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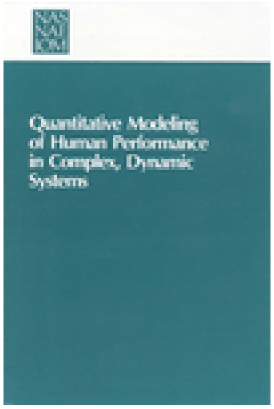

Quantitative Modeling of Human Performance in Complex, Dynamic Systems

Sheldon Baron, Dana S. Kruser, and Beverly Messick Huey, Editors; Panel on Human Performance Modeling, Committee on Human Factors, National Research Council

ISBN: 0-309-56464-6, 108 pages, 6 x 9, (1990)

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Panel on Human Performance Modeling
Committee on Human Factors
Commission on Behavioral and Social Sciences and Education
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1990

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National Academy Press 2101 Constitution Avenue, N.W. Washington, D.C. 20418

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This work relates to Department of the Navy grant NOO14-85-G-0093 issued by the Office of Naval Research under Contract Authority NR 196-167. However, the content does not necessarily reflect the position or the policy of the government, and no official endorsement should be inferred.

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S052
Printed in the United States of America

Library of Congress Catalog Card No. 89-63540
International Standard Book Number 0-309-04135-X

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Foreword

The Committee on Human Factors was established in October 1980 by the Commission on Behavioral and Social Sciences and Education of the National Research Council The committee is sponsored by the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Institute for the Behavioral and Social Sciences, the National Aeronautics and Space Administration, the National Science Foundation, the Air Force Armstrong Aerospace Medical Research Laboratory, the Army Advanced Systems Research Office, the Army Human Engineering Laboratory, the Federal Aviation Administration, and the Nuclear Regulatory Commission. The principal objectives of the committee are to provide new perspectives on theoretical and methodological issues, to identify basic research needed to expand and strengthen the scientific basis of human factors, and to attract scientists both inside and outside the field for interactive communication and performance of needed research.

Human factors issues arise in every domain in which humans interact with the products of a technological society. To perform its role effectively, the committee draws on experts from a wide range of scientific and engineering disciplines. Members of the committee include specialists in such fields as psychology, engineering, biomechanics, physiology, medicine, cognitive sciences, machine intelligence, computer sciences, sociology, education, and human factors engineering. Other disciplines are represented in the working groups, workshops, and symposia organized by the committee. Each of these disciplines contributes to the basic data, theory, and methods required to improve the scientific basis of human factors.

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Preface

Human factors work in the systems development process involves both analytic and empirical studies of design alternatives. The use of human performance models (HPMs) to evaluate candidate designs has become increasingly important as the cost, personnel, and time required to perform full-scale simulation studies have increased. People are an essential part of human-machine systems, and it is substantially easier and less expensive to consider the impact of human capabilities and limitations on system operation and modify the system before it is built, than to modify it to conform to human limitations after it has been constructed.

The development and use of human performance models have grown steadily since the successful application of servo-theory in the 1950s to tracking and other manual control skills. However, a number of problems and unresolved issues have restricted the utility and application of HPMs in the design and development of systems. Many different approaches to modeling have been taken, and a wide variety of limited models that focus on some particular aspect of human performance has been developed. The potential utility of these models would increase if an integrated representation of human performance was developed that users and managers could easily understand and support

Most models that exist today are generally poorly understood except by those who have contributed to their development. Even seemingly simple models are fairly complex when examined in detail. A particular problem is understanding the rationale behind the assumptions, choice of parameters, and actual values that are incorporated into a model. A great deal of experience with a model is required to fully comprehend its sensitivity to parameter changes and its robustness in different applications. Because of the general lack of knowledge of the limitations and utility of various

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models, an incautious user may apply a model inappropriately, whereas a conservative user may avoid employing a model well suited to a particular need. Of equal concern is the problem of verifying and validating models in the context of complex systems. This is compounded because new systems require that operators learn to use them, so a new system is essentially never available to experts to study.

There is evident need for guidance on ways to improve the utility. of existing models, to create more comprehensive models, and to validate them. To meet this need, the Committee on Human Factors established the Panel on Human Performance Modeling. The focus of the working group was on HPMs that are specifically useful in the design and development of complex systems.

The general purpose of the working group was to assess the capabilities and limitations of existing models, the conditions under which these models are useful, and the possibility of creating more comprehensive models of human behavior. It was beyond the scope of the panel to compare the solution of a problem with and without a model or to compare models with one another; however, alternative and complementary methodologies to modeling are discussed briefly. The primary goals of the panel were

- to evaluate the strengths and weaknesses of alternative modeling approaches;
- to assess the conditions under which current models are of practical use;
- to assess the potential for developing comprehensive models of human performance by integrating existing models or other alternative means; and
- to recommend research or other courses of action necessary to improve HPMs.

Chapter 1 of this report is introductory in nature and includes definitions and characterizations of human performance modeling and a discussion of its purposes. The chapter closes with a historical perspective on modeling approaches in the form of a genealogy of human performance models.

In Chapter 2, the approaches deemed most relevant to the development of comprehensive human performance models are discussed. These include models of limited scope and their relation to comprehensive model development and use; an information processing approach; a control-theoretic approach; a task network approach; and a knowledge-based systems approach. Brief descriptions of the approaches are provided along with their specific strengths and caveats on their use. A summarizing overview concludes the chapter by observing that a number of promising models for

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complex human-machine interaction exist, but none are mature enough for general use.

In Chapter 3, several applications of HPMs are discussed with a view to providing the reader with an indication of this scope as well as some of the problems in HPM use. Applications in the operation (control) of aircraft and nuclear power plants, in maintenance tasks, and in the monitoring and control of highly automated systems (supervisory control) are discussed.

Chapter 4 concludes the report with a discussion of the views of the working group concerning the most important issues in developing comprehensive HPMs and recommendations for addressing them in terms of both use and needed research.

The panel, which met over a four-year period starting in December 1983, included 10 experts in the areas of mathematical psychology, cognitive psychology, experimental psychology, human factors, modern control theory, and artificial intelligence. Special thanks are extended to the members of this group for their unflagging cooperation and involvement in this project.

I would also like to acknowledge the people who managed the mechanics of transforming the products of the working group into this report. Thanks are due to Stanley Deutsch, former study director, who guided the project in the beginning; to Harold Van Cott, the current study director, for keeping the project on track; to Dana Kruser, project coordinator, for putting the materials submitted by the working group into first draft form and editing first drafts; and to Beverly Huey for editing the final drafts. I express my sincere gratitude to each of these individuals for their significant contributions.

SHELDON BARON, CHAIR

PANEL ON HUMAN PERFORMANCE MODELING

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1

Introduction

SCOPE

This report discusses human performance models (HPMs) and their potential use in system design, development, and evaluation. The primary focus is modeling system operators performing supervisory and manual control tasks. The report does not address models of the designer or manager of a complex system, and it addresses models of maintainers only briefly (see Elkind, Card, Hochberg, and Huey, 1989, for a discussion of models pertinent to designers and managers). However, if a model cannot be understood by higher management, it is not likely to be used by them.

Of interest are complex technological systems of a dynamic nature in which humans play a central role in any of the functions: monitoring, control, decision making, supervision, and maintenance. Examples include vehicles (air, sea, or land), process control operations, power plants, some weapons systems, and a variety of manufacturing systems. Such systems are invariably costly and time-consuming to design and develop, and substantial risks are often involved in their operation. Faulty design or operation can be very expensive or dangerous, and systematic means of accounting for the performance of the human component in these systems is imperative.

A model is a representation or description of an or part of an object or process. A variety of models have been developed for a variety of reasons. Early models, which were often verbal, statistical, or mathematical descriptions or theories of some limited aspect of human performance, could not represent the complexity and comprehensiveness of human performance. However, modem computer technology is changing this situation. Until fairly recently, most human performance models were numerical or quantitative, but as a result of the progress in artificial intelligence and cognitive

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science, a substantial body of nonnumerical, qualitative, but calculable, models has been developed. These models are necessary for representing cognitive behavior and, although qualitative, are nevertheless computational.

Although the literature is replete with models that represent paradigms and tasks in which an individual's attention is fully committed to a single process, the challenge addressed here is to represent human performance in typical working settings in which operators perform a collection of tasks that overlap in time. For example, the submarine commander is engaged in navigation, control, and threat detection. At various times, these activities compete for attention. This added level of complexity poses important problems in modeling human performance. In addition to models that are appropriate for single tasks or activities, it is necessary to model the ways in which human operators manage their own resources so as to cope with the changing and sometimes conflicting demands of disparate activities. A major question that arises is: Can this be accomplished by integrating single-task models that have been developed previously for the activities performed in isolation, or is it necessary or better to model the complex task in a completely unified manner?

The extent to which simple task models can be usefully integrated to represent more comprehensive behavior depends on the nature of the gaps in coverage of the models and on the completeness of the linkages between them. A report by Elkind et al. (1989) addresses this issue in the visual and cognitive areas with specific reference to the tasks of a helicopter pilot. On the other hand, most existing comprehensive models contain little detail about specific aspects of human performance, reflecting the trade-off between breadth and depth. Therefore, at present, some trade-off decisions must still be made.

It should be noted that human performance modeling has additional purposes and uses beyond those of prime consideration here. Of special interest and import is the use of models in theory development and evaluation. Indeed, in the psychological literature a model of human performance is often used as a synonym for a theory of performance. In the psychological literature the model frequently is, or is intended to be, independent of the specific system or task context and thus is applicable to a variety of systems. This is an undoubtedly important area of human performance modeling, but it is not of central interest in this report.

WHAT IS HUMAN PERFORMANCE MODELING?

The term *human performance models*, as used in this report, refers to quantitative (analytic or computer-based) models of human operators or maintainers of complex dynamic systems. Many different kinds of HPMs

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have been developed. The characteristics that help distinguish among them can be represented along several important dimensions: output versus process orientation, predictive versus descriptive, prescriptive (normative) versus descriptive, top-down versus bottom-up, and single-task versus multitask. Models can also be characterized according to the types of theories or tools used in their development.

Output Versus Process

The dimension of output versus process relates to the degree to which a model (or modeling approach) focuses the system output versus the processes by which output is generated. An output model is a set of relationships between input and output states that is capable of (1) beginning with input states and (2) generating output states. This type of model predicts or describes the outputs of a person or a person-machine system for a given set of inputs. Such an output-oriented model places no requirement on the structure, or even the validity, of the internal mechanism (processes) of the model. All that is desired is that the model produce "correct" (i.e., useful in the context of the application) outputs for specified inputs.

On the other hand, a model can be a theory of how people perform certain tasks. The HPMs with this characteristic describe processes by which an output is generated and, as such, describe what humans do within the system, rather than just predicting the results of their actions. In this sense, process models are more complete descriptions than are output prediction models. For many purposes, though, output prediction is all that is needed.

Human performance models typically combine output prediction with some degree of process prescription. No general answer can be given to the question, What is the "appropriate" level of internal detail for an HPM? because the necessary level of process description depends on the application of the model

Predictive Versus Descriptive

It is important to distinguish between two distinct methods of employing HPMs: (1) predicting human-system performance with the model prior to collection of data and (2) describing (fitting the model to) human-system performance by adjusting free parameters of the model to conform to existing data.

Fitting models to data can be an end in itself (i.e., for descriptive purposes). It can also be a step toward developing predictive models. Virtually all HPMs have some parameters that must be estimated from

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experimental data. Predictions can be made for new situations by using the parameter estimates available from earlier, descriptive studies.

Clearly, predictive models, where they exist or can be developed, are intrinsically of more value than models that merely describe or summarize data; prediction is the real need of the system designer (prior to building the actual system). Moreover, a truly predictive model will also describe actual performance.

Prescriptive (Normative) Versus Descriptive

Models for human performance can either describe how a human is likely to perform a task or predict ideal behavior, given human and situational limitations. In the former case the model is called descriptive, whereas the latter type of model, which prescribes how the human should perform if he were to behave in a rational way that takes into account the information available, the constraints that exist, the risks, rewards, and objectives, is called prescriptive or normative.

The distinction between normative and descriptive can be blurred because prescriptive models often describe quite well the performance of humans that have been well trained for the task. This is particularly true when prescriptive models include in their formulation, representations of human limitations that constrain performance.

Top-Down Versus Bottom-Up

The top-down/bottom-up distinction refers to the extent that a model is dictated by system goals or by human performance capabilities. A top-down approach begins with a statement of system goals, then progressively elaborates subgoals and functions until the modeler reaches a level at which functions are accepted as primitives and are not explained further. A bottom-up approach begins by defining a set of primitive elements at both the human performance and the engineering levels. A system model is then developed based on the predefined set of primitive elements. Note that this distinction refers to the evolution of the model, rather than to the final model. Because of the nature of their evolution, top-down models are likely to focus on output (system performance), whereas bottom-up models are likely to focus on the processes leading to performance as well as output.

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Single-Task (Limited Scope) Versus Multitask (Comprehensive)

Most quantitative models have been developed with a single-task in mind, although that task may involve several subtasks or processes. Single-task models are models that range from simple movement to models for manual control or signal detection that can involve perceptual, motor, and even cognitive processes. With respect to the concerns of this report such single-task models are viewed as being of limited scope. Multitask models, on the other hand, are those that treat a variety of such tasks within a single unifying framework. These models are referred to as comprehensive HPMs.

MODELING METHODOLOGY

Another important way of characterizing HPMs is by the theories or tools that underlie the model or serve as a basis for its development. For example, there are task network models (network and reliability models), information processing models, control-theoretic models, and knowledge-based models. This is a particularly useful way of classifying comprehensive or multitask models and is the basis for much of the discussion of modeling approaches in Chapter 3.

One should not be confused by the many ways that HPMs can be described or defined. In simplest terms, a model may be viewed as a "thing" of which questions are asked about the real-world. The ultimate role of a model is to produce simulated performance (output or behavior) data. The resulting data should be sufficiently similar to real performance data to be useful to decision makers. Thus, a model is "good" if the same answers are obtained from the model that would ultimately be obtained from the real-world, regardless of the particular modeling approach employed.

One final general point: A model of human performance implies the existence of a model of the environment or system[1] in which that performance takes place. Thus, in this report, human performance modeling will almost always combine human with system performance models. The manner in which the environment is modeled generally will dictate the way in which the human is modeled and vice versa. For example, discrete event modeling of the system will tend to lead to task network models for the operator, whereas continuous time system models would involve corresponding representations of the humans.

[1] "System," in the report, refers to an interconnected set of parts making up a whole entity that has a common purpose. Thus, one example of a human-machine system would consist of human, turbine, reactor, etc., which collectively make up a nuclear power plant.

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WHY USE HUMAN PERFORMANCE MODELS?

Processes That May Benefit from Their Use

Human performance models are used in two ways: (1) to develop theories of human performance and (2) to design and evaluate systems. These applications are not mutually exclusive. Lessons learned in theory development can be of benefit to system design and vice versa.

Theory Development and Evaluation

To develop a model, one must be specific about one's theories of human performance. If a working model has been developed, the model may be exercised to determine if the simulated behavior of the modeled constituents corresponds to the behavior of those same constituents in the real-world under similar conditions. If the data obtained from the model do not correspond to data obtained from the real-world, it may be possible to determine which aspects of the theory need to be reconsidered. If the model is exercised under a variety of conditions and found to yield satisfactory results, then confidence is gained for using the model to predict the behavior of the constituents under novel conditions. Thus, the very attempt at developing a model is highly useful in discovering where such ambiguities exist.

System Design and Evaluation

Human performance models can play a role throughout the life cycle of a system. They can be used in design to help establish system configuration, parameter values, and operating procedures; in operation as integral components of a system (against which actual human performance may be compared); and in evaluation (e.g., of normal performance, accidents and incidents, or specific missions). The greatest contribution, however, is probably in design.

The importance of considering human performance during the design process has become increasingly apparent in recent years. People are an essential part of human-machine systems. It is substantially easier and less expensive to consider how human capabilities will affect system operation and modify the system before it is built, than modify it to conform to human limitations after it has been constructed.

Generally, the first stages of system development involve specifying functional requirements for the system and allocating those functions to human or machine components. Later stages involve translating functional

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and performance requirements into design specifications; translating proposed design specifications into a statement of projected performance of each component, including people; and comparing projected performance.

The sequence, in general, consists of four stages:

1. Analyze the purpose of the system and identify the tasks that must be accomplished to achieve it.
2. Describe the goals or performance requirements for the system.
3. Select a potential method for achieving those goals (i.e., a system configuration at either a gross or a detailed level).
4. Model the configuration to obtain performance estimates and compare the performance estimates to the stated goals. Then,

- if predicted performance does not satisfy the goals, redefine the goals or rethink the method and try again or
- if the predictions and goals seem to match fairly well, simulate the configuration, test it with human subjects, and, based on the results, proceed with development, make additional adjustments to the goals, or modify the model as dictated by the experimental data.

This iterative procedure helps to extract those system characteristics that are essential to meeting predefined system performance goals and are, at the same time, responsive to human performance capacities and limitations. It also provides a mechanism whereby HPMs can be systematically improved.

Alternative (or Complementary) Methodologies to Modeling

Expert Opinion

A relatively straightforward and inexpensive approach to predicting human performance is to have experts predict what people will probably do in a hypothetical system. Unfortunately, there is no way of knowing in advance how valid these opinions will be. Moreover, the inherent complexity and dynamic nature of the systems and problems of interest make it extremely difficult for an expert, or group of experts, to account for the effects of all possible interactions, particularly those with a low probability of occurrence. Nevertheless, the analyses of an expert are usually essential in defining initial alternatives and in evaluating the results obtained by using other design methods.

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Simulation

Simulation refers to person-in-the-loop[2] simulations that are, in fact, person-machine models, except that the human(s) and portions of the environment are real. Simulation has some important, although sometimes overstated, advantages over most modeling techniques. There can be little question about whether the people in the simulation are performing like humans (they obviously are), but whether they are performing like the humans of interest (e.g., fully trained operators of a system) can be questioned. This will depend on the amount of training and practice given to the operators of the simulation and the continuity of operation provided in the experiments. If the purpose of the simulation is to provide data for system design, the expense of building the simulator and the time consumed in designing it, training the operators, and collecting data on them may preclude drawing conclusions from their performance early enough to properly influence design of the real system. Even when this is not the case, the operating costs associated with person-in-the-loop simulation may severely constrain the amount of data that can be collected, which will adversely impact the scope of the system operation under investigation.

Despite these problems, simulation is, and will continue to be, an essential element in complex system design because of its advantages relative to testing in the real environment. Moreover, human performance modeling will, for the foreseeable future, require experimental verification in simulators (just as simulator results often require real-world verification). Indeed, substantial synergy is possible between human performance modeling and simulation. Models can be used to reduce the required amount of simulation by determining critical areas of investigation, and they can be used to understand and extrapolate the results of simulation. Simulation results can, in turn, be used to verify the model, identify model parameters, and generally advance model development.

Evaluation of Real Systems

Real-world testing and measurement represent the ultimate evaluation of a design. However, the same objections can be raised for collecting data by using real systems as for simulations: namely, that the data can come too late for cost-effective design changes to be made. A more serious objection concerns the potential risks of real-world operation if there is uncertainty about the outcome.

[2] Person-in-the-loop architecture refers to a system in which the human plays a more continuously active role in its control and management.

