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USING DISCRETE-EVENT SIMULATION TO MODEL HUMAN PERFORMANCE IN COMPLEX SYSTEMS

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ABSTRACT

System performance is often determined by the performance of the humans in the system. Yet, system models often leave out any significant representation of the humans that are operating and maintaining them. Recently, tools and methods for modeling the human in systems have begun to receive widespread attention. These tools and methods are consistent with other types of models and simulations that are used to model other system components. In this paper, the basic approaches to modeling human performance are discussed along with a brief case study.

1 INTRODUCTION

Human performance is often a high risk element in the overall operational effectiveness of many types of systems. For example, approximately two thirds of aircraft accidents are now attributed to pilot error. Unfortunately, the traditional design process tends to put a disproportionate focus on the technical performance of equipment, with little regard for the human component. Much of this was because human performance was widely perceived to be difficult to model with the same level of fidelity and predictability as other hardware and software system components. Given the highly variable nature of human performance – we do twice as well on good days as on poor days for many types of tasks – there is some validity to this concern. However, as long as humans remain the center of many systems and a critical component of virtually every system, they must be considered during systems design and engineering.

Over the past few decades, the design engineering and user communities have increasingly recognized this need to consider the human as an elemental component during design and, accordingly, to consider his or her capabilities and limitations. Designers have increasingly been called upon early in the system design and development process. Early input from all disciplines results in better and more integrated designs as well as lower costs than if one or more disciplines finds that changes are required later. Our goal as human factors and ergonomics practitioners should be to provide substantive and well- supported input regarding the human(s), his or her interaction(s) with the system, and the resulting human/system performance. Furthermore, we should be prepared to provide this input from the earliest stages of system concept development and then throughout the entire system or product life cycle.

To meet this challenge, many human factors and ergonomics tools and technologies have evolved over the years to support early analysis and design. Many of these technologies have taken the form of design guidance and user high fidelity rapid interface prototyping. Design guidance technologies, either in the form of handbooks or computerized decision support systems, put selected portions of the human factors and ergonomics knowledge base at the fingertips of the designers. However, this type of guidance will rarely provide good insights into the value of this improved element of the human's performance to the *overall system's* performance. As such, design guidance is less valuable for providing concrete input to *system level performance prediction*.

Rapid prototyping, on the other hand, provides system level analysis of how a specific design and task allocation will affect human and system level performance. The disadvantage of prototyping, as with all human subjects experimentation, is that it is costly. Also, in contrast to user-computer interface prototypes, hardware-based systems, such as aircraft and machinery, are relatively expensive to prototype at the system level, particularly at early design stages when there are many widely divergent design concepts. What is often needed is a methodology to extrapolate from the general knowledge base of human factors and ergonomics, as reflected in design guides and the literature, to make system level performance predictions as a function of human factors design alternatives. This methodology should also bind with rapid prototyping and experimentation in a mutually supportive way. As has become the case in many engineering disciplines, one of these methodologies is computer modeling and simulation.

Computer modeling of human behavior and performance is hardly a new endeavor. Computer models of complex cognitive behavior have been around for over 20 years and tools for computer modeling of task level performance have been available since the 1970s. However, there is an increased focus by the research community on the development of *predictive* models of human performance rather than simply descriptive models. For example, the GOMS model developed at Xerox PARC (Gray, John, and Atwood, 1993) represents the integration of research into a model for making predictions of how humans will perform in a realistic task environment. Another example is that much of the research in cognitive workload has been represented as computer algorithms. These are just two examples of the continued improvements in the knowledge base of first principles of human cognition and performance.

From another perspective, simulation allows the human factors and ergonomics team to "step up to the table" with the other engineering disciplines who also rely increasingly on computer models of the phenomena of interest. What we discuss in this paper is the human factors and ergonomics contribution to computer aided system design.

One technology that has proven useful for predicting human-system performance is a class of discrete-event simulation we refer to as *task network modeling.* In a task network model, human performance of an individual performing a function (e.g., performing a procedure) is decomposed into a series of subfunctions, which are then decomposed into tasks. This is, in human factors engineering terms, the task analysis. The sequence of tasks is defined by constructing a *task network*. This concept is illustrated in Figure 1which presents a sample task network for dialing a telephone.

