether they were expected or not; if so, they are simply used to update the current context; if not, they generally trigger the creation of new goals to handle an unexpected event; 2) agenda management: the goals on the task agenda are examined, based upon priority and the current situation, to determine which one to focus on next; 3) plan execution - once a goal is selected, it is used to retrieve the appropriate RAP from long-term memory, and this is in turn executed by selecting and "unpacking" the best method on the basis of the current context. This is done as follows: if the selected method consists of further goals, these are simply added to the task agenda; if they are primitive actions, these are generally passed on to the motor component for execution; if they are cognitive activities (such as computing a result), they are passed back to central processing.

```
(RAP
 (index (activate-camera))
 (succeed (or (and (brightness window light)
                   (state visible-light-camera-button pushed))
              (and (brightness window dark)
                   (state infra-red-camera-button pushed))))
 (method1
  (context (brightness window light))
  (task-net
   (t1 (fixate-on object visible-light-camera-button) (for t2))
   (t2 (move-effector-to LeftIndexFinger
        visible-light-camera-button) (for t3))
   (t3 (push-button visible-light-camera-button
        LeftIndexFinger))))
 (method2
  (context (brightness window dark))
  (task-net
   (t1 (fixate-on object infra-red-camera-button) (for t2))
   (t2 (move-effector-to RightIndexFinger
        infra-red-camera-button) (for t3))
   (t3 (push-button infra-red-camera-button
        RightIndexFinger))))
```

Figure 3. Example Reactive Action Package (RAP). The pilot is taking reconnaissance pictures - if it is light outside, the normal camera is activated; otherwise, the infra-red camera is used.

Effectors/Output Behavior

Output behavior is regulated by the motor control process. If required resources are available, a motor activity is created and processed, with both the operator's physical actions and their effects on equipment and/or environment objects modeled. Activities such as manipulating equipment, fixating on

an object, or making a speech utterance are all supported as primitive motor outputs. The MIDAS user is presented with a palette of 35 primitive operator tasks (Table 1) for defining a simulation scenario, consisting of 8 visual (v) and auditory (a) tasks, 5 cognitive (c) tasks, and 22 motor tasks. Each task has load values defined on 6 distinct channels (see below) derived from the TAWL data (Task Analysis/ Workload (TAWL), Hamilton, Bierbaum, & Fulford, 1990).

fixate-object (v)	visually-monitor (v)
track-object (v)	scan-with-pattern (v)
search-with-pattern (v)	listen (a)
monitor-audio-signal (a)	say-message (a)
recall (c)	recognize (c)
select (c)	compare (c)
compute (c)	walk-to
change-orientation	reach-object
press-with-foot	move-object
move-with-pattern	continuous-adjust
grasp	aim-effector
touch	push-and-release
push-and-hold	pull-and-release
pull-and-hold	release
adjust-rotate	adjust-slide
adjust-drag	adjust-track
write	type
touch-type	

Table 1

Attention

The attention model, which is based on multiple resource theory (Wickens, 1984), acts as a central resource and maintains an account of attentional resources in six different channels. Two channels pertain to encoding (visual and auditory input), two to cognitive central processing (spatial and verbal) and the remaining two to responding (manual and voice output). Before the central executive dispatches a primitive task, it is required to secure the necessary attentional resources from the model. If these are not available to the full extent, the performance of the executing tasks may be degraded, or the ongoing task may have to be interrupted or the new task postponed, depending on relative priorities.

The attention model requires a matrix of resource coefficients to compute the load in each channel of competing tasks. These coefficients were estimated using Multiple Resource Theory as a guide and are described here. Maximum overlap was assumed to occur within the same resource, and so each resource pair (the negative diagonal) received a coefficient of 1.0. Resource pairs within the stages of perception and responding received coefficients of 0.3 representing a moderate degree of overlap. The pair

formed by spatial and verbal cognitive resources was assigned a value of 0.5, representing a greater degree of overlap. Resource pairs presumed to use similar processing code received coefficients of 0.2. All remaining resource pairs were assigned coefficient of zero, representing minimal or negligible interference. The following expression depicts how the load of two competing tasks, t1 and t2, is computed. The workload in a single channel is the additive workload in that channel plus the additional cost of timesharing between multiple channels. The simple additive part results from multiplying the sum with a coefficient of 1.0. The contribution from the other channels comes from adding the products, which result from multiplying those sums with coefficient values of less than 1.0. If both tasks have loads of 0.0 in a channel, then the workload in that channel will be zero.

$$w_j = \sum_{i=1}^{i=6} (a_{t1,\,i} + a_{t2,\,i}) * c_{t1,\,i}$$

$w_j =$　　instantaneous workload of channel j at time T
$i, j =$　　1…6 interface channels
$t1, t2 =$ the operator's task
$a_{t,\,i} =$　load of channel i to perform task t
$t_i =$　　interface channel i associated with task t
$c_{i,j} =$　conflict between channel i and j
where either: $a_{t1,\,i}$ or $a_{t2,\,i}$ is non-zero

Equation 1

Performance is decremented if one or more channels exceed the threshold of 7.0. Currently, the model degrades performance linearly for values in the range of 7.1 and 16.0 for all competing tasks. Loads above 16.0 are not allowed and one of the tasks needs to be postponed. After gaining some experience with the model, it will be enhanced further so that the performance of the secondary task is more negatively impacted than the primary task for high load situations.

DISCUSSION AND FUTURE PLANS

The new MIDAS human performance model is an attempt to capture the major aspects of perceptual, cognitive, and motor behavior in an integrated framework sufficient to predict skilled responses in a complex environment. While this is an ambitious undertaking, some of the components are based on well established empirical studies and others fall into generally accepted information processing approaches. The next planned step for the project is the formation of an independent blue ribbon panel of appropriate human factors experts to conduct a more formal verification and validation of the overall model. Hopefully, the results will point towards the utility of this new human performance model as a powerful tool for the human factors practitioner.

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