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Laboratory Experimentation

Basic laboratory experiments are also used to aid design decisions. In particular, basic experiments (sometimes involving simple part-task simulations) are often conducted to choose between design alternatives or to test a particular concept or design. Care must be exercised in interpreting the results of these experiments. For example, a laboratory experiment that shows statistically significant differences may, or may not, reflect functionally significant differences in real-world performance. Moreover, because the laboratory context is carefully controlled (i.e., eliminates or holds constant many extraneous variables), the observed difference between alternatives could disappear, or even be reversed, in the real-world setting where these extraneous variables are a part of the task environment

These comments are not meant to imply that laboratory experimentation is of no benefit but rather to suggest that its usefulness in predicting real-world performance is variable. Laboratory experiments can be a relatively inexpensive way to make early decisions when they must be made. They also can be used to test or develop component models for single tasks that are used in constructing more comprehensive models. In short, they are useful adjuncts to, but not substitutes for, modeling, simulation, and real-world evaluation.

Benefits of Human Performance Modeling

Each of the options discussed above may be appropriately applied to the process of system design and development. However, in some cases modeling offers advantages over other methods for obtaining the same, or similar, data. Examples of the advantages of human performance modeling are (1) its relative speed compared to other nonmodeling methods, (2) its ability to give insight into whole new approaches or applications, and (3) its cost effectiveness relative to dynamic simulation or real system experimentation.

In other cases, human performance modeling can provide benefits not obtainable by other methods. For example, a model can be used to provide one or more of the following:

- a systematic framework around which to organize facts;
- an integrative tool which prompts consideration of aspects of a problem that might, otherwise, have been overlooked; and
- a basis for extrapolating from the information given to draw new hypotheses about human or system performance.

Broadly speaking, a model is nothing more than some modeler's representation of some thing or process. It may not be necessary for a model to be highly accurate to be useful (for example, a map of some area of

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the earth that is depicted on a two-dimensional plane surface uses the "flat earth model," which is a misrepresentation, but the map is useful nonetheless). This suggests that the issue of model utility must be considered in addition to its validity, as long as its users recognize that a useful model is not necessarily completely valid in terms of process as well as output. As discussed earlier, a model may accurately predict the output; however, the process used to arrive at this prediction may not accurately reflect the way in which a human would arrive at the same outcome.

Genealogy of Human Performance Models

The history of HPMs dates back to World War II. Of interest are the antecedents, and possible components, of the approaches to modeling described in this report. Figure 1-1 summarizes this history diagrammatically by highlighting four main approaches to human performance modeling: information processing approaches, control theory approaches, task network approaches (network and reliability modeling), and knowledge-based approaches. Each of these developments is considered in turn.

Information-Processing Models

The Mathematical Theory of Information (Shannon and Weaver, 1949), together with the ideas of Wiener (1950) concerning feedback controlled systems that he called cybernetics were the precursors of a whole new way to think about human behavior. Because it then became possible to think concretely about the abstract concept "information," and because information input, processing, and output represented human activities as well as activities that could be ascribed to a machine, it was only natural for the information processing analogy to be extended to the analysis of human performance.

This new approach was typified by Broadbent (1958) who formulated a block diagram analysis of information flow in human perception and memory. Although Broadbent's ideas were qualitative, they laid the foundations for quantitative models of elementary human information processing operations. As Neisser (1967) pointed out, this approach is not a computer analogy in the sense that the brain behaves like a computer, but rather a programming analogy that gave rise to a viable research strategy founded on the idea of discovering the algorithms by which human information processing takes place.

This approach spawned models of visual search and identification, short-and long-term memory, reaction time underlying simple decision processes, and movement control, to mention just a few. It has led to numerous attempts to formulate block diagrams of human information

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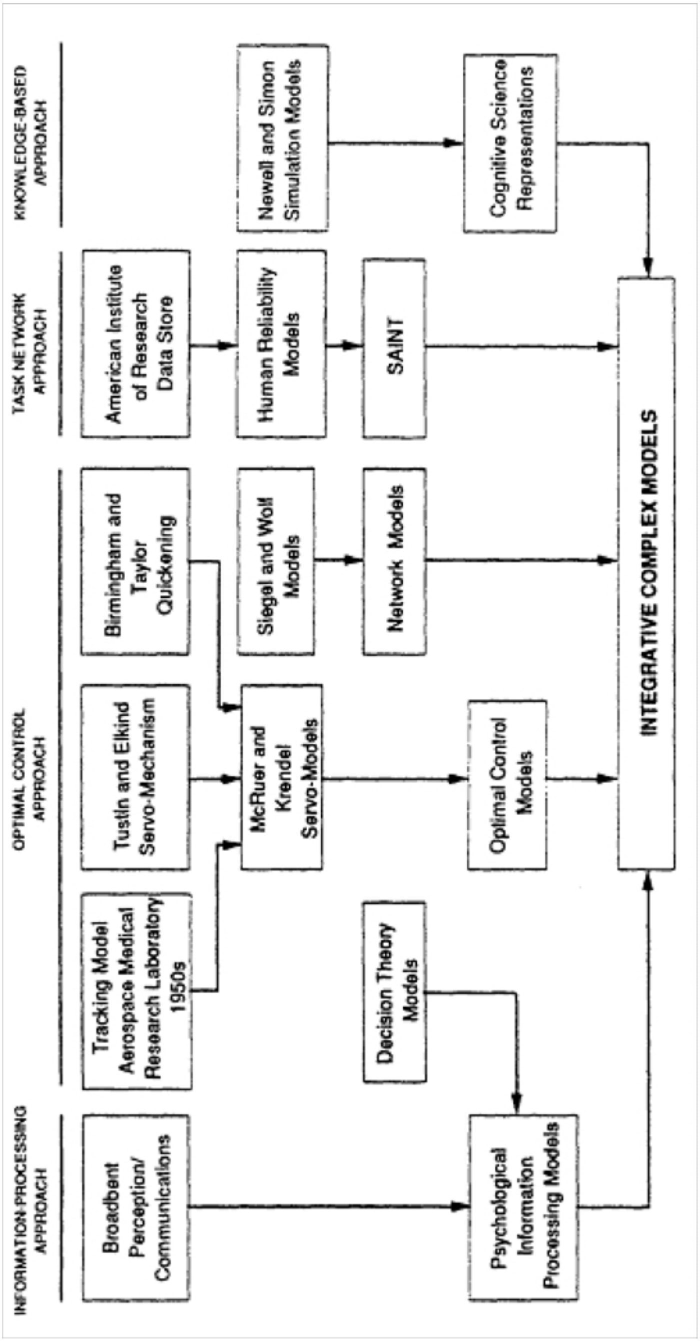

Figure 1-1
Four main approaches to human performance modeling.

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processing. From the viewpoint of this report, however, the models were of isolated psychological functions rather than integrative human performance.

The Human Operator Simulator (HOS), discussed in Chapter 3, was one of the first attempts to capture component information processing concepts in the form of an aggregated model that might be applied to system design and evaluation (Lane, Strieb, and Leyland, 1979).

Control Theory Models

Interest in manual control models was first stimulated by the need to understand how humans control antiaircraft guns and other closed-loop systems. The seminal paper on this subject was by Tustin (1947), a British electrical engineer who fit first-and second-order differential equations to the experimentally observed transient response of the human operator to step-input signals. This was an insightful analysis based on the understanding of servomechanisms at the time.

During this period a number of experimental studies systematically examined the effects of system variables on human tracking performance (Helson, 1944; Ellson and Hill, 1948; Rockway, 1955). At about this time Birmingham and Taylor (1954) published their landmark paper on "Man-Machine Control Systems." The concepts of quickening and aiding were introduced, and the theory was put forth that man operated most effectively when system constraints permitted performance analogous to that of a simple amplifier.

In 1956, Elkind provided the first comprehensive, systematic data and models of human control as a function of a variety of continuous band-limited Gaussian input signals and different controlled element dynamics. Elkind pioneered in the empirical measurement and analysis of power density and cross-power density spectra, as well as in the technology for measuring human tracking performance. Although the technology for such measuring has made giant strides since the 1950s, Elkind's data and analysis have never been seriously challenged.

Meanwhile, in the early 1950s, McRuer began advocating that analysis of the human pilot could be done in the same terms as analysis of the balance of the aircraft flight control system. He teamed with Krendel to generate new data and to undertake the first comprehensive review and analysis of all the manual control data available at the time. Their report, "Dynamic Response of Human Operators" (McRuer and Krendel, 1957) was the bible for work in this field for at least 10 years. McRuer and Krendel codified and systematized data in the form of quasilinear descrying function models, together with rules for their adaptation, as a function of the variety of system variables known at the time. A spin-off of their analysis was the Crossover Model, a simplified conception based on the observation that

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when the human and the system were represented as a unit, a simpler form of the model resulted (McRuer, Graham, Krendel, and Reisener, 1965). In effect, the human adapted his behavior so that the combination behaved like a simple first-order system with limited bandwidth. It was also found that systems that approximated a simple integration and, therefore, allowed the operator to behave like a proportional controller (i.e., a gain or amplification factor) were preferred. This confirmed Birmingham and Taylor's "simple amplifier" tenet.

In the 1960s, modern control theory, using a state variable approach and optimization techniques that permitted closed-form solutions to complex control problems, was applied to the manual control problem. Baron and Kleinman (1969) proposed a model for the operator, based on optimal control and estimation theory, to account for both control itself and the information processing necessary to support it. This model was developed further, with contributions from Levison, and has come to be known as the Optimal Control Model (OCM). The OCM introduced the concepts of observation and motor noise as stochastic components of the operator that limited human performance. It also made explicit the need for an internal model of system inputs and dynamics as a prerequisite for successful tracking performance. These concepts have been used for the quantification of attentional workload in the context of manual control (Levison, Elkind, and Ward, 1971) and for exploring the question of what is learned as one acquires tracking skill (Levison, 1979). The OCM has been applied widely, and the information processing portion of the model has been extended to tasks other than manual control.

The introduction of automation in aircraft cockpits and the vast increase in complexity of the avionics resulting from it have forced consideration of manual aircraft control in the larger context of aircraft systems management. These developments have led to the generalization of models to include the operation of management functions. The Procedure Oriented Crew (PROCRU) model (Baron, Zacharias, Muralidharan, and Lancraft, 1980) was a response to this need. PROCRU, a computer simulation model, is a derivative of the OCM that incorporates the execution of procedures in the context of manual control. It introduces the concept of expected net gain, a generalization of the performance index, as a means of predicting priorities among procedures to be executed.

Task Network Models

In parallel with these advances, the operations research community developed sophisticated models of system processes using a task network approach. With this approach a complex system is represented by a network

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of component processes, each modeled by statistical distributions of completion time and probability of success. The resultant computer program is run as a Monte Carlo simulation to predict the statistical distributions of measures of overall system performance. The PERT methodology for management of system development was one outgrowth of this approach. Siegel and Wolf (1969) first applied task network modeling to predict human performance in a systems context. One innovative concept they introduced was that of a moderator function. Human capacities were postulated to be sensitive to certain global variables such as motivation or stress. To explore the impact of these variables, moderator functions shifted the time distributions or completion probabilities for all component tasks to be performed by the human operator based on the setting of the moderator function. This permitted sensitivity analyses to be run easily to test the robustness of performance in the face of variations in stress level or motivation.

At about the same time, Swain and his colleagues working at Sandia became concerned with human reliability in the Navy and, later, in the nuclear power industry. They collected data on the probability of successfully completing some elemental human operations such as closing valves, reading displays, or carrying out simple procedures. System reliability analysis, which predicts the performance of mechanical components in a systems context, proceeds according to methods not unlike network analysis. Swain (1963; Swain and Guttman, 1980) developed methods for incorporating elements of the network, reflecting the reliability of both human and mechanical components of a system, in order to improve overall system reliability estimates.

The task network approach was further stimulated by the development of Systems Analysis of Integrated Networks of Tasks (SAINT), a simulation language specifically designed to make it easy to build task network models of human and system performance (Pritsker, Wortman, Seum, Chubb, and Seifert, 1974). This language has been used to study performance in a wide range of systems including digital avionics systems, command and control networks, and a hot strip mill; SLAM II represents the current state of the art with respect to task network simulation languages and modeling tools.

Knowledge-Based Models

About the same time that component models of information processing were being developed, Newell, Shaw, and Simon (1958) and their colleagues began work on the development of computer programs capable of logical reasoning. This work was based on the realization that a computer is basically a device for manipulating symbols, and that solving numerical problems (the purpose for which computers were developed) is only one example of symbol manipulation. The work of Newell et al.

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led to the development of the General Problem Solver program (GPS; Newell and Simon, 1972), which was capable of mimicking many of the behaviors observed when people attempt to solve logical problems with the general complexity of those in *Scientific American* puzzle articles. Newell, Simon, and their many colleagues and followers have pushed this work on knowledge-based models forward very rapidly, and today, many of the logical and programming techniques that they developed are the heart of modern artificial intelligence and expert system programs. In addition, the concepts they developed for thinking about thought are central to today's study of cognitive psychology.

Most of the work in this field has centered on modeling human problem solving rather than human-machine systems. More recently, though, several experimental studies of limited human-machine operations have been conducted. Many people believe that human-machine system modeling is the wave of the future, especially for situations in which the modeling effort views a person as a planner rather than a sensor or movement controller.

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2

Approaches To Human Performance Modeling

MODELS OF LIMITED SCOPE

The primary concern of this report is models that describe and predict the complex behavior of humans as components of human-machine systems. However, there are a number of models that represent aspects of human information processing in more limited domains. Generally, these models are the products of laboratory research on very specific human tasks developed to model human information processing rather than human-machine interaction. They, therefore, tend to ignore aspects of the environment or task that would modify the model's predictions. For example, models of human reaction time typically predict response time primarily as a function of the number of possible signals or their relative probability, and give secondary consideration to physical factors such as how far apart the response keys are, whether eye movements are needed to monitor signal occurrence, or anatomical dimensions of the operator that might affect performance. Several of the human information processing models have been adapted from engineering models to represent human behavior. Typically, they are based upon a single theory or technique. Such models invoke information theory, the theory of signal detection, sequential decision theory, theories of reaction speed and accuracy, sampling theory, psychophysical scaling theory, and fuzzy set theory. Many are descried in Sheridan and Ferrell (1974).

All of the models mentioned above have been used successfully to account for human performance at some time in a laboratory setting. For example, it has been well established that the reaction time of an observer to one of several possible signals is related to the uncertainty of the signals in the way predicted by Information Theory. This is a

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highly replicable result (Garner, 1962). Similarly, the frequency with which observers monitor instruments and the duration of their fixations when they look at an instrument have been predicted by Information Theory (Senders, 1983). Discrete movements are well described by Fitt's law (Fitts, 1954). Single axis closed-loop tracking is adequately modeled by the Crossover Model (McRuer and Krendel, 1957). There are also many models of short-term memory (see, for example, Norman, 1970). Yet, however successfully it is validated in a laboratory setting, each models only a small part of human information processing, and the interaction among models of limited scope cannot be specified nor can the overall behavior of the human be predicted.

An example of the strengths and limitations of a typical model of limited scope can be found in the application of Information Theory to predictions of pilot workload and the design of instrument displays. Senders and others (Senders, 1964; Senders, Elkind, Grignetti, and Smallwood, 1964) applied the Nyquist Sampling Theorem and Shannon's Information Theory to predict the frequency, duration, and pattern of eye movements when an observer monitored a group of instruments. The observer's task was to report any excursions of instrument pointers to extreme values. The instruments used were driven by band-limited, zero-mean Gaussian white noise forcing functions, with bandwidth differing from one instrument to another. The Sampling Theorem describes the necessary and sufficient sampling strategy to ensure that all information is extracted from the display, and Senders successfully used it to predict the observer's visual sampling behavior. Senders was also able to predict the relative duration of fixations and the pattern of transitions among instruments.

Clement, Jex, and Graham (1968) applied the model to predict workload in the cockpit of a real aircraft and to predict the optimal layout of instruments. In doing so, they were forced to make a number of arbitrary corrections to the model In particular, they had to assume, on the basis of empirical evidence, that the sampling rate was considerably higher than that predicted by the sampling theorem Although they gave no theoretical justification for the values they chose, their predictions of the instrument layout matched the actual cockpit design that evolved for the particular aircraft they studied.

As Senders (1983) himself has pointed out, a number of crucial assumptions were made in the model Operators were all highly practiced. Forcing functions were statistically stationary. The instruments were all of equal importance and had no intrinsic meaning or interest to the operator, who was not required to reset the instruments or exert any control actions when extreme values were observed. The model is in no sense a general model of human performance or human information processing. Also, insofar as the operators are in situations where costs and payoffs are important, where the conscientious exercise of strategies is important, where

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emergencies make one instrument more important than another, where monitoring is shared among several operators, or where so many displays must be monitored that there is insufficient time for eye movements and short-term memory becomes important, the model becomes increasingly poor at predicting behavior.

The most important requirement for applying a model of limited scope is knowledge of the boundary conditions within which the model may be applied. Outside those boundary conditions other models may be preferred or empirical parameter values must be determined. It is because of such limits that an overall model of human performance, which expressly includes a variety of causal factors, is to be preferred for human-machine system design and assessment.

In applied settings, particularly in system design, only a small subset of human behavior can be predicted by a model of limited scope. If other aspects of information processing affect the output of the model in uncertain ways and if the properties of the environment (such as the spacing of displays or the force required to activate a control) are not represented in the model, it becomes apparent that more elaborate models are required. Those described here must have as their goal to model the performance of a human-machine system as a whole, rather than modeling the behavior of the human alone or understanding the psychological mechanisms by which behavior is mediated.

LARGER, OR INTEGRATIVE, APPROACHES

The remainder of this chapter provides examples of comprehensive, or macro, models. These examples were selected to illustrate the variety of possible approaches to the development of global overall human performance models (HPMs) and to provide the foundation for subsequent discussion of the current issues and research needs in the field of human performance modeling.

Although all of the modeling approaches discussed here may be employed to model the same general class of problems, they differ in a number of important ways. These differences arise largely from the differing origins of the approaches, both disciplinary and institutional, and from the fact that, in most instances, model development was driven by a particular class of person-machine problems.

Models of limited scope, aimed at the analysis of single-task subsets of the comprehensive problem, serve as a resource for each of these macro-models. The approach is basically eclectic, drawing on various disciplines for theories and techniques. Four general approaches to macromodeling

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are described: (1) information processing, (2) control theory, (3) task network, and (4) knowledge-based.

The assumptions of the information processing approach are based on psychological theories of human information processing and the belief that observed or predicted human performance can be explained (i.e., modeled) by the aggregation of the (micro) internal processes required to execute a series of procedures that define the task. A task consists of a set of subtasks, and each subtask can be modeled. All of these models are then employed to explain the overall task behavior. Because Human Operator Simulator (HOS), the exemplar of the information processing approach, also has a strong systems orientation and includes a system model, it predicts total (closed-loop)[1] performance, which is unusual for psychologically based models.

Control theory models come from an engineering discipline and are principally oriented toward continuous time descriptions, optimization of closed-loop person-machine performance, and process representations of human performance at a macrotask level (such as state estimation or manual control).

The task network approach, which emerged from operations research, is oriented primarily toward the sequencing of large numbers of discrete tasks arranged in an appropriate network so as to achieve a particular goal; models based on this approach focus on the time required to complete individual and total tasks and the error probabilities associated with performing these tasks.

The knowledge-based approach has roots in cognitive psychology and in computer science/artificial intelligence. The field of cognitive science, which represents the intersection of these disciplines, has as its goal the development of formal representations of human cognitive processes, such as decision making, problem solving, planning, understanding, or reasoning. Sometimes these representations are algorithms; more often, they are expressed in the form of simulations of the processes believed to be undertaken by the human. The tools of the artificial intelligence specialist, such as object-oriented programming, are beginning to be used to implement these simulations and are being applied to the modeling of person-machine systems. They provide the basis for very flexible models that can be tapped easily to produce performance metrics or augmented with computer graphics summary outputs.