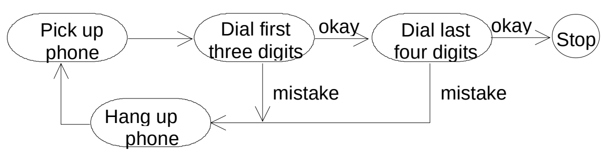

Figure 1: A Task Network for Dialing a Phone

Task network modeling is an approach to modeling human performance in complex systems that has evolved for several reasons. First, it is a reasonable means for extending the staple of the analysis of manned systems – the task and function analysis. Task analyses organized by task sequence are the basis for the task network model. Second, in addition to complex operator models, task network models can interact with sophisticated models of other system hardware and software to create a closed-loop representation of the human/machine system allowing the prediction of system dynamics. Third, task network models can be built into computer simulations using commercial discrete-event simulation packages, so the technology is there to support it. Finally, task network modeling has been demonstrated to provide reasonable input to many types of human/system design issues. With a task network model, the human factors engineer can examine a design (e.g., control panel redesign) and address questions such as "How much longer will it take to perform this procedure?" and "Will there be an increase in the error rate?" or "Will I need to add more people?" Generally, task network models can be developed in less time and with less effort than would be required if a prototype were developed and human subjects used.

2 WHAT GOES INTO A TASK NETWORK MODEL?

To represent complex, dynamic human/system behavior, many aspects of the system may need to be modeled in addition to simply list tasks and sequence. In this subsection, we will use as an example the task network modeling tool *Micro Saint*.

The basic ingredient of a Micro Saint task network model is the task analysis as represented by a network or series of networks. The level of system decomposition (i.e., how finely we decompose the tasks) and the amount of the system which is simulated depends on the particular problem. This basic task network is built in Micro Saint via a point and click drawing palette as shown in Figure 2. .

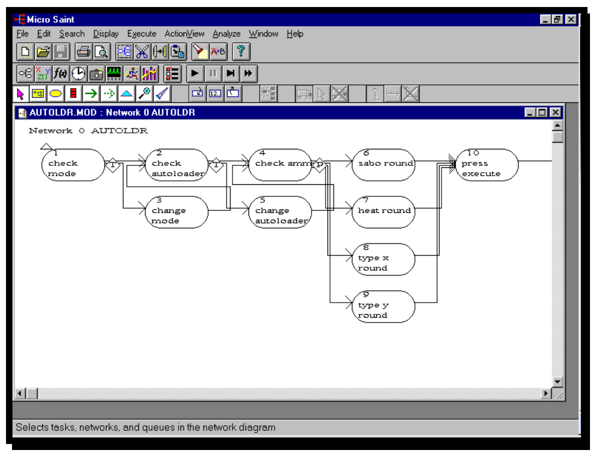

Figure 2: The Main Window in Micro Saint for Task Network Construction and Viewing

To reflect complex task behavior and interrelationships, information such as that shown in Figure 3 must also be provided for each task. Information that can be entered to describe the behavior of the task includes timing information(e.g., means and standard deviations), conditions that must be met for the task to start (e.g., available resources, other system state requirements), and how task performance affects other aspects of the system (e.g., the effects of a task's beginning and ending). Anywhere that a number can be entered, equations, algorithms, and logic of any complexity can also be entered.

Another notable aspect of the Task Network Diagram Window shown in Figure 2 is the diamond-shaped icons that follow some tasks. These are present every time more than one path out of a task is defined. In a task network model, this means that there are several tasks that may commence at the completion of this task. Implicitly, this means that a decision must be made by the human to select which of the following potential courses of action should be followed. To define the decision logic, the user of Micro Saint would double-click on the diamond to open up a window as shown in Figure 4.

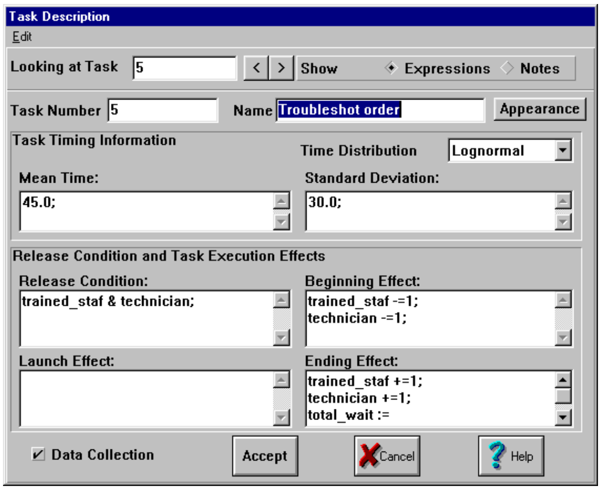

Figure 3: Information that can to be entered on individual tasks

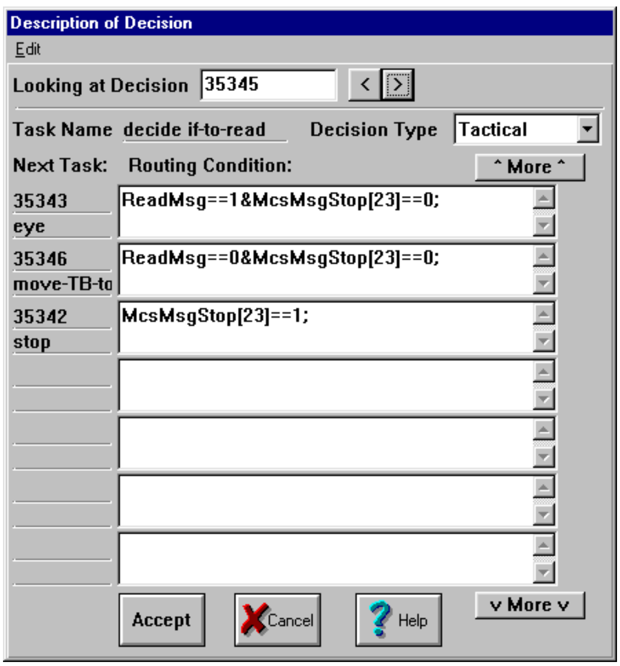

Figure 4: Defining human decision logic

There are other aspects of task network model development including the definition of a simulation scenario, defining continuous processes within the model, defining queues in front of tasks, and several other features. Further details of these features can be obtained from the Micro Saint User's Guide (Micro Analysis and Design, 1999).

3 AN EXAMPLE OF A TASK NETWORK MODEL OF A PROCESS CONTROL OPERATOR

This simple hypothetical example illustrates how many of the basic concepts of task network modeling can be applied to studying human performance in a process control environment. It is intended to practically illustrate some of the concepts described above.

The simple human task that we want to model is of an operator responding to an annunciator. The procedure requires that he or she compare two meter readings. Based on the relative values of these readings, the operator must either open or close a valve until the two meter values are nearly the same. The operator activities for this model are represented by the task network in Figure 5. Also, to allow the study of the effects of different plant dynamics (e.g., control lags), a simple one node model of the line in which the valve is being opened is included in Figure 6.

The operator portion of the model will run the "monitor panels" task until the values of the variables "meter1" and "meter2" are different. The simulation could begin with these values being equal and then precipitate a change in values based on what is referred to as a scenario event (e.g., an event representing the effects of a line-break on plant state). This event could be as simple as:

meter1 = meter1 + 2.0;

or as complex as an expression defining the change in the meter as a function of line break size, flow rates, etc. An issue which consistently arises in model construction is how complex the plant/system model should be. If the problem under study is purely operator performance, simple models will usually suffice. However, if overall plant behavior is of interest, then the models of plant dynamics, such as meter values, are more important. Again, we recommend the “start simple” approach whenever possible.