[1] A closed-loop system is one in which the output controls or regulates the input. An open-loop system, on the other hand, is one in which there is no feedback control.

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Information Processing

Background

A plethora of models of limited scope exists to describe the information processing abilities of the human operator. Many are described in Boff, Kaufman, and Thomas (1986). Classical information theory describes the relation of signal probability to reaction time (Hick, 1952). Signal detection theory accounts for the relative effects of signal strength and the observer's response bias in the detection of sensory information (Green and Swets, 1966). Quantitative models have been proposed both for short-term memory and for the retrieval of information from long-term memory (Norman, 1970). Models exist for both discrete movements (Fitts, 1954) and continuous tracking (McRuer and Krendal, 1957). In fact, for almost every block in the typical flowchart proposed for human information processing, several models can be found in the literature. It would therefore seem attractive to create a global, comprehensive model by aggregating a group of models of limited scope so that all aspects of information processing are included. By incorporating anatomical and physiological models as required, it should even be possible to account for such factors as the time required to move about the environment, position the body, reach, and grasp an object such as a control

Exemplar

The human operator simulator is a computer system, a collection of programs for simulating a user-machine system performing a complex mission. Illustrated in Figure 2-1, HOS simulates the total system: the hardware and software of interest, various "external" systems (friendly, hostile, or neutral), and the behavior of humans operating within the system. It provides a general "shell," a user-oriented, Human Operator PROCedure (HOPROC), language, and a resident Human Operator Model (HOM). A model for a particular system is instantiated when the user specifies, via HOPROC, the equipment characteristics and the procedures to be followed by the operator.

HOPROC is an English-like language that can be used to define hardware, software, and human processes or actions at any desired level of generality or specificity. Fortran-like statements can be incorporated in the language, which is useful for describing, where necessary, the dynamic equations of motion of simulated hardware systems and information that can be mentally calculated by humans based upon other knowledge available to them. Human tasks and actions need only be defined and described in HOPROC at a level that might be found in a typical operator's manual.

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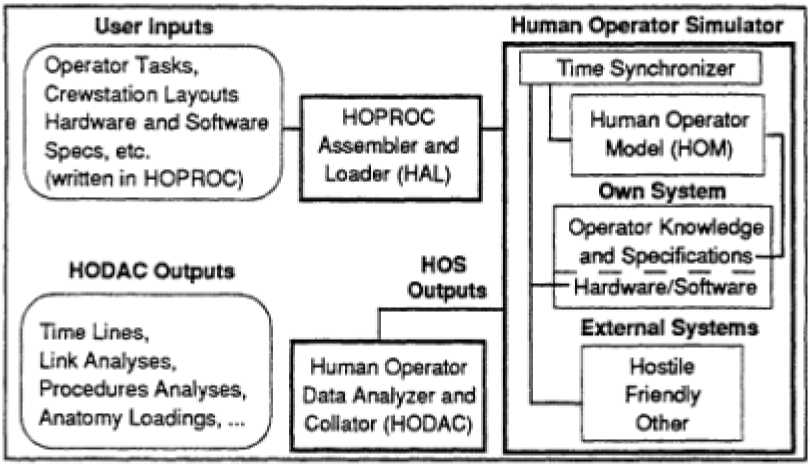

Figure 2-1
Structure of the Human Operator Simulator (HOS) showing inputs, outputs, an d major subsections.

With HOS, all human responsibilities, functions, and tasks, and all hardware and software processes, regardless of their complexity, are referred to as procedures. The operator's procedures represent an important part of long-term memory for the simulated operator, who is assumed to be fully trained in using those procedures. The locations and types of the operator's displays and controls are also entered by the user and assumed to be in the operator's long-term memory store.

The passage of time during a HOS simulated mission is primarily dependent on time changes determined by submodels of the HOM that is pan of the HOS structure. Execution of human actions necessitating human-machine interaction (i.e., the transfer of information from displays or to controls) causes the simulation of the systems to advance to the point in time when the transfer would occur.

What makes HOS more than a simulation language is its resident general-purpose HOM. This contains and controls a highly integrated set of information processing submodels, each with its own set of algorithms and rules of operation.

The rationale underlying development of the HOM process submodels is that, although thousands of different operator tasks exist, they require only a limited number of different microactions such as reaching for and manipulating control devices, recalling information from short-term memory, looking at displays, and absorbing information from them. Each microaction requires some amount of time to perform. Other things being equal, similar microactions in different tasks should require similar times

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of any given operator. Thus, efficient and internally consistent predictions of human task performance should be derivable from a HOM organized around a mutually exclusive and exhaustive set of microactions. Furthermore, performance times for each microaction should be predictable by (1) evaluating the physical difficulty of microactions (e.g., extent of required reorientation/movement of anatomy parts) and (2) knowing, for each type of microaction, the level of skill of the particular operator being simulated.

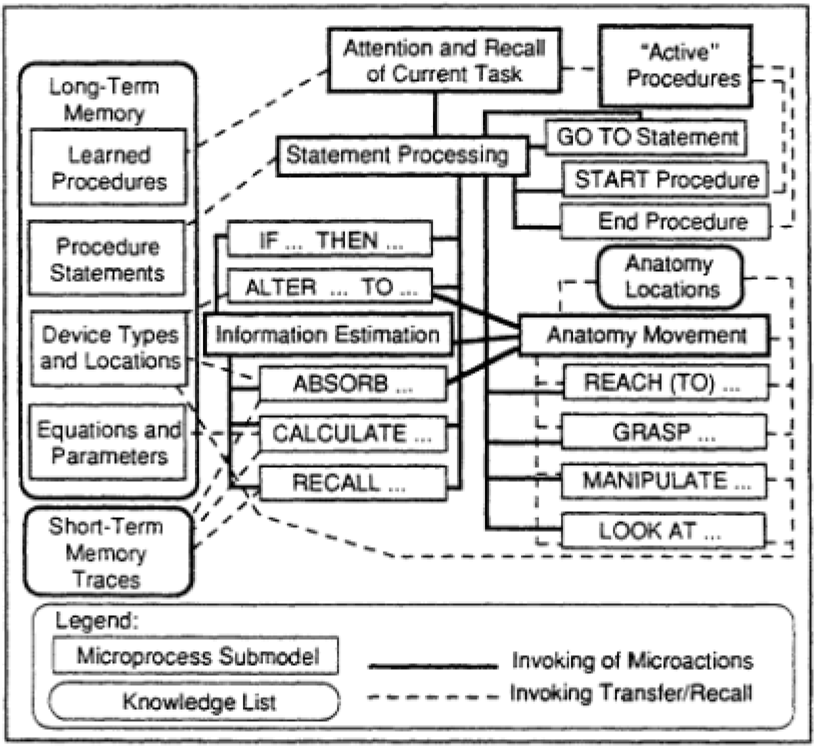

Figure 2-2
Major submodels and knowledge lists in the Human Operator Simulator (HOS).

The major HOM process submodels in HOS are shown in Figure 2-2 and discussed briefly below. More detailed descriptions of HOM submodels and HOS can be found in Wherry (1976), Lane, Strieb, Glenn, and Wherry (1981), Meister (1985), and Harris, Glenn, Iavecchia, and Zalkad (1986).

- *Long-term memory retrieval*: Learned procedures and the types and location of display and control devices are assumed to be resident in

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the simulated operator's long-term memory.

- *Attention and recall of current task responsibilities*: The HOM assumes operators can work on, or attend to, only one active procedure at a time, although rapid changes in attention among active tasks are permitted. The attention submodel, when accessed, computes a figure of merit (FOM) for each active procedure and selects the one with the highest FOM to attend to.
- *Statement processing*: Compiled HOPROC statements are treated as goals. The Statement Processing submodel uses its rules and algorithms to determine the next microaction to invoke in its attempt to satisfy the overall goal of the statement.
- *Information estimation*: This submodel contains strategies for estimating required information-Depending on the current situation and type of information needed, it may invoke short-term memory recall, information absorption, or information calculation to obtain needed estimates. Successful estimation by any of the three methods results in a short-term memory trace for that specific information.
- *Short-term memory retrieval*: Probability of recall for a previously estimated value or state is computed by this submodel, based on the strength of the trace when last estimated, the time elapsed since the last estimation, and the capability of the simulated operator for this process. This submodel is also used to determine the need for physical manipulation of controls or displays and hence the need to take account of movement time.
- *Information absorption*: This HOM process corresponds to the perception of information from external sources such as displays and controls. Anatomy movement submodels for various sense modalities are used, when required, to model touching or visual fixation prior to the actual absorption of displayed information. Time required to absorb information is determined by the nature of the information source and may require several sampling instances to build up sufficient evidence.
- *Information calculation*: When information cannot be directly absorbed from external sources or accurately recalled, it may be calculated by using HOPROC-written calculation equations. Users must supply the model with times required to perform these calculations.
- *Anatomy movement*: This submodel determines the part(s) of the anatomy that must move in order to access a display or control, and whether the desired anatomy part is currently busy. If busy, the submodel may decide to use an alternative method (e.g., swap hands), and determine the appropriate time charges for the movement For example, the time to perform procedure LOOK AT is a function of the required angular changes for the head and eyes.
- *Decision making*: Users can incorporate decision rules into procedures using the HOPROC format "IF (assertion) THEN (consequences)."

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Assertions can be simple (e.g., ALTITUDE IS LESS THAN 1,000 FEET) or highly complex (i.e., by using logical ANDs, ORs, and NOTs). A decision making time charge is levied for evaluating each assertion following the IF until the assertion is judged to be TRUE or FALSE. When an assertion is judged to be true, satisfaction of the goal (s) for the consequences following the THEN will be attempted. If assertions are judged to be false, the stated consequences will be ignored.

- *Accessing relevant portions of procedures*: Complex operator and hardware procedures often have multiple pathways to successful completion. The HOPROC language contains a function that makes it possible to bypass portions of procedures that have become irrelevant to the current situation.

Constants in equations for HOM microaction times are based on reviews and reanalyses of hundreds of research studies found in the open psychological literature and from experiments conducted by HOS development teams. Although HOS is typically run by using default constants representing an average operator, users can manipulate the time equations to determine whether system performance would be dramatically altered by operators having more or less than average skill for completing various microactions. There are parameters or equations, such as those needed to define criticalities for the attention model, that are system, mission, or task specific and must be supplied by the user.

The HOS system provides a number of outputs of use to system designers and analysts. The starting and ending times for all actions and events occurring during a simulated mission are recorded by HOS. Levels of detail for logged events vary from macroevents (e.g., deciding to work on a particular task) to microactions such as orienting the head and eyes to a particular display.

A data analysis package—part of the HOS system—yields standard statistical human factors analyses and descriptions of logged events (e.g., time lines, link analyses). Analyses of human and system performance at various levels of aggregation can also be constructed, and descriptive statistics are available for the times of all tasks to be simulated. Because the HOS system simulates a total system, it also produces an expected mission time line as an output rather than requiring it as an input. Existing versions of HOS require mainframe computers, but a microcomputer version is under development (Harris, Iavecchia, Ross, and Schaffer, 1987).

Strengths

A major strength of HOS is that it is a complete system and was conceived as such. Much care and effort went into those aspects of HOS that make it both general and relatively easy to use. Thus, the HOPROC

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language is capable of describing both operator procedures and other constituent portions of the system in an English-like language. A resident, general model of the human operator (HOM) frees the user from developing the operator model except for specifying procedures and necessary parameters for the HOM. The HOS also includes a package of programs called the "Human Operator Data Analyzer/Collator" (HODAC) for analyzing the human operator data generated by a simulation. Finally, user and programmer manuals exist for each version of HOS.

As a human-machine simulation, HOS can produce data similar to that produced in person-in-the-loop simulations. Thus, its basic output is a time history of the simulation, including significant events as well as human operator actions. These simulation histories can be analyzed to evaluate performance as a function of operating procedures or other system variables. In addition, operator loading, down to individual body pans, can be examined.

A significant advantage of HOS lies in the manner in which task times for the resident HOM are determined. Unlike HPMs that require completion times to be input by an analyst or determined by sampling time distributions provided by the analyst, the time to perform tasks is built up from the times determined from execution of HOS's human performance submodels. This reduces the data input requirement for HOS. Furthermore, at least in theory, it allows HOS to be used to predict completion times for new tasks involving combinations of micromodel activities, rather than requiring that they be estimated or determined empirically. It also guards against invalid conclusions about higher-level system functions that may be drawn from simulations, which fail to adequately consider detailed human-machine interactions that must occur in the real system

Various aspects of HOS have been tested in a series of studies of increasing complexity (Strieb, 1975; Glenn, 1982). These investigations demonstrated several important attributes of HOS:

- The HOPROC language is flexible and robust with respect to modeling operator and equipment procedures, and the sequence of actions generated as a result of these procedures is reasonable.
- The resident micromodels in the HOM reproduce baseline experimental task data from which they were derived with sufficient accuracy to ensure that micromodel interactions do not introduce unanticipated artifacts. Model simulations of additional, carefully controlled, human performance experiments are of sufficient accuracy to continue with application of HOS to more complex situations.
- The HOS simulates full-scale, complex systems, as demonstrated by simulations of operators in Navy and NASA aircraft applications: the Air Tactical Officer in a LAMPS helicopter, sensor station operators 1 and

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3 on board three different versions of P-3C ASW (anti-submarine warfare) patrol aircraft, a pilot in a NASA Terminal Configured Vehicle (TCV), and the Tactical Officer (TACCO) on board a P-3C during antisubmarine warfare (ASW) missions. These studies (see Chapter 3) demonstrate that HOS can identify actual system/operator problems and provide a user with insights that can lead to solutions.

The HOS is particularly sensitive to the types and layout of displays and controls in a simulated operator's workstation, as well as to the number and type of multiple-task responsibilities allocated to the simulated operator. Thus, HOS appears to be useful for uncovering problems in control/display design, workstation layout, and task allocations, as well as evaluating ways of improving operator and overall system performance through changes in them.

Although almost every HPM dealing with the prediction of operator performance times assumes either additivity of component activities or a model of the ways in which activities interact, the aggregation of times in HOS concerns microlevel events not represented in other HPMs. A rationale, theoretical basis, and methodology for identifying microprocesses whose times can be aggregated has recently been described (Wherry, 1985).

Caveats

The HOS currently contains no simple way of specifying an operator's mental or internal model for controlling rapidly changing, multidimensional, complex systems. Acquired through experience and practice, such internal models permit operators to determine needed amounts of control device changes and to anticipate system responses without verifying all of them from displayed information. Any internal model can be represented in HOS by using HOPROC-written information calculation equations, but this does not solve the problems of deciding what constitute appropriate equations or how much mental calculation time should be charged when they are invoked.

Although micromodel outputs have been tested against data, and the results of pan-task HOS simulations have been compared with experimental results, there has been little quantitative comparison of experimental data and HOS simulation results for complex systems. Further data are needed before the extent of HOS's ability to make statistically valid quantitative predictions of human performance in complex tasks can be evaluated.

The simulation level of HOS includes each human-machine interaction; however, there is no interactivity of components. The HOS simulates human performance at a level that may be inappropriate to those interested only in higher-level system functions. Such detail is required for evaluation of control/display design and layout. If HOS is to be used for simulating

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complex systems during early design when valid simulation data would be most helpful to the design team, the system parameters must be developed. These HOS inputs would include types and locations of displays and controls, written procedures for how the simulated operator will use displays and controls, and procedures for the hardware/software subsystems. For a new, complex system, this can be difficult and time-consuming. Experience with HOS indicates need for an input development team composed of subsystem engineers and human factors specialists who can rapidly bring their expertise to bear on the decisions to be made. Subsequent modifications of initial inputs can usually be made rapidly to test the impact of suggested changes on any portion of system design, and HOS can have its greatest impact on system design when used in this way.

A goal of HOS development was to minimize the need for users to estimate the means and variances of the hundreds of task times that might be required by a task network approach model. However, for HOS to determine the microprocesses to be invoked, detailed descriptions of each operator task to be simulated, estimates of the criticality of these tasks, and specification of the types and locations of displays and controls are required. Users of HOS, like users of knowledge-based models, find themselves more involved with problems of describing operator protocols and less involved with predicting task times.

It must be recognized that the quality of a model's predictions always depends upon its basic premises. The HOS should produce useful results when three requirements are met:

1. users have adequately described operator procedures and any necessary internal models;
2. the resident HOM

- attends to appropriate operator procedures at the right times,
- contains and invokes appropriate microprocesses, and
- calculates valid microprocess times; and

3. the microprocess times are additive.

Meeting these premises limits generalizability to other situations; however, the robustness of the model when one or more of the above premises is not met, is unknown at present.

Control Theory

Background

The modeling of continuous manual control of dynamic systems, such as aircraft or automobiles, has received a great deal of attention in the human performance literature. Investigations have ranged from modeling

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human, performance in basic and simple tracking tasks to applications of models to complex, multivariable control problems. From the standpoint of human performance modeling, manual control problems have proven to be rich in content and importance, and have provided experimental situations in which extensive measurement of human performance is possible. Thus, they have provided fertile ground for the development of HPMs. Furthermore, the literature reveals that it is a mistake to view the manual control area as one of limited scope which only requires, or is a source of, simple models of human psychomotor performance. On the contrary, manual control models for problems involving several variables and complex, dynamic interactions tend to include submodels for a range of perceptual, cognitive, and motor activities. For example, manual control models include submodels for activities such as instrument scanning, attention sharing, state estimation and prediction, and neuromuscular performance. In addition, techniques used to develop manual control models, as well as some of the models themselves, have been used successfully to model human performance in tasks other than manual control.

The most successful approaches to modeling human manual control performance have drawn on the theory and techniques of control system design, analysis, and evaluation. The resulting class of human performance models is known commonly as control theory models. These models begin with a consideration of the system to be operated and its performance goals, in which the inanimate systems of interest are dynamic in nature and describable by differential or difference equations.

Two central integrating concepts or assumptions underlie control theory models. First, the human operator is viewed as an information processing or control/decision element in a closed-loop system. This is sometimes referred to as the cybernetic view of the human. In this context, information processing refers to the processes involved in selectively attending to various sensory inputs and using this information, along with the operator's understanding or model of the system, to arrive at an estimate of the current state of the world. Second, in most models based on this approach, it is assumed that trained operators approximate the characteristics and performance of good, or even optimal, inanimate systems performing the same functions, but that their performance, and therefore that of the overall system, is constrained by certain inherent human sensory, cognitive, and response limitations. Control theory models require that these human limitations be described in terms commensurate with other elements of the dynamic system description. This imposes a need for human performance data appropriate to limitations in dynamic processing and response, rather than those appropriate to discrete task completion.

The performance issues of interest in control theory models are associated with overall person-machine performance and tend to relate to

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such measures as accuracy of control and information processing, system stability and responsiveness, and ability to compensate for disturbances. A major focus is the interaction between system characteristics and human limitations and the consequences that flow therefrom. Thus, these models are intended to help system designers determine whether or not the information provided and the control or handling characteristics of the system are adequate to allow a trained operator to perform the task with a reasonable amount of physical and mental effort.