When the transient occurs and the values of "meter1" and "meter2" start to diverge, the annunciator signal will go on. This annunciator would be triggered in the plant portion of the model by a task ending effect such as:

if meter1 <> meter2 then annunciator = 1;

Once the plant model sets the value of the variable "annunciator" to 1, the operator will begin his or her

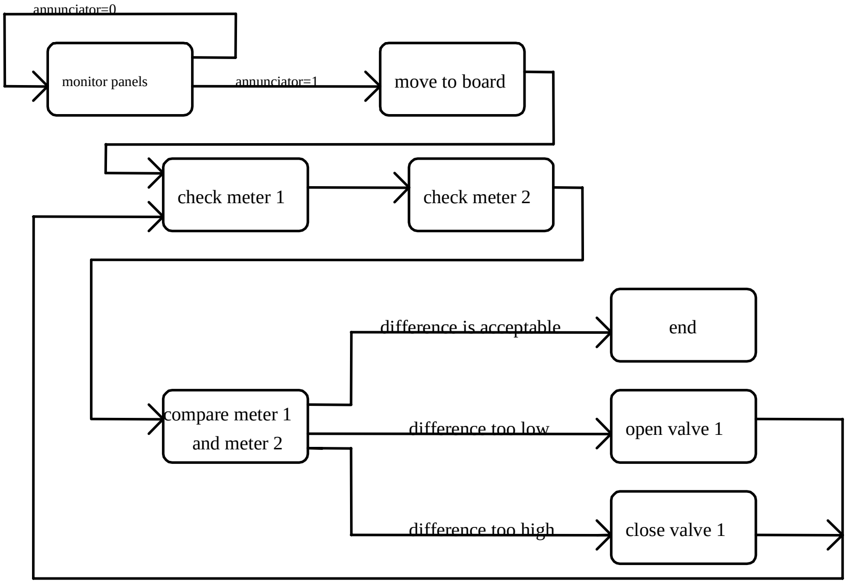

Figure 5: Example of task network for Process Control Operator

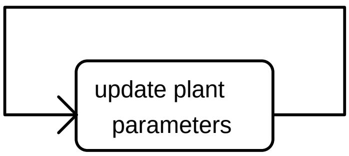

Figure 6: Simple Plant Model

activities by moving to the appropriate board. Then, he will continue through a loop where he checks the values for "meter1" and "meter2" and either opens "valve1," closes "valve1," or makes no change. The determination of whether to make a control input is determined by the difference in values between the two meters. If the value is less than the acceptable threshold, then the operator would open the valve further. If the value is greater than the threshold, then the operator would close the valve. This opening and closing of the valve would be represented by changes in the value of the variable "valve1" as a task ending effect of the tasks "open valve1" and "close valve1." In this simple model, operators do not consider rates of change in values for "meter1" and, therefore, would get into an operator-induced oscillation if there was any response lag. A more sophisticated operator model could use rates of change in the value for "meter1" in deciding whether to open or close valves.

Again, this is a very small model reflecting simple operator activity on one control via a review of two displays. However, it illustrates how large models of operator teams looking at numerous controls and manipulating many displays could be built via the same building blocks used in this model. The central concepts of a task network and shared variable reflecting human/system dynamics remains the same.

Given a task network model of a process control operator in a "current" control room, how might the model be modified to address human centered design questions? Some examples are:

- Modifying task times based on changes in the time required to access a new display
- Modifying task times and accuracies based upon changes in the content and format of displays
- Changing task sequence, eliminating tasks, and/or adding tasks based upon changes in plant procedures
- Changing allocation of tasks and ensuing task sequence based upon reallocation of tasks among operators
- Changing task time and accuracies based upon stressors such as sleep loss or drug effects

The above list is not intended as a definitive list of all the ways that these models may be used to study design or operations concepts, but should illustrate how these models can be used to address design and operational issues.

4 A CASE STUDY – EVALUATING THE NECESSARY SIZE OF A HELICOPTER CREW

In the late 1980s, there was interest in the feasibility of a one-man cockpit for an Army helicopter that had traditionally been manned by two operators. The central design issue was workload - could one individual reasonably be expected to perform all of the tasks required within the available time? Task network modeling was used to study this issue.

The basis of this technique is an assumption that excessive human workload is not usually caused by one particular task required of the operator. Rather, it is the human having to perform several tasks simultaneously that leads to overload. Since the factors that cause this type of workload are intricately linked to these dynamic aspects of the human's task requirements, task network modeling provides a good basis for studying how task allocation and sequencing can affect operator workload.