Without question, the most developed area of control-theoretic modeling is continuous manual control This field has been dominated by two models, namely, quasilinear describing function models based on frequency-domain techniques (see McRuer and Krendel, 1974, for a review) and the optimal control model (OCM) based on time-domain techniques (see Baron and Levison, 1980, for a review). These two models differ in important respects. One difference is the nature of the submodels that each approach aggregates. Both approaches incorporate submodels for sensory and neuromotor dynamics but in different ways. Also, the treatment of visual scanning and its impact is quite different in the two approaches. The quasilinear model uses Senders' information theoretic, visual sampling model (Senders et al., 1964). The OCM uses an attention sharing model (Levison et al., 1971) oriented toward optimizing control performance. Finally, the OCM incorporates models for state estimation and prediction as well as an explicit representation or model of task requirements. These are basic to the OCM approach but are not generally part of the quasilinear models.

Notwithstanding these important differences, each model has been shown to be capable of describing or predicting human performance in a variety of manual control tasks; however, their predictions have not been compared in the same situations. Both have been extensively validated and applied. They have been used to analyze aircraft and other vehicle control and display problems, to determine the effects of various stressors on performance, to evaluate simulator requirements, and to assist in experimental and simulation planning. Although the results of these applications and tests of the models demonstrate that they can be applied successfully to a large class of manual control problems, each requires further development. The principal areas of manual control modeling needing further work are multivariable control, control of nonlinear systems, control of highly automated and slowly responding systems, and modeling the performance of less than fully trained operators.

Two distinguishable trends in HPM development using control theory have emerged over the past decade. One trend is the advance from single-variable to multivariable control tasks. The other is a trend from problems concerned mainly with skilled motor performance (i.e., manual control) to those involving a significant degree and variety of additional activities such

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as monitoring, failure detection, and derision making. These trends may be viewed as a shift from relatively simple manual control problems to complex problems involving higher levels of control that may also include a significant manual control component.

The extension of control-theoretic models to asks other than manual control has been based largely on the approach and models associated with the optimal control model (OCM). This can be understood in light of the structure of that model as illustrated in Figure 2-3. In this figure the model of the system to be controlled is an integral part of the OCM: it is a person-machine model The diagram indicates that the OCM of the human operator incorporates submodels for perception, sate estimation, and sate prediction. These submodels provide an overall model for information processing in a dynamically changing environment that is robust and general. It accounts for human sensory limitations and for selective attention sharing. The information processing model represents the operator's ability to construct from his understanding of the system, and to derive from incomplete and imperfect knowledge of the moment-by-moment sate of the system, a set of expectancies concerning the actual system state as needed for control or decision making.

The OCM structure described above, with the continuous control portion replaced by appropriate decision elements, has been used as a basis for human performance models of failure detection (Gai and Curry, 1976; Wewerinke, 1981), monitoring (Kleinman and Curry, 1977) and decision making (Levison and Tanner, 1971; Pattipati, Ephrath, and Kleinman, 1980). Recent efforts have been directed at applying control theory approaches to the development of comprehensive models of the type of prime interest here. These models cover a range of operator activities including monitoring, continuous and discrete control, situation assessment, decision making, and communication. The models were developed in a variety of application contexts. Baron (1984) discusses the models and provides the outlines of a general model for supervisory control based on the control theory approach.

Exemplar

Of the control-theoretic models developed thus far, the Procedure-Oriented Crew Model (PROCRU) best illustrates how the approach can provide a framework for developing comprehensive models. This model was developed with the goal of providing a tool that would permit systematic investigation of questions concerning the impact of procedural and system design changes on the performance and safety of commercial aircraft operations in the approach-to-landing phase of flight. It is a closed-loop system model incorporating submodels for the aircraft, the approach and

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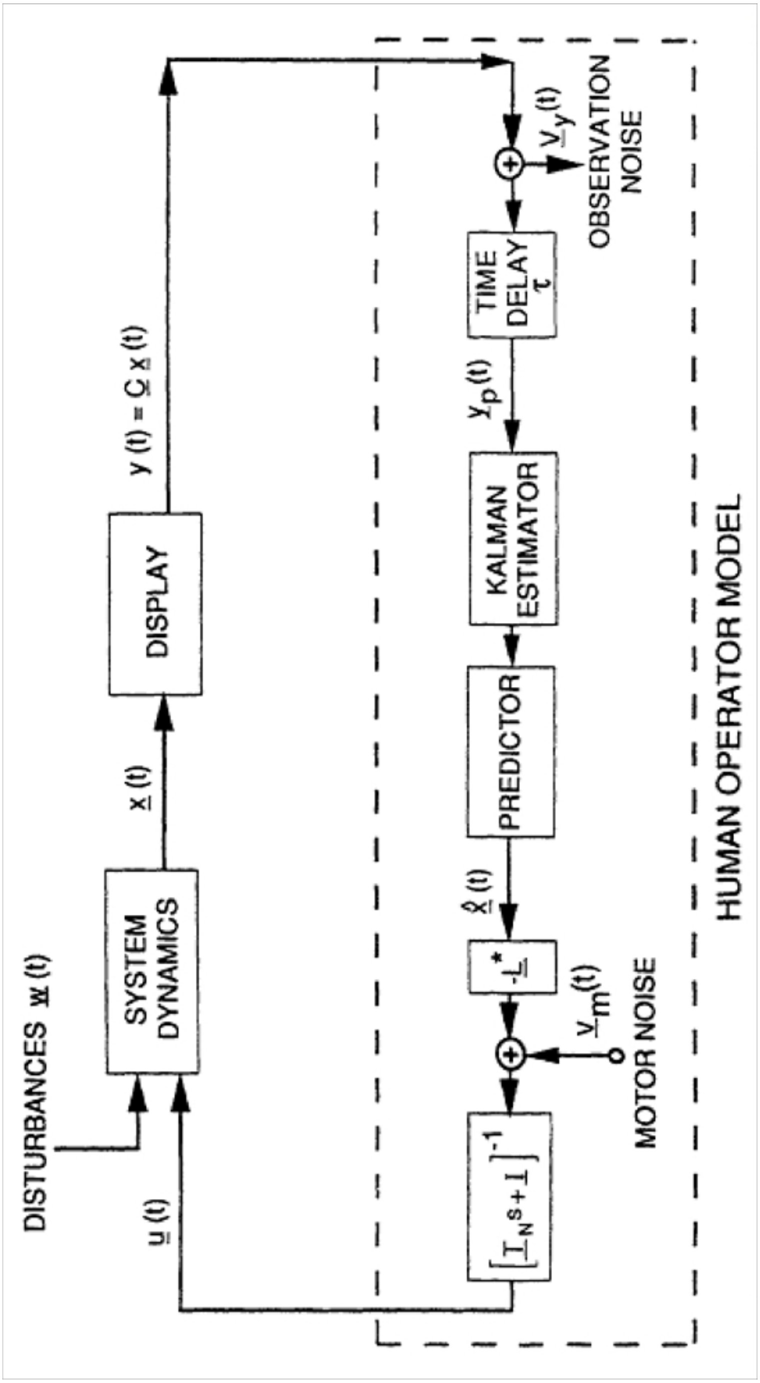

Figure 2-3
Structure of the Optimal Control Model (OCM).

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landing aids provided by the air traffic control system, three aircraft crew members, and the air traffic controller (ATC). For convenience in development, only two members-the Pilot-Flying (PF) and the Pilot-Not-Flying (PNF)-are represented by detailed HPMs. The models for PF and PNF had the same basic structure. Differences in behavior result from specifying different task assignments, task priorities, and information sources for the two models. The models for PF and PNF are comprehensive in accounting for the wide range of crew activities associated with conducting a typical commercial ILS (instrument landing systems) approach to landing, display monitoring, information processing, decision making, flight control and management, execution of standard procedures, and communication with other crew members and with the ATC.

The PF and PNF models employ derivatives of the basic information processing structure used in the OCM and other control-theoretic models mentioned above. To this structure, mechanisms are added for dealing with the multitask environment, including those necessary to account for task selection and the execution of routine procedures or discrete tasks. The necessary extensions are provided by defining a crew member's overall goals in terms of a set of procedures or sub tasks and by incorporating models for procedure selection and execution.

In general, a procedure in PROCRU may be comprised of discrete steps (e.g., execution of a checklist), or it may involve continuous actions (e.g., regulation of the aircraft's flight path). In both cases, procedures consist of several elements: an enabling event, which is a condition that must be satisfied before the procedure is eligible for execution; an expected gain function that determines the importance or urgency of executing the procedure at a given time; a recipe or prescription for carrying out the procedure; and for discrete procedures, a time to complete the procedure or individual steps in the procedure. An enabling event may be viewed as a situation or predicate for executing a procedure, thus making procedures analogous to production rules of the form IF (situation) THEN (action). In PROCRU, if more than one situation is evaluated as true at a given time, the expected gain calculations provide the control structure for selecting the appropriate rule to activate. Moreover, situations are assessed or evaluated by the modeled human information processor and, therefore, on the basis of information corrupted by modeled human perceptual and cognitive limitations. Similarly, actions that result from the execution of procedures reflect appropriate human performance limitations. Thus, although not developed from an expert system or artificial intelligence perspective, PROCRU may be viewed as a complex, albeit somewhat unusual, production system whose inputs, outputs, and control structures account for human limitations and goals.

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Strengths

The control-theoretic approach to developing comprehensive HPMs, as exemplified by PROCRU, has several strengths. It leads to modular structures allowing for the inclusion of submodels of limited scope that have been developed and validated separately for such activities as detection, decision making, and control. The principal integrating mechanisms are the information processing and task selection aspects of the model. The information processing model, which has been validated in numerous contexts, provides relatively direct ways of handling multiple sources and types of information (e.g., information available from different sensory modalities). The task selection portion of the model allows system goals and priority structures to be formalized as part of the model specification. With this structure, when a particular task is *selected, the* comprehensive model will be executing (i.e., will reduce to) a single-task model that has been developed, and possibly validated, for that task. In addition, the structure lends itself to a synthesis of various approaches to modeling human performance. For example, in addition to aspects drawn from existing control theory models, PROCRU models discrete tasks and rule-based procedural activities in fashions that are analogous to those used in the task network and knowledge-based approaches, respectively.

The models account for human limitations in information processing and response execution, often in a manner that allows these limitations to be defined independently of the specifics of the task. This feature increases the predictive potential of the models to the extent that it allows data concerning the operator's inherent performance limitations to be context independent.

The comprehensive models developed with the control theory approach are analogous to person-in-the-loop dynamic simulations. Therefore, they can provide the same kind of performance data that would be available from such simulations. These models also yield predictions of internal states of the operator(s) which, although not verifiable through measurement, can be extremely useful for uncovering or diagnosing system problems. Finally, the models provide a variety of outputs related to task demands and operator workload. For example, they produce activity time lines which, unlike those provided by traditional human factors analyses, are dynamically generated in response to the model of the evolving situation. Operator actions are not completely preprogrammed but, instead, depend on previous (possibly random) events or disturbances and responses to them. This allows the analyst to change model parameters related to the system, the scenario, or the human operators and have a new, different time line generated automatically.

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Caveats

The major caveat concerning comprehensive control-theoretic models such as PROCRU is the lack of experimental validation for the overall integrated models. The core, continuous information processing model has been validated many times in different contexts, as have some of the single-task, limited-scope models that would also be used. However, even if all submodels have been validated, it does not guarantee that this aggregation and integration will yield a valid comprehensive model

The control-theoretic approach appears to be well suited to highly structured situations with well-defined goals. However, it is likely to run into difficulties when this is not the case and operators have a great deal of discretion in how they perform their tasks. Even when the goals are well specified it is unlikely that mathematically "optimal" solutions can be calculated. This imposes a need for developing approximate, or suboptimal, solutions that compromise the normative nature of the model and increase the modeler's subjective input.

An important drawback to the control-theoretic approach has been the level of mathematical and control theory background and sophistication necessary to develop or use the models confidently. This has limited the user population significantly and may continue to do so. Another drawback is that the software required to implement such models is quite complex and, presently, not of a general nature. Although work is in progress to alleviate this problem, unlike some of the other models and methods discussed here, no software package exists that could readily be applied to a new problem. For the near future, a modeler interested in applying this technology faces full development of the computer implementation of the model This fact is likely to slow model development, validation, and application.

Task Network

Background

The task network approach views the human operator interacting with the environment through a sequence of activities or tasks. The environment includes other operators and equipment as well as the world. A task is usually described by an operator action, an object of that action, and other qualifying or descriptive information, for example, time to complete the task A procedure is a collection of tasks required to accomplish some goal. A task network is a collection of procedures and tasks that contains hierarchical and sequence information.

The task network approach has been the basis of many early uses of human performance models in complex, practical, real-world systems. The

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primary focus of these early modeling efforts was to determine the time required to complete procedures and tasks, as well as error rates, under different conditions (Siegel and Wolf, 1969). There are several important reasons for the success of these early efforts:

1. Procedures and tasks are simple to comprehend.
2. Task network descriptions are a natural by-product of functional requirements analyses in system design. Furthermore, task analyses are the basis for many equipment designs and human factors and training analyses. A standard for military task analysis has just been proposed (Myers, Tijerina, and Geddie, 1987). These functional requirements and task analyses can be the basis for many task networks.
3. For the above two reasons, procedures and tasks require less investment of analyst time to obtain useful results; moreover, and not insignificantly, the task network approach can easily be comprehended by higher management.
4. The task network paradigm encourages top-down modeling and allows use of existing libraries of models and procedures.
5. The task network approach may be used at many levels of human performance modeling from high-level mission performance to low-level button-pushing tasks.
6. The task network approach is general enough to accommodate a wide variety of situations that will be necessary in modeling human performance in complex human-machine systems.

These reasons are valid today, more than 20 years after the original applications of the task network approach.

Illustration

The task network approach is described here by means of an example, which is pursued far enough to show the strengths and weaknesses of the approach and to reveal why other macromodels have been developed.

The primary outputs of the original task network models were the time and accuracy to complete certain procedures. Suppose it is desired to determine the average time to "Go to Work"; the first step is to construct the basic medium of communication, the task network (see Figure 2-4) which is a diagram of procedures and tasks.

The highest-level procedure is "Go to Work." This is composed of the two procedures "Get Up" and "Get to Office." The arrow in the diagram indicates that the procedures must be performed in that order. The lowest-level blocks in any procedure are the tasks. For the "Get to Office" procedure, these tasks are "Leave House," ..., "Walk to Office."

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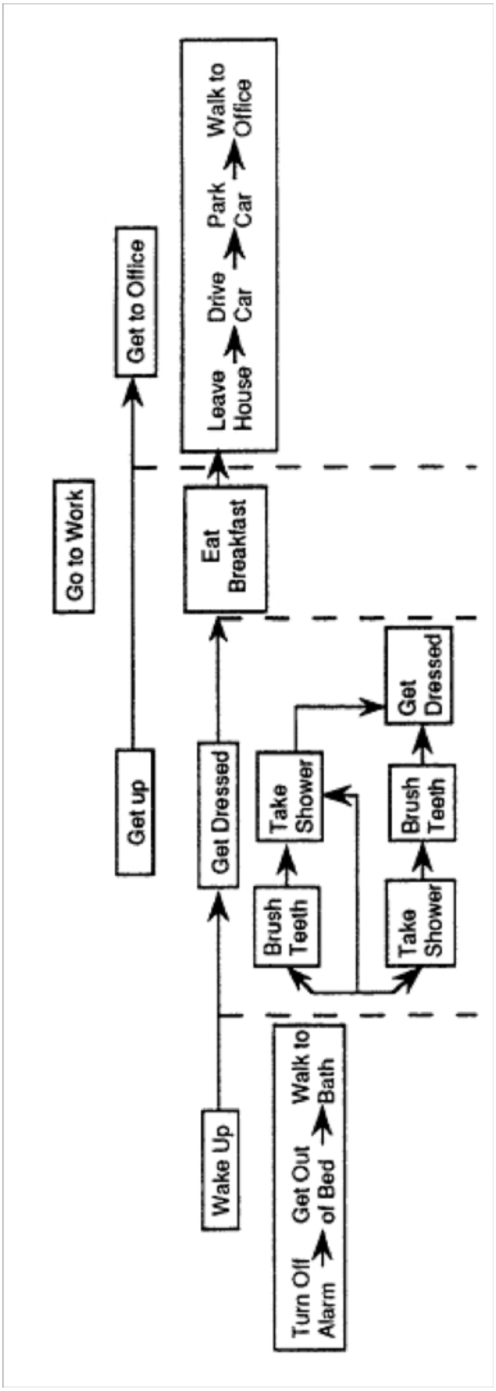

Figure 2-4
Task network for the "Go to Work" example.

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The "Get Up" procedure contains two procedures ("Wake Up" and "Get Dressed") followed by the task "Eat Breakfast."

This network shows that there is more than one way to "Go to Work." The three paths for the "Get Dressed" procedure show that it is possible to brush teeth before or after taking a shower, or to even skip brushing the teeth, but not the shower.

Time/Accuracy Models

There is no explicit human performance information shown in the task network, but there are some implicit assumptions about human performance: tasks will be done in the order shown, and a procedure/task cannot be started until the preceding procedure/task has been completed. The early applications of the task network approach assigned attributes to each task, such as time to complete a task and probability of correct execution; these attributes were used to compute performance.

Two classes of information are required to compute the average time: the time to complete each task and the path through the procedure(s). A first approximation is to assume that each task takes a fixed, constant amount of time and that each of the three possible paths is equally likely. Then the time to complete the network is the sum of task times plus the average time to complete the procedure(s).

No additional modeling is required if a single point estimate of time will suffice. However, it is easy to see how more realistic estimates can be obtained by using more realistic estimates of the task times. Usually, task times are assumed to come from probability distributions that are estimated by an analyst or derived from real-world measurements. When the time distributions are independent of one another, it is straightforward to perform a Monte Carlo simulation and statistical analysis to estimate the mean, standard deviation, and other properties of the total time.

There is no end to the improvements that can be made to task time distributions or branching decisions. For example, a variety of factors may reduce the time devoted to certain procedures. The branching decision is influenced by the current situation. If the operator is rushed, then an error is more likely to occur. These factors have been identified by Siegel and Wolf (1969) as moderator functions, or functions that change tune/accuracy performance in response to the state of the simulation.

Other Performance Measures

Time and accuracy were the primary focus of the early application of the task network approach. However, other performance measures have since been found to be useful. These performance attributes are assigned

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to each task, and a simulation of the network produces a time history or profile of the attribute.

Operator loading is an example. Workload estimates for aircraft operation have been estimated by developing a task network for piloting an aircraft and operating the on board equipment (e.g., radios and weather radar). The aircraft/ equipment operation has been characterized by the human resources required, typically at the level of right hand, left hand, right foot, left foot, vision, etc. (Miller, 1976). The task network is then executed, usually without random task times, to determine a time profile of operator loading. These models are useful for the identification of points in time at which the normally expected sequence of tasks can lead to operator overload or other problems.

The model based on use of the operator's hands and feet has been criticized because it does not take into account the thinking required by an operator. This observation led to tasks being characterized by the load, or requirements of four information processing components: vision, audition, cognition, and perception (Corker, Davis, Papazian, and Pew, 1986). Subjective values of each vital component are provided by subject matter experts. Execution of the network predicts situations in which the information processing load on the operator may be excessive.

Processing Models

The "Go to Work" and operator loading examples highlight different aspects of a human performance characteristic that is not visible in the task network: task processing. The "Go to Work" example is typical of *time-required processing*. Each task is done in sequence and may not be started until prior tasks are finished. The time from start to finish depends on the times for the constituent tasks. There is an implicit assumption that the individual is working at full capacity or else the spare capacity would be used to reduce task execution time.

The operator loading models described above are typical of *demandrequired processing*. Each task is done at a scheduled time, and the demands for all tasks are added together to give the total demand required to accomplish the tasks on schedule. Demand-required processing makes the assumptions that there is no upper limit to operator processing capability and that all tasks can be accomplished in parallel

Open-and Closed-Loop Models

The time-required and demand-required models represent another attribute of human Performance models: open loop or closed-loop. Both open-loop and closed-loop models of the operator may respond to the

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environment (e.g., execute an engine-fire procedure in response to an engine-fire warning). However, an open-loop model does not complete the circuit by feeding information about environmental changes due to that response back into the simulation, whereas a closed-loop model generates and incorporates such information. In the engine-fire example, the actions of the open-loop pilot model cannot influence the outcome of the remaining simulation, whereas with a closed-loop model, the outcome of the engine-fire procedure depends on whether or not the model of the pilot selects the correct engine when performing the procedure.

Models of Limited Scope

The task network approach is a useful framework in which to embed isolated and independent single-task models of human performance. The characteristics of each task can be specified by a model of that task, rather than by analyst estimates or an underlying human performance model which, as in HOS, can be applied to all tasks. Workload models, previously discussed, are an example. Examples of other models that can be applied to estimate task performance are manual control models to determine performance in the control of dynamic systems, signal detection models to determine the time and accuracy of detecting events and signals, and information-theoretic models to determine choice reaction time. Decision models, using, for example, multi-attribute utility functions, Luce's choice model, or Dynamic Decision Model (Pattipati et al., 1980), or knowledge-based rules can be used to determine the path of execution through the task network.

Aggregation Issues and Macromodels

The first aggregation issue is the assumed additivity of task attributes. In the "Go to Work" procedure, it is assumed that the time to "Get Dressed" and "Eat Breakfast" is the sum of the two task times. This may not be the case when these two procedures are in sequence because of shortcuts taken by the human, such as tying shoes while waiting for coffee water to boil. Similarly, the operator loading attributes are assumed to be additive in the demand-required model, but the actual loading could be better or worse when tasks are performed simultaneously.

Another aggregation issue is the integration of models of limited scope in the network: Does the aggregate model predict actual human performance? This is especially important because many of these models were developed in isolated laboratory experiments.

There is no single macromodel for the task network approach to human performance modeling because there is no unique method to model the two

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most important features of a macromodel: task selection and simultaneous task execution. The most direct way to build a macromodel is to have the analyst specify task order in procedural form without variation and with no simultaneous tasks. Other forms of task selection are probabilistic branching and knowledge-based branching (see the section on production systems). A lot of effort has been devoted to modeling task selection logic within the existing macromodels.

Simultaneous task execution is difficult to model Suppose the person going to work is also attending to another task network called "Asking for a Raise." It can be imagined that a lot of mental activity would be devoted to this task, and much of it could be going on during the execution of some of the "Go to Work" network (e.g., during the "Take Shower" task). How is the joint accomplishment of tasks represented? What are the resources being shared? How are they being allocated? What are the effects of one task on another? Task selection and simultaneous task execution are dealt with by macromodels.

Most macromodels avoid these questions by developing the task network down to a level at which it can be argued that the tasks are really performed serially rather than in parallel This involves much more detail than desired in some instances, and requires setting tasks and task selection logic for ongoing tasks such as monitoring.

Exemplars

The task network approach was extensively developed by Siegel and Wolf (1969), who used simulation and tasks described by completion times and accuracies. The U.S. Air Force sponsored the development of Systems Analysis of Integrated Networks of Tasks (SAINT), a simulation language to support the development of task network models (Pritsker et al., 1974). SAINT has been used to evaluate a variety of systems, including avionics systems (Kuperman, Harm, and Berisford, 1977) and submarine displays (Kraiss, 1981). The task selection logic emphasizes task precedence, resource availability, and random choice, but there is no specification of how to accomplish simultaneous tasks. In addition, SAINT allows the use of resource parameters that could be employed to represent human information processing resources.

THERP (Technique for Human Error Rate Prediction; Swain and Guttman, 1980) is an example of the assessment of human reliability by using the task network approach. The network is actually a fault tree, and empirical data are used to predict probabilities of errors. Tasks are not selected and are not done in parallel; rather, the probability of reaching certain nodes is assessed.

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Queuing models (e.g., Chu and Rouse, 1979) are another example of the task network approach. The macromodel controls tasks consisting of controlling an aircraft and correcting subsystem faults. The model selects tasks based on a computed priority and processes one task at a time. The tasks queue up until they are processed, as in the time-required model described earlier.

Strengths

The advantages of the task network approach to human performance modeling are its intrinsic generality and the ability to formulate HPMs at any desired level of detail. The task network approach encourages top-down modeling. It also offers a promising approach to system modeling when it includes knowledge-based branching, symbol manipulation capabilities, sampling distributions, and limited-scope models. The task network approach also provides means for the specification and incorporation of uniquely human traits such as task stress, goal gradient, and proficiency to increase the probability of making an accurate prediction.

It can be seen that the task network is quite intuitive and self-explanatory for the procedure/task sequences and hierarchy. This example also demonstrates several advantages of the task network approach: (1) there is a natural and convenient hierarchy to the tasks and procedures; (2) the task network encourages, if not enforces, top-down modeling; and (3) with top-down modeling, it is easy to expand those procedures that must be examined in detail ("Get Up" in the example), whereas other, less important procedures need not be developed ("Get to Office").

Caveats

The disadvantages of the approach also arise from its generality. If interactions between two or more task network modules are known, these interactions can be modeled in principle. In practice, however, highly interacting modules lead to levels of complexity that make checkout and validation very difficult. As with other models, the quality of the results depends on the quality of the supporting data: many times, subjective estimates of times and probabilities, or data derived from incorrect contexts, are used when more reliable data could be gathered.

Other disadvantages of the task network approach include the following:

- The identification and development of subprocedures and tasks are often not unique; that is, there are many possible procedure/task descriptions to determine how long it will take to "Get to Work." This may lead to an inadequate model if important tasks or events are not modeled.

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- Libraries of commonly used procedures can be included in the task network, even though the network is counter to top-down development. This can be an advantage if the libraries contain assumptions and procedures that are appropriate but a disadvantage if they do not.

It must be noted again that the task networks represent some, but not all, constraints among tasks and are not, per se, models of human performance because most HPMs are employed to describe how the network is executed, e.g., what resources are required for each task, how the tasks are sequenced, and how tasks are performed simultaneously. (Note how little human performance modeling is displayed in Figure 2-4.) Inasmuch as each new task network can be, in a sense, a new human performance model the validity of extrapolations to new domains or modifications of new tasks in a domain must be evaluated carefully.

Knowledge-Based

Background

Knowledge-based models of human performance are explanations of how people decide what is to be done to solve a problem. This is different from the typical goal of human performance modeling, which is usually to predict how accurately or reliably a person will execute a procedure under the assumptions that the person knows what is to be done and that failures occur only became of imperfect sensing or inadequate motor movements. This distinction can be illustrated by a hypothetical example from aviation. Suppose human performance is to be modeled in a situation in which a commercial aircraft requires more than normal power during the climb immediately following takeoff. A traditional modeling question would be to determine the distribution of times before the crew noticed the problem. A knowledge-based study might begin with problem detection and identification, and then ask how the crew diagnosed the situation.

Knowledge-based approaches grew out of Newell and Simon's seminal research on computer simulation of human problem solving (Newell et al., 1958; Newell and Simon, 1963, 1972). Newell and Simon realized that computer programs can be thought of as manipulating symbols, rather than doing arithmetical calculations. They argued that human thought is also an example of symbol manipulation and therefore can be modeled by computer programs. This discussion is restricted to the more limited issue of the impact of their work on modeling human performance.

The basic idea behind the computer simulation approach is that knowledge can be represented by symbol structures and rules for operating on them. To take a trivial example, an automobile driver may have knowledge that says (1) the warning light is on, and (2) when the warning light is on,

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examine the instrument panel This principle can be extended greatly. For instance, some modern expert system programs contain 500 or more rules of the sort just described. The problem-solving processes of experts are modeled by programming computers to execute the expert's knowledge of what to do and are used to alter a symbol structure representing what the expert knows about the current program.

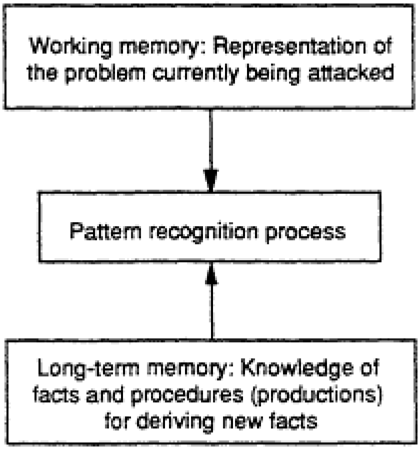

Figure 2-5
The organization of knowledge in memory.

The idea that thought can be modeled by computer programs does not in any way imply that the machinery of the human brain is logically similar to modern digital devices. In particular, knowledge-based models use an architecture of the mind that is quite different from the architecture of a conventional Von Neuman machine. As Figure 2-5 shows, knowledge is organized into two distinct classes: information in working memory and information in long-term memory. Each of these is considered here in turn.

A problem solver (in this context, the person being modeled) is assumed to have a set of beliefs about a problem at hand. These are collectively called the problem representation. The problem representation is stored in working memory as a set of propositions. Propositions may refer to knowledge about the problem to be solved or about the problem solver's own intentions. In addition, the problem solver knows a variety of potentially relevant facts and problem-solving methods. This information about how to go about solving problems is assumed to be resident in long-term memory. The facts and methods are referred to as declarative and procedural information about problem solving.

The basic idea can be grasped by considering how problems are solved in plane geometry. The initial statement of a problem presents certain facts. Geometry students know inference rules (e.g., the side-angle-side

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rule) that permit them to derive new facts from old ones. A geometry problem is solved by applying inference rules to deduce new facts from old, until the statement to be proved is generated as a fact. In theory, any geometry problem could be solved by rote application of all inference rules, iteratively, until the desired statement was generated. In practice, however, this is not feasible bemuse it leads to a combinatorial explosion of facts, most of which are irrelevant to the desired proof. Therefore, a good geometry problem solver will give priority to the development of propositions that are related to subgoals chosen because they are likely to be part of the eventual proof. For instance, suppose a geometry student wants to prove that two triangles are congruent and already knows that two corresponding angles are congruent. A good student will then set as a goal proving that the sides between the angles are congruent. This is a specific example of a general problem-solving rule, "If the goal is to prove statement X, and a rule of the form 'statement Y implies statement X' is known, then try to prove statement Y."

The problem-solving procedures stored in long-term memory are coded as "if-then" statements, called productions. Note that the rules of inference in geometry and the general problem solving rule just illustrated can be stated in if-then format Goal-directed problem solving can be achieved by making the presence of goals in the working memory part of the "if" section of a production, and the placing of these goals into working memory a possible action of some other production.

The geometry example illustrates another important aspect of know-ledge-based models, the distinction between domain-specific rules, such as the side-angle-side rule, and rules that apply to problem solving in general, such as the rule about establishing subgoals. General problem-solving rules are called weak rules because they are only weakly dependent upon the context in which they are used. In expert systems research, weak rules are sometimes referred to, collectively, as the inference engine, because they control the process of inferential reasoning that is applied within a specific problem-solving domain.

Problem solving proceeds by pattern recognition. Time is organized into discrete time cycles. At each cycle the problem representation is examined to see if it contains information that satisfies the "if" condition of any of the productions in long-term memory. When a match is found, the associated action—the "then" part of the production—is taken. A variety of different rules have been proposed for modifying this general scheme, but discussing them would be too detailed for the purposes of this report. The sequence of pattern matches and actions is continued until working memory contains information equivalent to a problem solution.

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When production systems are used to implement knowledge-based models, limits in performance are expressed in three ways: by the complexity of the propositions admissible in working memory, by the accuracy of the pattern recognition process, and by the information that the problem solver is assumed to have stored in long-term memory. In general, knowledge-based models are concerned with the intellectual aspects of knowledge use and response selection. They do not normally contain models of the perceptual detection of signals or the execution of motor movements, although attempts have been made to extend knowledge-based processing to these fields (Hunt and Lansman, 1986).

Because of this limitation, current knowledge-based problem-solving models are likely to be most useful in situations in which system performance is limited by what the human operator decides to do, rather than how quickly or how accurately it is done. Put into the terms of modern systems engineering, these knowledge-based models are appropriate ways to understand the supervisory aspects of operator performance, but are less likely to help in understanding how humans act as detectors or effectors.

In the sense that the term is used in this report, knowledge-based modeling was historically a comprehensive (macroscopic) effort, then became more limited in scope (microscopic), and now shows some signs of becoming macroscopic again. Newell and Simon's initial studies were macroscopic, in the sense that they were aimed at uncovering general laws of problem solving that were applicable to many specific situations. This is shown most clearly in studies of the General Problem Solver (GPS), a program that relied on context free inference rules to solve problems, given only a minimum of domain specific knowledge. For example, given appropriate minimal definitions of the domain, the GPS program solved problems in chess, calculus, and symbolic logic (Ernst and Newell, 1969; Newell and Simon, 1972). In terms of this report, the GPS was a macroscopic model of the human problem solver bemuse it could be applied to many tasks. The literature on knowledge-based problem solving puts this somewhat differently, by describing GPS as a program that emphasized weak inferential rules rather than context-bound inference rules.

In the late 1970s, the emphasis shifted from a search for the weak problem-solving methods that humans use to a concern for domain-specific knowledge. The shift was prompted in part by observation of human problem solving in extralaboratory situations, such as elementary physics and thermodynamics, and in pan by the desire to create expert system programs that could emulate human reasoning in economically important domains such as medicine. It was found that human problem solving is characterized more by the use of domain-specific heuristics than by reasoning from first principles embodied in weak problem-solving rules. This is particularly true when the human being modeled is familiar with

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the problem-solving domain. In general, this would be the appropriate assumption to make in modeling human performance in human-machine systems.

Quite successful domain-specific models of human performance have been constructed, covering areas ranging from problem solving in school arithmetic to college-level physics. In this work the focus has been on the problem solver, working in a fairly simple environment. This contrasts with the typical human performance situation in which the modeling effort also focuses on person-environment interactions. More recently, the knowledge-based approach has been applied to the latter class of situations. Rouse (1983) provides a review of applications in detection, diagnosis, and compensation for failures in complex systems such as aircraft, process plants, and power plants. Rasmussen (1986) has also offered an ambitious treatment of human performance and problem solving in complex systems.

Knowledge-based models are seldom used to make quantitative predictions about performance. They provide a way of summarizing complex sets of observations about past performance. The model-based summarization is then used to make a qualitative prediction of how people are likely to perform in a new system, on the assumption that they use the same knowledge base and reasoning rules that generated performance in the previously observed system. Models for knowledge use that are derived in this way may also be embedded in computer-based systems for aiding and training personnel in complex systems (Anderson, Boyle, and Reiser, 1985; Rouse, Geddes, and Curry, 1987). In these applications the model should be evaluated by its utility in training and decision making, rather than by scientific evaluation of its truth as a model of human reasoning.

Exemplars

Although the current literature emphasizes microscopic models of single tasks, macroscopic considerations have been introduced in three ways. Each is discussed here in turn.

A number of programs are commercially available for designing expert systems. These programs are shells or inference engines containing weak rules that organize the domain-specific rules established by the user (Alty and Coombs, 1984; Goodall, 1985). Examples of shells include EMYCIN, KAS (Knowledge Acquisition System), and EXPERT. The first two were developed for constructing rule-based diagnostic systems, whereas the third is most suited to classification problems.

The programs are intended to facilitate the rapid development of expert systems. They succeed in doing this by removing the burden of programming once the domain-specific rules are known. However the labor-intensive part of the effort lies in establishing these rules. Some

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attempts have been made to develop programs that would conduct formalized interviews with experts, thus reducing the labor costs of establishing the rules themselves (e.g., Boose, 1986). There are at present insufficient data to evaluate the utility of this approach.

The details of production execution imply a model of information processing. From Figure 2-5 it can be seen that a production executing system assumes the existence of certain undefined primitive elements. The chief ones are

- the mechanism for pattern matching, which determines whether or not the "if" part of a production rule is satisfied by the propositions in the problem representation;
- the data structures that are used to state the problem representation; and
- the conflict resolution rules used to determine which productions are to be executed when more than one production's pattern part is recognized in a problem representation.

In an analogy to computer programming, these elements play the role of operations within a programming language. They are organized into a model by writing specific productions, just as the operations of a programming language are organized into a specific computation by a program.

There is another sense in which macromodels can be introduced into knowledge-based modeling. Knowledge-based models, as presented here, depend on the execution of specific productions. Numerous authors have argued that production systems are themselves organized into higher-order frameworks, variously called schema, frames, and scripts (Minsky, 1968; Schank and Abelson, 1977). These are organized systems that direct the execution of certain rules, as soon as the system itself is seen to apply. Larkin's (1983) study of physics problem solving serves as a good example. She found that experienced physicists classify problems as being of a certain type (e.g., balance-of-force problems). As soon as the classification is made, the problem solver immediately executes the computations appropriate for that type of problem and then examines the results to determine whether or not the problem at hand has been solved.

A knowledge-based model of problem solving that uses schema is in some sense intermediate between our definitions of comprehensive and limited-scope models. Programs have been developed that utilize schemas appropriate for solving certain classes of problems in different fields, ranging from word problems in school arithmetic to problems in elementary physics. These programs are general in the sense that they solve more than one type of problem within a field, but special in the sense that they are still limited to a particular domain of endeavor.

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Strengths

The strength of knowledge-based modeling is that it offers a way of modeling the manner in which people use what they know to solve difficult problems when the person being modeled is in a situation that offers several options in choosing actions. For this reason, knowledge-based modeling is particularly likely to be of assistance in understanding the way in which people execute supervisory control in man-machine systems. This is especially true if the sort of control being exercised depends on complex judgments and cannot be reduced to a set of instructions that anticipate every foreseeable circumstance.

How accurate are knowledge-based models? As a quite broad generalization, it appears that models can be constructed which account for a substantial portion of the actions that people make in certain problem-solving situations. Identifying situations in which a model does not account for performance can be an illuminating exercise in itself. For example, if a model cannot perform successfully when given the knowledge that people would be given in a training course, then the adequacy of the course can be questioned.

The knowledge-based approach to modeling is undergoing extensive and rapid development, particularly in the education and training fields. As the above examples illustrate, knowledge-based modeling has been used to explain how people solve problems in a variety of difficult educational fields. The approach has been extended to learning by including within knowledge-based modeling a model of how the problem solver incorporates new knowledge into old (Anderson et al., 1985). Although the applications of modeling plus learning have thus far been used only in industrial training and conventional school education, there is no reason they could not be extended to modeling the way a person becomes an expert supervisory control operator. Such applications have not yet appeared in the general literature, but they are being explored as basic research endeavors by the U.S. Air Force and Navy.

In summary, knowledge-based modeling appears to be a very promising way of modeling human cognitive activities in complex supervisory control situations.

Caveats

Knowledge-based problem-solving models have only recently been applied to traditional human performance problems. Exemplary studies are now being conducted in such areas as aircraft operation (Rouse et al., 1987) and nuclear power plant operation (Woods, Roth, and Pope, 1987), but there is not yet an extensive literature on the success of these ventures.

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Thus, it is not certain that the favorable experiences observed in educational and laboratory settings will transfer immediately to the human performance field. Four problems can be foreseen. It is worth noting that these may not necessarily be due to peculiarities of present knowledge-based modeling methods. The problems may be inherent in the attempt to model human supervisory control and complex decision making.