However, some workload evaluation techniques estimated workload by comparing the time available to perform a group of tasks to the time required to perform the group of tasks. However, it has long been recognized that this simplistic analysis misses many aspects of the human's tasks that influence both perceived workload as well as ensuing performance. At the very least, this approach misses the fact that some pairs of tasks can be performed in combination better than other pairs of tasks.

Based on a review of the literature, Drews, Laughery, Kramme, and Archer (1985) concluded that the most promising theory of operator workload which was consistent with task network modeling was the multiple resource theory proposed by Wickens (e.g., Wickens, Sandry, and Vidulich, 1983). Simply stated, the multiple resource theory suggests that humans have not one information processing resource that can only be tapped singly but several different resources which can be tapped simultaneously. Depending upon the nature of the information processing tasks required of a human, these resources would have to process information sequentially (if different tasks require the same types of resources) or possibly in parallel (if different tasks required different types of resources).

The approach characterizes the workload demand required by each task in each of four channels, 1) the visual channel, 2) the auditory channel, 3) the cognitive processing channel, and 4) the psychomotor output channel. Benchmark scales such as the one below for visual workload were developed for each channel so each task could be rated:

Value:	Activity:
1	Monitor, scan, survey
2	Detect movement, change in size
3	Trace, follow, track
4	Align, aim, orient
5	Discriminate symbols, numbers, words
6	Discriminate based on multiple aspects
7	Read, decipher text, decode

All operator tasks were then analyzed using these scales.

During the simulation, the operator model was often required to perform several tasks simultaneously as defined by the task network. The task network model evaluated total attentional demands for each of the four channels (visual, auditory, psychomotor, and cognitive) by simply summing the attentional demands across all tasks which are being performed simultaneously. For example, let us assume that at some point in the mission, the operator is simultaneously monitoring the altimeter while he or she is looking at the multifunction display to evaluate weapon status. Let us assume that the attentional demands of these tasks are as follows:

Tasks	Monitor Altitude	Evaluate Weapons	Total
Visual	3	2	5
Auditory	1	0	1
Cognitive	2	5	7
Psychomotor	0	0	0

The last column above indicates what his combined attentional demands would be for each of the four channels during the simulation.

Drews *et al* constructed a task network model that represented the above effects. This task network model was then used to simulate the performance of the pilot's tasks under different scenarios. The models produced estimates of the total attentional demands on the pilot across all tasks throughout the simulation. These workload values were characterized graphically over the course of a mission, an example of which is shown in Figure 7. Any value of workload over seven was cause for concern and, when these were observed, further reviews were conducted. By

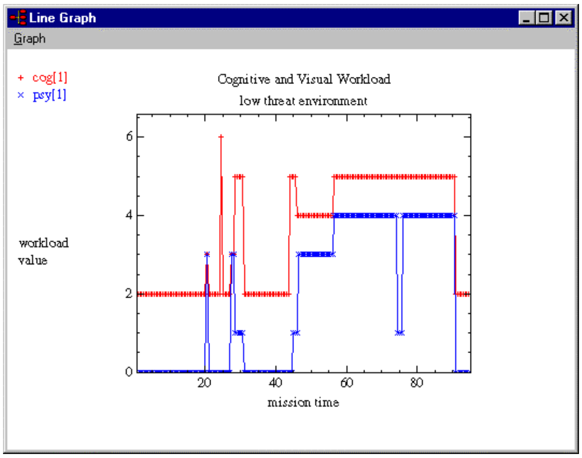

Figure 7: Sample Predicted Workload Profile

examining the points in the mission at which these attentional demands are high, Drews *et al* were able to assess the mission segments for which operator workload would be excessive.

At the end of this study, it was determined that a one-man cockpit was going to be quite difficult to achieve, even with the most optimistic projections of aiding, automation, and pilot support that could be achieved. These findings were supported by other research and the helicopter was built as a two-person system.

5 SUMMARY

Task network modeling provides one way to assess the value of human-computer interface designs in the operating environment. Together with usability analysis to ensure model accuracy and systems analysis to define how the system will be used, a better assessment of the value of the human interface can be gained.

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