First, constructing knowledge-based models requires intensive study of the individuals to be modeled. Modeling is most successful if separate models are constructed for every individual of interest. Models that depend on group knowledge are less useful, simply because problem solving is often done on an individual basis. Given the varieties of behaviors that can be involved, there is no easy way to evaluate a model by examining collective behavior.

Second, knowledge-based models typically deal with relatively slow processes, in which the time between actions varies from tens of seconds to several minutes. This is quite a different time frame from that of traditional human performance modeling, which has been concerned with actions that take place in seconds or fractions of seconds. There is no clear tie between models of the way people think and models of the way they perceive or control motor responses. It is doubtful that models of perception and motor responding can simply be attached to knowledge-based models because there is a considerable amount of evidence showing that certain types of thought processes selectively interfere with certain aspects of perception and responding. Thus, the macromodel that aggregates submodels of perception, cognition, and motor responding will have to model the interactions between submodels. The scientific data base for constructing models of these interactions does not exist at present. Furthermore, the tendency of psychologists to specialize in the study of just one of these fields mitigates against the development of the necessary research program.

Third, knowledge-based models are expensive to construct. In any modeling effort, the first thing that must be accomplished is model identification, which means determining the appropriate structure for the model and estimating its parameters. The control theory models mentioned earlier in this report contain explicit structures and have well-understood methods for parameter estimation. Such is not the case for knowledge-based modeling. There is considerable latitude for structuring knowledge-based models. The variables are symbolic and the relations are logical rather than algebraic. As a result, knowledge-based modeling is usually approached by the analysis of verbal protocols or reports (Ericsson and Simon, 1984). This is time-consuming and subject to the analyst's biases of interpretation. Algorithmic methods for identifying rule-based models would be highly desirable. Some initial efforts in the development of such methods are now

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underway (Lewis, 1986; Lewis and Hammer, 1986) but cannot be regarded as mature at this time.

Fourth, knowledge-based models are extremely hard to evaluate. Proponents of knowledge-based modeling have argued, convincingly, that conventional statistical tests of agreement between model and data are simply inappropriate. Unfortunately, the same proponents have failed to specify what criteria for model evaluation are appropriate. Until this problem is solved, the use of knowledge-based models will, to an unfortunate degree, depend on social acceptance rather than formal validation.

One of the purposes of modeling is to be able to generalize beyond situations that have already been observed. The logic for generalizing knowledge-based models is certainly not as well understood as the logic for generalizing results applicable to conventional mathematical models of information processing. In fact, there may be a logical limit to generalization. The knowledge-based approach was developed to handle behavior that was dependent upon the context-specific knowledge used by particular individuals. To the extent that context specificity and individual problem-solving styles are important, generality should not be expected, no matter what the method of modeling. Major developments in the use of knowledge-based models in the areas of supervisory control and maintenance operations are expected to occur over the next 10 years.

SUMMARY OF MODELING APPROACHES

In this chapter, four of the more promising or heavily investigated approaches to modeling human performance in the operation of complex systems have been reviewed. As the discussion of the individual approaches shows, each has its strengths and each has caveats that should be borne in mind when considering it for a particular application. Where these strength/caveats differ significantly across approaches, they are important to note. However, to overemphasize the differences between the approaches discussed herein would, to some extent, miss three important points. First, in many respects, the various approaches are converging. For example, HOS developers are considering the inclusion of continuous control concepts; control models are incorporating discrete tasks and procedures; and task network models are beginning to include dynamic state variable models. In addition, proponents of the information processing, optimal control, and task network approaches are in various stages of exploring, implementing, and testing methods for including knowledge-based behavior of one sort or another within their respective models.

Second, some significant general concerns apply to all of the approaches:

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- As one moves from limited-scope models to comprehensive models, their complexity introduces a new set of problems for designers and users.
- All models, to a greater or lesser degree, require users to supply parameter values prior to execution; the more complex and comprehensive the problem and model, the greater is the number of parameters to be provided.
- None of the approaches can claim an exemplar having full traditional validation.
- None of the approaches, as yet, has effectively dealt with the problems of operator discretion and cognitive behavior.
- Most modeling efforts, thus far, have dealt primarily with the ideal, well-trained operator and have largely ignored individual differences.

Finally, it is significant to note that there are several viable approaches to developing comprehensive human performance models of pragmatic utility to system designers and developers. Presently, and for the foreseeable future, no single approach is likely to dominate the field; rather, it is to be expected that the various approaches will be applied most effectively in problems closest to their original focus of development.

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3

Applications

This chapter discusses the application of human performance models (HPMs) to four classes of real-world problem areas. The first two concern human-machine interaction in relatively well-defined operational situations: piloting of aircraft and control room operation of nuclear power plants. The third category concerns maintenance—a type of activity which, although relatively well defined and economically critical, has been somewhat neglected. The fourth is a broad class of human-machine interactions wherein the human operator does not perform the task directly, but instead supervises one or more automatic control systems that execute the direct control The latter area, which includes autopilots in aircraft, semiautomated nuclear or chemical plant control, and robots in factories, space, or undersea, poses new challenges for human performance modeling.

In the following sections it may seem that certain HPM approaches are constrained to specific application areas (i.e., that procedure/task—network and reliability—models are specific to the needs of the nuclear power industry or that information processing models are specific to the needs of cockpit designers). This is not the case. The appearance is due to the fact that each methodology was developed initially for a specific area of application. Most of the models discussed in this report are being expanded to other areas, but it is still reasonable to expect to find more instances of a model's use within its area of origin than outside. This does not necessarily imply either that a model, or an approach to modeling, is the only appropriate choice for a particular application or that it is an inappropriate choice for some other application.

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HUMAN PERFORMANCE MODELS IN AIRCRAFT OPERATIONS

The rapid development of aircraft during World War II gave rise to increasing problems for aircrew members. By the late 1950s, significant analytical efforts were underway in three human-machine areas that had been especially affected by changes in aircraft design and their missions:

1. flight control problems associated with new flight regimes and modified handling qualities;
2. crew workload problems associated with an expansion of mission requirements and a proliferation of aircraft subsystems with their corresponding displays and controls, and aggravated by generally shortened response times available to the crew, and
3. air-to-surface search and targeting problems associated with new flight regimes, new sensors, and improved surface-to-air defenses.

Each of these areas is treated briefly in the following pages, with reference to summary documents for more details.

Flight Control

Background

The expansion of operational envelopes and mission requirements for flight vehicles that occurred in the past two to three decades, and the resulting increase in task difficulty and pilot workload, have stimulated a strong need for systematic means of analyzing the pilot-vehicle system and predicting closed-loop performance and workload.

This, in turn, has led to substantial efforts aimed at developing quantitative engineering models for the human pilot performing closed-loop manual control tasks. As a result of these efforts, there exist an extensive HPM-directed data base, two well-established HPMs for continuous manual control tasks, and a long list of applications of these models in the flight control arena. Applications of these models include display and control system analysis, flight director and stability augmentation system design, analysis of vehicle-handling qualities, analysis of the limits of piloted control, analysis of pilot workload, and determination of flight simulator requirements.

A useful, alternative categorization of these applications that emphasizes pilot-vehicle system problems addressable by HPMs for the human controller is to relate them to flight test, design, and simulator planning problems; this was done by McRuer and Krendel (1974) and, more recently, by Ashkenas (1984). Each of these references provides three tables that illustrate quite succinctly the broad scope of application of human performance modeling to aircraft control-related problems. Ashkenas (1984)

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also provides a reference list by application category. These references focus principally on applications of the quasilinear modeling approach. Applications of the optimal control model (OCM) and related monitoring and decision making models are indicated in Baron and Levison (1977, 1980) and Rouse (1980). A major source of references on the application of these and a variety of other HPMs to control problems is the series of proceedings from the NASA-university conferences on manual control (1967-present).

Glenn and Doane (1981) used the Human Operator Simulator (HOS) to simulate pilot eye-scan behavior during manual, as well as more automated, flight control modes for both straight-in and curved approaches to landings of a NASA Terminal Configured Vehicle (TCV) aircraft. The HOS produced eye-dwell times on various flight display systems that had a high correspondence (r = .91) with empirical results obtained in an independent study of actual pilots who had flown those same approaches. Although this was the initial application of HOS to simulating complex piloting tasks, it provides some evidence that aggregated information processing models can also provide useful predictive data in cases where manual control and automated systems monitoring dominate an operator's tasks.

Current Issues

The evolutions of aircraft, control and display systems, and mission requirements are posing new problems in control: innovative aircraft configurations with different dynamic characteristics and, especially, with highly augmented controls; new types of control including six degrees of freedom controls; and different paths to fly. These new systems are not wholly understood, to say the least, and there have been persistent difficulties in design, including pilot-induced oscillations, excessive pilot workload and inadequate pilot-vehicle interfaces. There is a need both for data and for extension of the predictive capability of pilot models to such tasks.

Because of the increasing costs associated with simulation and training of flight control skills, it has become desirable to use models to assist in specifying simulators and in defining or monitoring training programs. In this area, a major limitation is the lack of adequate models for the way in which flight skills are acquired or learned.

The concern most often raised in connection with future modeling and understanding of the pilot in the aircraft control loop is the changed and changing nature of the pilot's tasks owing to the introduction of substantial amounts of automation. Thus, the roles of flight management and supervisory control (monitoring, decision making, interacting with intermediary computers) are becoming dominant in many pilot-vehicle display applications. As might be expected, the data and models needed

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for understanding these roles are not at all up to the standards of those for manual flight control tasks and are clearly in need of further development.

Summary

The changing, not fully understood, nature of flight tasks, the costs associated with aircraft development and production, as well as those of training operational personnel, and the history of unanticipated pilot-vehicle interface problems arising in development—all argue for the need for systematic, crew-centered design techniques. These techniques must be capable of addressing the problems of the pilot (crew) in the total system context of mission, vehicle, environment, automation, displays, etc. Although much work remains to be done, the lessons learned in analyzing manual flight control and some of the modeling techniques that have emerged from that endeavor can provide a sound foundation for the development of suitable analytical and experimental methods for the problems of interest. Some evidence for this is given by the Procedure-Oriented Crew (PROCRU) model (and its potential variations and generalizations) discussed in Pew and Baron (1983) and Baron (1984).

Aircrew Workload

Background

Crew workload and the allocation of functions to humans and machines in aircraft have been recognized as significant and related problems at least since the early 1950s (for example, see Fitts, 1951). A more recent survey (Air Force Studies Board Committee, 1982). documents that both problems are still with us.

Prediction of crew workload is a complex and labor-intensive task. One of the first published models developed for this purpose was based on a task network approach (Siegel, Miehle, and Federman, 1962). It calculated the times required for discrete operator actions from an extension of information theory. Many subsequent estimations of workload for discrete tasks, including more recent work by Siegel and Wolf (1969), have reverted to the use of measured or estimated task times or task time distributions. Exceptions include the HOS (Wherry, 1969, 1985), which was designed to calculate task times and to predict and diagnose such workload problems as poor display/control layouts or too many allocated tasks by aggregating the times required for microbehaviors (eye movements, information absorption, etc.); and Boeing's Computer-Aided Function Allocation System (CAFES), which contained Function Allocation Modules (FAM-I and FAM-II) and

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Siegel-Wolf type network approach Workload Assessment Modules (WAM and SWAM).

The Vought Workload Simulation Program (WSP) was developed in the early 1970s to aid in the analysis of workload problems in carrier landings by Navy aircraft. It was later expanded to cover all phases of flight. The WSP had separate modules for discrete and continuous control tasks, with a scheme for blending them. As in most models of the time, task sequences, task times, flight path tolerances, cockpit geometry, and system configurations were all developed externally and entered the model as inputs.

The Pilot Simulation Model (PSM) was in active use at McDonnell Douglas from 1975 to 1978. It utilized stored data on task times to generate workload estimates on discrete tasks, with particular attention to the effects of G-load on performance.

Greening (1978) provided a critical review of the then-known crew workload models for aircraft operation which indicated that three aircraft companies, Vought, McDonnell Douglas, and Boeing, were employing different computer models to estimate crew workload. The models reviewed were, in essence, bookkeeping models. The Greening report showed that significant parts of the aircraft industry were using HPMs to estimate workload. Task time distributions and priorities were inputs to the models; workload emerged from a comparison of task times with available time. As part of this working groups' effort, the three companies that reported using workload models in 1978, plus six other airframe contractors, were contacted to update the status of aircrew workload modeling.

Of the three airframe manufacturers who were using workload models some years ago, two (McDonnell Douglas and Boeing) have replaced the models, and the third (Vought) still uses the WSP model when needed but has not exercised it for several years. The primary reason for the shift to newer models is the rapid expansion of computer capability. The new models are interactive with the designer and have much more capacious and sophisticated data bases. In the ease of McDonnell Douglas, the newer models also involve different approaches to human performance modeling, including the OCM and operator models developed in the simulation language SLAM.

None of the six other manufacturers contacted indicated a use of workload models. It seems that these companies rely wholly on human factors expertise (including manual time line analyses) and manned simulation for uncovering and relieving problems of workload.

During the 1970s, both HOS and CAFES were run on large mainframe computers belonging to the Navy and were, therefore, not generally available to outside users. Similar restrictions applied to the use of Systems Analysis of Integrated Networks of Tasks (SAINT; funded by the U.S. Air

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Force). Therefore, many aircrew workload problems were investigated during the 1970s and early 1980s by human factors groups within the military, rather than by airframe manufacturers. For example, HOS and WAM were applied to the development of several emerging Navy aircraft (e.g., LAMPS helicopter, P-3C Update, VPX, and F-18); SAINT has been used to study workload problems in several Air Force aircraft and other systems; and the Army is currently investigating the use of several types of HPMs for studying workload problems in its MANPRINT program.

The brief history presented here indicates that much of the funding for HPM development, as well as the study of workload problems, has been stimulated by the military services. Although not all airframe manufacturers use computerized techniques for studying aircrew workload problems, the U.S. Navy, Air Force, and Army continue to recognize and advocate the utility of HPMs for investigating and resolving these problems.

Current Issues

Although task analysis of aircraft missions has provided an acceptable basis for modeling aircrew workload, a number of fundamental definition and measurement issues have been raised over recent years. One of these is that task-based measures are not deemed an acceptable definition of workload by some researchers and users. Some investigators feel that a clean distinction should be made between human operator performance requirements, such as result from task analysis, and human operator mental effort expended (i.e., a trained operator might perform a task with time and cognitive resources left over, whereas a novice may be fully occupied). They emphasize that the human mental effort expended (not physical calorimetry, which is largely irrelevant) in psychomotor skills or cognitive tasks is important, and if an individual human-centered measure (performance and effort expended) could be found, it might become a more sensitive predictor of human limitation and system failure than either a task-based measure or a system performance measure.

One performance related measure occasionally used is secondary task performance, which helps assess how well the operator can do an artificially imposed task added to the primary task. However, this measure is often deemed unacceptable by pilots and others because it interferes with the primary task. Many physiological measures of workload have been tried, but all exhibit significant measurement noise and require many seconds or even minutes of data to establish a single workload data point Probably the most acceptable mental effort measurement technique is the subjective rating scale now employed by Airbus Industries and the U.S. Air Force.

Recent research has sought to determine whether psychomotor business, emotional stress, and pure cognition can be measured separately, and

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whether the components are additive in determining total subjective mental workload.

Summary

Task analyses have yielded models for pilot workload in terms of percentage of hypothetically available time required by sensing, motor, and cognitive activities. Recent efforts have sought to measure and model mental workload.

Air-To-Surface Search and Targeting

Background

The problem of finding objects on the earth's surface from a moving aircraft has been recognized since the early days of flight. One of the earliest models of the air-to-surface search process was published as part of a study of the especially difficult regime of nap-of-the-earth flight (Ryll, 1962). This and many other early modeling efforts were summarized by Greening (1976).

As new sensors were added to aircraft equipment, the search and targeting activity became more distinct from piloting and was often performed by a separate crew member. A number of models for the use of quasivisual sensors television (TV) and Forward Looking Infra Red (FLIR) were summarized in a report by General Research Corporation for the Naval Weapons Center (Stathacopoulos and Gilmore, 1976).

The HOS model was used as the basis for an Operator Interface Cost Effectiveness Analysis (OICEA) by Lane et al. (1979) to examine the effect of proposed additions of FLIR-related tasks to an electronic countermeasures (ECM) sensor operator's job in a Navy P-3C aircraft To provide comparative data, three versions of the aircraft were simulated: the baseline version without FLIR equipment or tasks, the prototype version that had added (but not integrated) FLIR equipment and tasks, and a proposed Update version with more integrated and automated FLIR equipment and tasks. Comparison of HOS simulation results for the baseline and prototype versions confirmed actual fleet results which had shown that performance of the normal ECM tasks would be significantly degraded and performance of the FLIR tasks would rarely be successfully completed in the prototype aircraft. However, the study also showed that the Update version would permit all of the FLIR-related tasks to be successfully completed and performance on the ECM tasks to be enhanced.

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Current Issues

The multiple-sensor aircraft poses problems of a special sort, especially when used in high-intensity conflict where line-of-sight exposure to the target area may be dangerous, and an active sensor such as radar can be used only briefly and intermittently. The targeting decision process then becomes one involving difficult trade-offs between the risks associated with search and the need for current target data. Nonimage data (such as flight vectors or coordinates) must be blended with the output of automatic classifiers and with intermittent imagery in the most efficient way. A modeling approach to this problem is being developed at the Naval Weapons Center and elsewhere (Greening, 1986).

Summary

Numerous target acquisition models have been developed and used over the past 25 years. However, the bulk of model development and validation work is becoming obsolete because of changes in tactics, the proliferation of sensors, and advances in sensor technology including a variety of automatic targeting systems.

Because of the substantial lag in modeling relative to advances in technology and changes in tactics, models have not, in general, had substantial impact on the development of new or improved sensors. Their utility has been greater in tactical planning and related, postdesign activities.

The most active air-to-surface sensor modeling areas currently are those directed toward (1) enlarging the scope. to include more of the relevant context and (2) keeping up with developments in sensor technology.

HUMAN PERFORMANCE MODELS IN NUCLEAR POWER OPERATIONS

Background

The number of human performance modeling simulations actually applied within the nuclear industry is at present very small. Although considerable theoretical work has been done (e.g., Sheridan, Jenkins, and Kisner, 1982), translation of that work into everyday plant operations has been limited. Other than instances in which cognitive modeling has been incorporated into operator aids (e.g., Westinghouse's DICON work; U.S. Department of Energy, 1983), the majority of applications have been associated with risk assessment and nuclear power plant safety (U.S. Nuclear Regulatory Commission, 1982). Most of these cases have involved responses to requirements of the Nuclear Regulatory Commission.

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In a recent meeting, nuclear experts discussed the capabilities of methodologies currently used for risk assessment. That meeting provided useful insights into the status of human performance modeling as well as the reasons behind that status. It became evident that human performance modeling should not be considered as isolated from other techniques because actual plant usage was the result of many implicit decisions about strengths and weaknesses in available methods. Consequently, this discussion considers HPMs within a framework of the available technology.

There are five main techniques used for the assessment of human related risks: Technique for Human Error Prediction (THERP), Operator Action Trees (OATS), Maintenance Performance Prediction System (MAPPS), Sociotechnical Approach for Human Reliability (STAHR), and SLIM/MAUD (Success Likelihood Index Methodology/Multiattribute Utility Decision). Of the five, only MAPPS utilizes discrete task network simulation as the sole basis for prediction. Why the large body of theoretical models that exists has not been utilized more completely is best seen by a relative comparison of the strengths and weaknesses of other techniques. A brief summary of the methods follows.

The THERP technique (Swain and Guttman, 1980) is probably the oldest and most established human reliability assessment method and was originally developed by Swain (1964) at Sandia National Laboratories for military applications. The method relies on task decomposition into microscopic actions via a highly detailed task analysis. This analysis breaks down operator behavior to a level of individual actions such as reading a graph, reading an instrument, or turning a control knob. Each series of operations is described by a probability tree composed of sequential actions in which the probability of an action at any branch is drawn from tables. In a few cases these probabilities are based upon objective evaluations, but in most cases subjective expert opinion is used.

The OATS also utilizes probability trees to structure operator actions but has much larger units of analysis, usually plant functions rather than operator tasks (U.S. Nuclear Regulatory Commission, 1984). A probability is placed on each function, based on the time that would be available to perform the function within particular scenarios. As a result, heavy use is made of time/reliability curves relating probability of performance to available time. Times are computed based on the time required to recognize and diagnose a plant condition. Each time is defined as total time available minus the time required to execute an operator action. Currently, OATS uses three types of curves to provide a human reliability value; each is based on the nature of the operator action.

The MAPPS system is a discrete event simulation (Siegel, Bartter, Wolf, and Knee, 1984). In its current form, it addresses only maintenance behavior. It is menu driven and includes a variety of parameters whose

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values can be specified by the user or provided by the system as default values. A unique feature permits the interpolation of branch performance times from partial data. The system uses Monte Carlo simulation to produce estimated numbers of maintenance errors as a function of number of attempts. An important difference is that failures are based on step by step criteria because of the possibility that other later failures could depend upon seemingly trivial step responses. This is in contrast to other methods that calculate macroscopic or total event probability and thus tend to omit tenuous paths.

The STAHR is a quantified expert judgment method based on influence diagrams. Teams of experts break problems into microscopic sets of influences, which are then rated and recombined into a final decision value. This method is particularly strong in analyzing unexpected factors in plant accidents because of the extreme richness of attention given to team member insights and the rationale used. Emphasis is on situation-specific problems. The method is particularly well suited for the analysis of cognitive processes largely due to its ability to represent detail and task uniqueness or to handle trade-off decisions. However, it is not, strictly speaking, a human performance model as the term is generally used.

The final approach, SLIM/MAUD (Embrey, 1984), is also a group judgment technique, but it is partially computerized and uses a combination of the Success Likelihood Index Methodology (SLIM) to identify human performance variables and MAUD 4 decision theory code. The SLIM code is driven by human performance variables. Variables are, in turn, related to reliability estimates through a scalar anchoring process analogous to a Thurstone ranking procedure.

It is difficult to determine which approaches work well and where they are successful in the nuclear application because the amount of available data on plant accidents is limited. As a result, assessment of risk prediction adequacy has generally relied on intuitive expert agreement. One exception is the area of maintenance where information exists on many component operations, such as frequency of repair records. In preliminary comparisons with this information the MAPPS program has shown good agreement with actual data. However, it should be emphasized that there are few historical data even for known errors. The data problem is most noticeable when there is a need to know how errors were made rather than their result.

Although certainly not a unanimous opinion, some preliminary conclusions can be attempted. When task analysis data are available, THERP appears to be appropriate. For a quick screening analysis, time/reliability curves such as OATS represent an easy approach if existing curves apply. For cases involving substantial cognitive efforts, techniques such as STAHR and SLIM/MAUD appear best if there is good industry cooperation. The MAPPS has not yet been applied to enough cases to draw final conclusions;

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it appears better than existing methods for maintenance analysis, possibly bemuse the other approaches are oriented toward operators.

Analysis of the other methods' strengths suggests the following. First, HPMs may require more parametric data than are usually available in actual industrial settings. Second, labor-intensive techniques can provide subtle decision rationales that may be lost in stochastic methods such as Monte Carlo simulations. Third, expert group techniques provide greater flexibility for considering situation-dependent tasks. Finally, dimensions of plant cooperation and ease of use weigh heavily in applications. Human simulation methods currently do not have an effective interface to normal plant user environments.

A comparison of where the approaches are deficient provides additional insights. Regarding THERP, its strengths are that traceability of final event probabilities to original situations is good. Flexibility is high because it can deal with unusual tasks. It is weak in that it requires what many consider to be an inordinate amount of training, it is extremely resource intensive because it requires task analysis for every task, and it can be very vulnerable to misuse or biasing if not used as prescribed. The latter results from a tendency of users to skip to probability tables and bypass important intermediate steps.

For the OATS approach, traceability is also good because only one variable is involved. Reproducibility (i.e., interrater reliability) is good, and there is a low requirement for training, which is largely due to the somewhat simplistic nature of the method. This approach tends to be inflexible because it can be used only for certain events, and it is very low in completeness because it operates at too general a level of analysis to encompass the full range of probabilistic risk assessment problems.

In the MAPPS simulation, reproducibility, but not traceability, is high because MAPPS uses stochastic branching. Compared to the analysis level of THERP, the resources required are minimal. The model is strong on completeness because the effects of variables have been quantified carefully and are drawn from a systematic analysis of years of research into factors important for maintenance performance. In terms of weaknesses, MAPPS currently deals only with maintenance; it is also weak in its ability to handle unique task factors.

The STAHR approach is strong in the last area. It can be readjusted quickly by changing influence diagrams; it has good traceability because the reasons for using each value are documented, the group procedures reduce individual biases, and extended discussion of plant characteristics and actions permits great specificity of task definition. Weaknesses are similar to THERP in that training is needed to permit groups to work effectively together, and it is both resource and time intensive. In contrast to THERP, the resources are people rather than data.

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The SLIM/MAUD approach is high on traceability, flexibility, and specificity of task definition. One of its principle weaknesses is that the structure appears to preclude the evaluation of performance variable interactions.

To draw conclusions, it appears that the greatest gains for the industry may come from using human performance models as a part of a hybrid technique rather than in a stand-alone mode. Because the above approaches do not all operate at the same content level, analysis may best be made through combinations of techniques rather than a single approach.

Current Issues

Within the domain of plant safety, four issues currently appear to be the most important. The first is how analysis can best be applied to cognitive tasks, particularly in such areas as confusion between competing symptoms of plant events. Such questions have been studied by using confusion matrices that have symptoms on one axis and plant events on the other.

Additional issues concern identification of those human variables that are really important in plant performance. What constitutes a satisfactory cognitive model of the operator, how the costs of HPMs can be compared to their benefits, how potential users should be acquainted with the technology available, and how human and power plant hardware models can best be integrated are all examples.

Validation is clearly the most important current issue. It manifests itself in three ways: data collection problems including the acceptability of hardware simulator data and the difficulty of field data collection; the interpretation and reduction of collected data; and the comparison of potential approaches. The most fundamental criterion is how well a model works in the field. To answer that question, better data are needed. Because obtaining data is difficult, the use of human performance modeling techniques is slow, particularly for rare accident events.

A second area concerns issue selection. The questions involved are whether the selected performance variables are correct ones and how the nuclear industry can be certain they are.

A third area concerns the ability of models to deal with events outside the realm of the expected because rare accident events are central to plant safety.

A fourth area is misdiagnosis behavior and how it can best be addressed. This area may or may not become less important because of recent emphasis on symptom-based (i.e., unknown cause of abnormality) diagnostic procedures instead of event-based (i.e., known cause of abnormality) procedures.

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A fifth area is the previously mentioned question about coupling of methodologies. Specifically, can human simulations effectively couple to already existing techniques such as THERP or SLIM/MAUD? Another area is the use of human operator models in design specification, particularly for purposes of increasing human reliability. The final area concerns what can be done to eliminate confusion and increase correct diagnosis probabilities, given the occurrence of a misdiagnosed event.

Summary

This section has examined human performance modeling for the nuclear industry from a particular perspective, namely, human reliability and risk assessment. That perspective was adopted for two reasons. First it depicts the way in which it is actually applied in industry. Second, insights into why models are and are not used were discussed by comparing an existing model (MAPPS) with the limited set of methods currently used for risk assessment. By considering other approaches, it was possible to place a human performance model into the perspective of an entire technology area. This has often been difficult in many broad-based technology areas such as military applications. As a result, direct comparisons of strengths and weaknesses could be made to highlight not only what role the methods serve, but also to identify more directly what trade-offs had been made among recurrent questions such as ease of use, resource requirements, specificity of analysis, reliability, and traceability. As mentioned at the beginning, the actual use of human-related models in the nuclear industry is extremely limited. The models applied appear to be the result of a practical mix of many of the factors described above. The extent of future model usage will probably hinge more on the result of changes in available data and resource support than on the actual state of human model technology.

HUMAN PERFORMANCE MODELS IN MAINTENANCE OPERATIONS

Background

Maintenance is different from many of the other tasks discussed in this report. In particular, although time is an important attribute (i.e., the sooner something is repaired, the better), system maintenance is usually a static task because the system state does not change without human input. Of equal importance, maintenance can be a very complex task when unexpected and unfamiliar failures occur. In such situations, problem-solving skills are central and psychomotor skills are of secondary importance.

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This section briefly reviews HPMs for *predicting maintenance* performance. One model, MAPPS, has been discussed in the context of nuclear power operations. For the purposes of this review, maintenance performance is characterized at three levels:

1. action-by-action sequences of observations, tests, and repairs (referred to as SEQUENCES);
2. overall times and errors associated with particular sequences (referred to as TIME/ERRORS); and
3. mean time to repair and probability of error across sequences or equipment systems (referred to as MTTR/PERR).

The maintenance models discussed here produce outputs in one or more of the above levels. Inputs to these models include one or more of the following:

1. representations of the equipment, either physically or functionally;
2. representations of the maintainer in terms of

- general characteristics (e.g., parameter variations),
- action selection criteria (e.g., maximum information gain or minimum time),
- knowledge and skills (e.g., understanding of equipment); and
- 3. results of task analyses (i.e., maintenance SEQUENCES).

Based on the above characterizations of outputs and inputs, six representative maintenance models are summarized in Table 3-1. It is interesting to note that the approaches underlying these six models (second column of Table 3-1) represent the full range of modeling approaches discussed in this report. Thus, there is no one-to-one mapping from application domain to appropriate modeling methodologies.

In distinguishing among the models in Table 3-1, Wohl's (1982) model and that of Siegel et al. (1984) emphasize global performance measures such as MTTR. Traditional labor-intensive maintainability analyses have a similar focus (Goldman and Slattery, 1964). In contrast, the models of Hunt and Rouse (1984) and of Towne, Johnson, and Corwin (1982) emphasize fine-grained predictions of SEQUENCES. The model of Madni, Chu, Purcell, and Brenner (1984) falls on the global side of these fine-grained approaches. Therefore, the choice among the models in Table 3-1 depends on the level of performance to be modeled.

Summary

It would seem feasible to use fine-grained models to produce the SEQUENCES to meet the task analysis requirements of the global models. This approach would reduce the analytic effort required and produce performance predictions at all levels. However, the knowledge-engineering effort

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TABLE 3-1 Attributes of HPMs for Maintenance Tasks

		Inputs Required			Outputs Produced			
HPMs for Maintenance	Approach to Modeling	Representation of Equipment	Representation of Maintenance	Task Analysis	Predicted Sequences	Predicted Time/Errors	Predicted NTTR/PERR	Domains of Application
Goldman and Slattery (1964)	Statistical calculation	Physical	Not required	Required	—	Secondary	Primary	Many military systems
Hunt and Rouse (1984)	Rule-based, fuzzy set theory	Functional	Knowledge and skills	Not required	Primary	Secondary	Secondary	Simulated automobile and aircraft power plants
Madni et al. (1984)	Petri nets	Functional	Not required	Required	—	Primary	Secondary	Example for a shipboard propulsion system
Siegel et al. (1984)	Task network simulation	Physical	General characteristics	Required	—	Secondary	Primary	Nuclear power plants and others
Towne et al. (1982)	Optimization	Functional	Action selection criterion	Not required	Primary	Primary	Secondary	Electronic systems
Wohl (1982)	Optimization	Functional	Action selection criterion	Not required	—	—	Primary	Electronic systems

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required to undertake this (relative to both equipment and maintainer) is probably impractical when the modest levels of investment normally made in maintainability analyses, which are sometimes viewed as a necessary evil, are considered.

HUMAN PERFORMANCE MODELS IN SUPERVISORY CONTROL

Background

Supervisory control is an example of an important merging class of human operator activity in which HPMs are needed but for which proven models do not now exist. Simply stated, supervisory control refers to all the activities of the human supervisor who interacts via a computer with a complex semiautomatic process. It can substitute for direct manual control of vehicles or plants.

The term supervisory control is derived from the close analogy between the characteristics of a supervisor's interaction with subordinate human staff members and interaction with automated subsystems. A supervisor of people gives general directives that are understood and translated into detailed actions by staff members. In turn, staff members aggregate and transform detailed information about process results into summary form for the supervisor. The degree of intelligence of staff members determines the level of involvement of their supervisor in the process. Automated subsystems permit the same type of interaction to occur between a human supervisor and the process (Ferrell and Sheridan, 1967). As indicated in another report of the Committee on Human Factors (Sheridan and Hennessy, 1984), supervisory control behavior is interpreted to apply broadly to vehicle control (aircraft and spacecraft, ships, undersea vehicles), continuous process control (oil, chemicals, power generation), and robots and discrete task machines (manufacturing, space, undersea mining).

In the strictest sense, the term supervisory control indicates that one or more human operators set initial conditions for, intermittently adjust, and receive information from a computer that closes a control loop through external sensors, effectors, and the task environment, as illustrated in Figure 3-1. Typically, supervisory control involves a five-step cycle of the supervisor's activity (Sheridan, 1986), which includes the following functions:

1. *planning* what to instruct the computer to control automatically, which involves the supervisor in (a) coming to understand the nature of the controlled process, inputs, and other physical constraints, (b) deciding on the trade-offs between various benefits and costs, and (c) thinking through a strategy for arranging the task;

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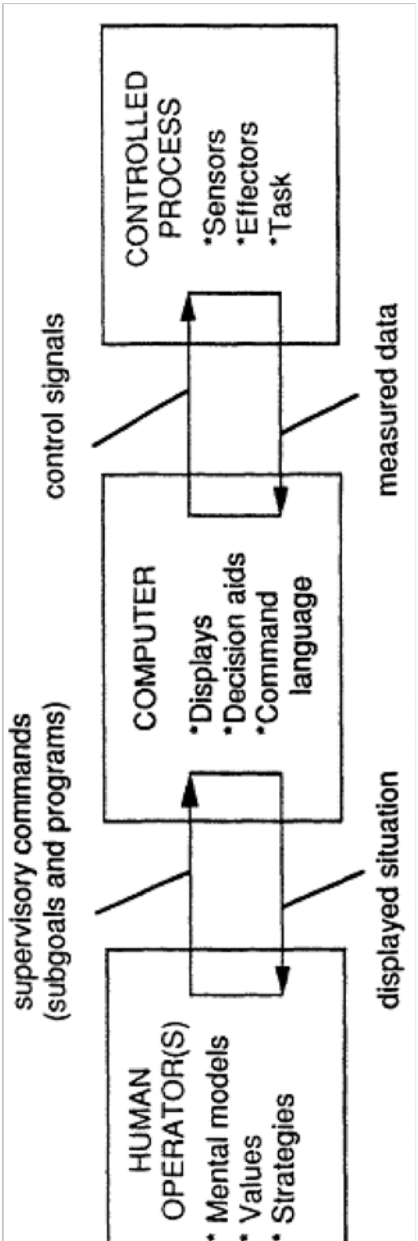

Figure 3-1
Human-computer interaction in supervisory control.

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2. *instructing* or actually programming plans into the computer to do (or start to do) certain things automatically for normal operation or to stop some actions when they are complete or abnormal;
3. *monitoring*, that is, (a) allocating attention among many sources of information about what is going on, including direct sensors, biocomputer knowledge bases and expert advisory systems, documents and human experts, or others in order to watch the (usually normal) automatic operation of the system, and (b) estimating the current system state and deciding if it is satisfactory, or if not, to diagnose what has gone wrong;
4. *intervening* that is, breaking into the automatic control loop either in a minor way to adjust set points of automatic control or in a major way to stop one task and start a new one, to take emergency actions (fault management) manually, or for maintenance or repair; this involves reprogramming (loop back to step 2); and
5. *learning*, that is, acquiring from experience what is necessary for better future planning (loop back to step 1) or other supervisory functions.

Each of these functions and subfunctions may be said to involve a separate mental model, though the term as used today is mostly restricted to step 1(a). Each may be augmented by a computerized decision aid of some type, in addition to the computerized automatic control.

Although a variety of models of supervisory control have been proposed, including the PROCRU model discussed earlier, there is little consensus on which way to proceed. One of the major problems in modeling human supervisory control is that formulation of the objective function is an active role of the supervisor; it is not given a priori. There are usually as many objective functions as there are people or occasions where one objective has different strategies. None of these is easily specifiable in other than fuzzy linguistic terms.

A model can be (1) a paper description of a system, i.e., a theory. Alternatively, it can be (2) a functional model implemented on a computer, which emulates the function of a system, or (3) a mental model, an internal representation of a system held in the mind of an operator, designer, or researcher. Supervisory control is particularly complex because multiple elements of (2) and (3) must be combined into a single physical system which must, in turn, be combined with (1).

From Figure 3-1, it is clear that a model of supervisory control must be a model of the entire system, not just the human. The situation is similar to that found in models of the human operator in manual control systems, where the particular realization of the model depends in each case on the properties of the rest of the system. Humans modify their behavior to compensate for, or complement, other elements of the system; for that reason, all of them must be represented.

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A supervisory control system is one in which there is little or no overt human activity for considerable periods. The tasks that a human must carry out are initiated by plant states or by operators receiving goals from a higher authority such as management. Each special function requires a model, and a model of the supervisory controller would describe the interaction of human and computer as a function of plant state.

Several models of limited scope may be relevant to supervisory control. Moray (1986) reviews some 10 models of monitoring. There are many models of decision making and several models of fault detection for a variety of different tasks (Rouse, 1983; Moray, 1986; Wohl, 1982). Intervention to trim the system set point could probably be modeled by a conventional expert system. However, none of these models supervisory control If other models of planning, monitoring, and fault management existed, they might be used to predict behavior in supervisory control, provided that the state of displayed information was also known. For example, if the operator had recently looked at variables (Y_1, Y_2, ..., Y_h, ..., Y_n,) and those values were known, a model might suggest that the operator would recognize that the system was in state S_i, and that, by using a production system, one might predict planning or action P_j, A_k from S_i and a knowledge of the operator's goals.

A unique feature of supervisory control is the passing of control backward and forward between operator and computer (see, for example, Sheridan and Verplanck, 1978). There is an ability of the system to make judgments on the basis of its knowledge and to enter into a dialogue with the human operator. There have been a few attempts to provide solutions for the allocation problem, such as those of Sheridan (1970) and Moray, Sanderson, Sluff, Jackson, Kennedy, and Ting (1982), but these are algorithms (comprehensive procedures for obtaining a desired result) rather than models of human performance.

The situation is reminiscent of Simon's (1981) attitude toward human behavior:.

> A man viewed as a behaving system, is quite simple. The apparent complexity of his behavior over time is largely a reflection of the complexity in which he finds himself.... We can often predict behavior from knowledge of the system's goals and its outer environment, with only minimal assumptions about the inner environment.

In this regard, Sanderson (1985) notes that

> It is obvious that the sort of goals being pursued in basic cognitive research and those being pursued in applied cognitive engineering are very different.... The questions being posed in basic research are often conceptually sweeping and are ideally task-free.... The concern is that .. fundamental principles ... emerge.... In an applied cognitive setting

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> however the task takes precedence.... When trying to understand, say, how an expert does a task a great deal of the researchers' time and effort goes into understanding the task itself. The model of human behavior which emerges has more reference to the task than is normal, or even considered proper, for basic research.

This may be a good point of departure for developing a model of supervisory control. Because the human plays a quantitatively slight but qualitatively important role in such systems, a model of the machine is as important as one of the human. Of the existing models, PROCRU is a good start because the expert system portion of it allows planning, reasoning, and procedure choice to be modeled.

Summary

Supervisory control is an emergent class of systems wherein humans supervise computers and computers perform the direct control. It poses new demands for integrated human performance modeling, inherently demanding component models of high-level activities such as planning, teaching, monitoring, failure detection/intervention, and learning. It also poses a new perspective with respect to dependence on both the task and the initiative of the human operator.

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4

Issues and Research Recommendations

OVERVIEW

In examining the state of the art of human performance modeling as it applies to complex dynamic systems, a variety of models and modeling approaches exist and have been, or are being, used in meaningful applications. Nonetheless, there are issues concerning the technology of modeling that need to be addressed before human performance models (HPMs) can have the kind of impact envisioned by their proponents. In this report, the issues of principal interest are generic rather than specific to a particular model or approach.

First, there is a constellation of five interrelated issues that are associated with attempts to extend the scope and applicability of HPMs to the kinds of complex problems that are of concern here.

1. *Complex/comprehensive models*: Most existing HPMs have been developed only for relatively simple situations. Many of the real-world person-machine systems of interest today are highly complex, involving multiple operators, multiple tasks, and variable environmental or equipment contexts. Preferred methods for developing HPMs for these systems have not been identified.
2. *Model parameterization*: As models become more complex, the number of parameters related to human performance in the model is likely to increase. The human performance data necessary to specify the parameters, and therefore to support the HPMs, will be more difficult and costly to obtain. Existing data bases are unlikely to be adequate for a priori definition of the HPMs and, in most cases, data appropriate to the

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technology incorporated in current and anticipated person-machine systems will not be available.

3. *Model validation*: As models become more complex, they also become more difficult and costly to validate. This is as true for models in economics and physics as it is in human performance modeling. As such, comprehensive HPMs lack the kind of scientific validation that has been achieved for many simpler models. This is unlikely to change, and the feasibility of extensive validation of comprehensive models is problematical.
4. *Underutilization/inaccessibility of HPMs*: Most complex HPMs have not been used widely or subjected to independent evaluation. Unless some way to simplify their acquisition and facilitate their increased use is devised, this situation is unlikely to change.
5. *Potential for misuse/misunderstanding*: As models become more complex, they also become significantly more difficult to use. Misuse of models is potentially costly for the user and harmful to the credibility of the modeling community.

Three additional issues, related to modeling the future role of operators of complex systems and to recent developments and emphases in psychology, emerged from the working group's deliberations.

1. *Accounting for mental aspects of tasks*: In an attempt to deal with cognitive aspects of the operator's tasks, there has been increasing interest in incorporating mental models into HPMs. This is particularly true as the operator undertakes planning and other supervisory roles relative to semiautomatic systems. Methods and data for accomplishing this are ill defined.
2. *Developing and using knowledge-based models*: Along with the increased interest and popularity of artificial intelligence (AI), there has been a rush toward the development, integration, and use of intelligent or knowledge-based models (or submodels). The popularity of the concept may have outpaced methodological developments in the knowledge engineering (knowledge gathering and representation) necessary to support the development of HPMs.
3. *Accounting for individual differences*: The effects of individual differences have been largely ignored in HPMs to date, in favor of using average indices of human characteristics representing the ideal, fully trained operator. Many individual characteristics may have a significant impact on human, and therefore on system, performance and need to be considered.

These issues are elaborated below, and recommendations for addressing them are presented.

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SPECIFICS

Complex/Comprehensive Human Performance Models

Issues

In the past, HPMs have tended to be designed or selected for specific situations and used to simulate a single-function, person-machine system. Examples include search models with sequential looks, signal detection models with successive samples, game theory models with successive moves and defined payoffs, and tracking models with defined limits.

In many, if not most, real-world situations the system operator is faced with a mixture of tasks and inputs that vary along dimensions such as form, validity, importance, redundancy, cost, and response requirements. The underlying truth may be known only vaguely by the operator: intercorrelations may be significant but unknown; critical functions may interrupt routine ones. One result is that the person-machine system must reconfigure itself to handle different types of functions. An appropriate HPM should be capable of similar changes of focus and state. The implication of this is that a comprehensive HPM must incorporate a model to account for properties and performance consequences of human attentional mechanisms. That is, it must account for changes in focus of attention and the resulting effects of both subtask and total system performance.

These considerations and implications give rise to basic questions concerning the direction that the development of comprehensive HPMs should take:

- Should a supermodel be developed, based on a single overarching theory, that will predict all the performance of interest? If so, what are reasonable expectations for, or limitations of, such a model?
- Should comprehensive models be developed by providing a suitable framework for integrating existing unitary or single-task models? In concept, the set of existing single-task models could be combined, like Tinker toys, into the most appropriate or efficient format for specific modeling tasks. In practice, the questions will be, What is a suitable framework? How does one interface models that have very different bases? and Are the component models additive?
- Should the total system modeling effort and the development of comprehensive HPMs simply be abandoned and existing models used as part-task analysis tools? In other words, should "business as usual" prevail, with research efforts aimed at improving existing models or developing single-task models for the new tasks of interest?

Two other issues relate to the appropriate scope of future complex/ comprehensive HPMs. First, until 10 years ago, most HPMs focused

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on the structure of tasks of interest but not the context. Control theory, signal detection theory, information theory, and other extant approaches tend to capture the structure of tasks in general but not the specific meaning of model parameters in relation to particular situations. Certainly, most models reflect the context, but the context is not explicit. For example, models for performance on psychomotor tasks do not generally account for any differences that might be involved in initiating that task after completing or interrupting a cognitive task as opposed to another psychomotor task. Insofar as context changes may have a significant impact on the ability of humans to change their focus of attention, the explicit modeling of context may be an important component in the development of comprehensive HPMs.

Second, many systems of interest are sufficiently complex to require more than one human for operation. Quantitative models for group performance are seriously lacking. A complete and reliable empirical data base on group performance is not currently available. Moreover, it will be extremely difficult to obtain appropriate and generalizable data. The sources of variability are increased when teams of individuals are involved. Requirements such as the needs for trained subjects and relatively long experiments impose large financial and human burdens. Some important questions related to multiple operator models include the following:

- How does one account for a crew member's internal model(s) of other crew members?
- Can factors such as social interactions and leadership be accounted for quantitatively?
- Is it possible to conceptualize team activity so as to distinguish clearly the components of performance associated uniquely with the interaction of team members from those associated with members acting individually?

Recommendations

Inasmuch as modeling attention is going to be an important component of any comprehensive modeling efforts, it is recommended that fundamental research in the area, having a quantitative perspective, be pursued.

With respect to constructing comprehensive HPMs, it is highly unlikely that a single supermodel incorporating all levels of complexity could be developed in the foreseeable future or, for that matter, that it would be a particularly useful tool. A truly universal HPM is almost certain to be too complex to understand and use efficiently. In addition, it would incorporate large amounts of "excess baggage" for any specific application. Identification of the reasonable limitations to size and complexity in a functional HPM will, most likely, have to wait until models exist that go

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significantly beyond those of today. On the other hand, the "business as usual" approach to part-task modeling and the refinement of single-task models seem too narrow to have the kind of impact on HPM system design and evaluation that is needed and justified.

Thus, models that rely on integrating various submodels should receive the most attention. Because the potential variety of HPM situations is great, and because it is premature to decide on one favored approach to developing comprehensive HPMs, a gradual extension or aggregation of well-validated models to deal with new or compound situations, is recommended. The aggregated models should be validated experimentally to the extent possible.

It is also recommended that methods of accounting explicitly for context be explored. In particular, it appears that AI constructs may be relevant to this problem and that linking traditional numerical models with newer symbolic models, in an attempt to incorporate the richness of contextual situations within HPMs, would be an attractive area to explore.

Of the possible extensions to current modeling approaches, the first area to be investigated should be the development of models for tasks involving two persons. This would serve as a foundation for larger modeling efforts and for addressing multiperson modeling issues.

Model Parameterization

Issues

The problems associated with the parameterization of comprehensive HPMs will be substantially more difficult than those for simple, single-process models. To help understand the difficulties somewhat, note that model parameters generally fall into four classes:

1. Parameters that are defined by the initial conditions under study, such as hardware variables for which specification forms a part of the problem statement. Examples include the distance between controls or the maximum speed of a vehicle.
2. Parameters that form an integral part of the human operator model, but that may be assumed to be invariant (or have invariant distributions) over the range of conditions to be studied. These values or distributions may be estimated by aptitude/achievement tests, laboratory experiments, theory, or assumption. Human time delays and observation noises in tracking tasks, reach times or eye movement times for a given hardware configuration, or memory recall times for certain tasks and contexts are examples.

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3. Parameters that may vary from condition to condition, but for which theory or experiment defines the rules of variation contingent on the context in which they are to be *assigned*. For example, the parameters describing distributions for task completion times in task network models may be based on empirical data for the specific task/condition or a related one; they may be predicated on some theoretical basis such as Fitts' law; or they may be various parameters of the describing function models for control tasks which are specified on the basis of verbal adjustment rules that result from theoretical considerations and empirical data.
4. Free or unknown parameters that are given assumed values at the time the model is exercised in order to predict performance or are adjusted after the fact to produce the best fit to data obtained in experiments or operation. Examples are parameters related to human performance objectives such as cost function weightings or task criticalities.

A general goal in any modeling effort is to limit the free parameters used in predicting behavior to the smallest number possible. For relatively simple situations such as linear, time-invariant systems and normal distributions, there are strong theoretical results to help resolve the questions concerning numbers of free parameters as well as algorithmic methods for estimating parameters and statistical results to establish confidence limits.

Given the complexity of the systems of interest today and for the future (e.g., nonlinear, time varying, mixed discrete plus continuous distributions), existing formal system identification and parameter estimation methods are not likely to be applicable to the problem of rigorously identifying all the parameters of complex HPMs. This fact raises a number of significant questions:

1. How constrained must a model be in order to make useful predictions or generalizations?
2. Is there a reasonable ratio of unconstrained parameters to dependent variables that leads to useful models? How much uncertainty in parameter settings can be tolerated before the predictions lose accuracy and credibility?
3. Simple models have the potential to exploit statistical procedures for identifying parameter values and maximize the goodness of fit to a data set However, models of the scope considered here are less amenable to these approaches because of the complex interactions involved. Is it possible to devise systematic approaches to estimate parameters that do not have full statistical rigor, or even the rigor of efficient hill climbing algorithms, yet provide some bounds on the time, effort, and confidence in the values obtained?

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Some of these questions seem to depend on the particular model or application domain being considered, but some general statements might be made as experience with alternative model forms accumulates.

An issue closely related to questions about the number and disposition of free parameters within a model is the quality and validity of the data base from which values for those parameters are drawn. Questions related to this issue include the following: What is the quality of the data used to establish values for parameters within a model? How good was the quality of the data base on which the model was first established? From how wide a population were the data collected? Is the data base population representative of the prospective system operator population?

Recommendations

The true degree and nature of the parameterization of particular HPMs is often opaque to all but the model developers. It is recommended that in documenting HPMs, developers be encouraged to identify and classify all parameters of the model. It would be useful if general classification schemes were employed in the process. The four classes given above represent one classification scheme. This scheme may have to be augmented to reflect parameters related specifically to computer implementation of the HPM, such as sample rate and bit size.

Research into systematic methods of parameter identification, estimation, and evaluation for complex HPMs is needed. For example, the impact of trade-offs between the number of parameters that must be estimated from data in live simulations and the number of system performance measures to be predicted from the HPM in simulation should be examined. It should also be a goal of research to develop estimation techniques that aim at uncovering distributions of parameter values, rather than simply point estimates, so that HPMs can be used to predict the range of expected performance and not just average performance.

Existing human performance data bases should be reexamined to determine their relevance for specifying parameters of HPMs. However, efforts will probably be required to develop a more systematic data base for HPM development Such efforts are to be encouraged.

Problems With Validation

Issues

Issues of validity have been difficult to resolve for simple models. They will be substantially harder to address for the complex models required in future applications. Most models have been validated only for single-task

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situations. The human's ability to perform a particular task may depend on the nature of the other tasks for which he or she is responsible. For example, it may be that sequentially moving among regulation, recognition, and problem-solving tasks can lead to degraded performance relative to that achieved in single-task situations. On the other hand, different tasks may be complementary in the sense that the performance of one task may make performing another task easier. For example, there may be a natural relationship between tasks, in terms of information requirements, that leads to transfer from one to the other. Although it is probable that the models developed for single tasks will ultimately prove suitable as constituent models in an overall multitask formulation, most models have not yet been validated in this manner. Relevant questions include the following:

- To what extent can models of limited scope that have been validated independently in a research environment be assumed to be valid when incorporated as submodels into an integrated model?
- Which single-task models can be combined to yield valid multitask models?

In many computer-based systems, operators serve a supervisory, rather than a direct control, function. As such, the amount of human sensory-motor performance data available for comparison with model performance data will be limited.

- How is the operator's cognitive contribution to be modeled?
- How does one validate a model for the long periods in which there is little or no overt behavior?

With mathematical or simulation models one usually looks for quantitative validation or tests of model accuracy. For models of complexity sufficient to represent full-scale human-machine system performance, problems of validation go well beyond selection of the proper goodness-of-fit statistics. The standard theoretical and statistical assumptions and constructs used for testing or validation of simpler models such as linear systems, normal distributions, and point estimation may be wholly inadequate. Are existing tools adequate for the validation process? If so, what are they; if not, can they be developed?

As a result of these difficulties, comprehensive HPMs lack extensive scientific validation—a compilation of several independent, critically examined studies showing that in a variety of human-machine systems the crucial statistics on operator performance are in close agreement with the statistics predicted by a comprehensive HPM. Such a body of data does not exist for any current comprehensive model Furthermore, developing such a data base would be an extremely expensive and time-consuming process requiring extended studies of several large-scale human-machine systems.

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While one would certainly like to see the results of such a program, it may be unrealistic to expect them.

However, there are other ways to evaluate a model. A model may have demonstrated an adequate level of practical utility by repeatedly producing satisfactory answers to real-world engineering questions. Ultimately it is the user, not the model developer, who decides if the model has sufficient utility. To determine whether or not this is true, the user needs access to comparisons of model predictions and experimental results relevant to the applications of interest.

Recommendations

It is recommended that HPM practitioners and users continue basic validation research using standard mathematical and experimental techniques while actively pursuing the development of additional validation tools. In particular, methodological studies to identify and examine the usefulness of new validation concepts are recommended. These studies should allow for varying degrees of precision and accuracy.

To facilitate the user's decision making process with regard to model utility, there is a need for practitioners or users to collect and publish comparisons of models versus experimentally obtained data for independent judgment of model scope and predictive accuracy. There is also a need for comparative evaluations across models (applications, performance, and validation). It is recommended that the feasibility of benchmark testing for the relative utility of models be explored. One major component of that exploration would be identification of the numbers and types of tasks and tests required to fairly evaluate the comparative strengths and weaknesses of various models and modeling approaches for a variety of applications.

Underutilization/Inaccessibility of Human Performance Models

Issues

Considerable use is made of specialized HPMs, which are often constructed for the task at hand. Relatively little use is made of large, comprehensive HPMs except by their developers and groups associated with them. There are three barriers to more extensive use. Up to the present, comprehensive models have been available only on a few computing systems; learning how to operate the program has been difficult. A second barrier to the use of models has been a general unfamiliarity with the concepts of human performance modeling in general and a conceptual basis of the particular comprehensive model of interest. Finally, potential users have

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not had sufficient faith in the utility of the models to invest time and effort in acquiring and learning how to use them.

The first barrier to using comprehensive models, accessibility and ease of use, is now being addressed. Models are being rewritten to run on the personal computers and workstations that have come into widespread use and are easy to learn how to operate.

The issues of learning about models and relying on them are more subtle. The problem/s a circular one. Models must be exercised repeatedly to demonstrate their utility. People learn to use techniques that they perceive to be useful However, until enough use is made of comprehensive models to demonstrate their utility, people will not invest the time required to learn to use them.

Recommendations

In general, efforts should be made to reduce the costs of comprehensive HPMs and to make available to potential users enough information so that they can make an informed decision concerning model use. When relevant experts, not just the original developers, find a comprehensive HPM to be useful, government agencies should support the development of easily used versions on the most inexpensive machines possible. This support should include the development of user friendly interfaces and documentation. Support should also be provided for the publication of papers descrying the scientific basis for the model in sufficient detail so that potential users can evaluate its appropriateness for their own projects.

Users of comprehensive HPMs should be encouraged to publish both positive and negative experiences with them. Sponsors of model use should regard such publications as appropriate activities for funding and should encourage preparation of the necessary reports as part of a systematic program of model improvement.

Whenever possible, these publications should be presented in the open, refereed literature. Sponsors of model development and use should insist on this provision. Potential users are at present handicapped in making decisions about model use by the absence of independently evaluated, easily accessible reports by both developers and prior users.

There is also a need to locate, review, and integrate the applications that have already been published in sources such as the *IEEE Transactions, Proceeding of the Annual Conference on Manual Control*. Unfortunately, funding is easier to obtain for new efforts than for efforts aimed at determining and integrating what is already known. One possible approach to the necessary integrative effort is to provide an explicit mandate to Department of Defense (DoD) Information Analysis Centers (e.g., CSERIAC)

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to review, synthesize, and update the HPM efforts that have already been published.

Potential For Misuse Or Misunderstanding

Issues

The HPMs discussed here are complex, not completely mature, and not fully documented. Currently, their use requires a significant degree of expertise with, and a detailed understanding of, the model or modeling approach. As problems of underutilization and inaccessibility are resolved, the risk of misapplication or abuse of assumptions and limitations may increase. For many models, the underlying assumptions are fully understood only by model developers. Moreover, key assumptions can exist in any of the following areas:

- assumptions about the operator (e.g., steady-state behavior, nature of performance limitations, level of training/alertness, error rate);
- mathematical assumptions (e.g., correlations among certain inputs, randomness of events, linearity of relationships, statistical independence of events/activities); and
- assumptions concerning the computing facilities and software (e.g., 8 bits versus 32 bits, memory capacity, methods for propagating dynamic equations).

Assumptions of this type are required to define the model in an analytically and computationally tractable form. However, user problems can arise from a lack of explicit knowledge of the specific assumptions within the selected model, and a lack of guidelines as to the significance of departures from assumed conditions.

Recommendations

If models are to be used effectively, agencies funding the development of models must begin to provide funding for the production of careful technical documentation on the models. This is a nontrivial cost that must be borne to allow for proper evaluation and application by users other than the model developers. Documentation of fundamental assumptions, theoretical bases, and embedded data, as well as software implementations, should be a deliverable in contracts involving the development of a human performance model that is proposed for immediate or near-term application. However, research efforts in fundamental aspects of HPMs should not be impeded by such requirements.

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Given the potential for misunderstanding or misuse of models, they should be exercised by individuals with training specifically related to human performance modeling. One way to ensure this is to require that people having input into the human engineering of systems be trained in the use of HPMs, either as part of their basic educational curriculum or as part of a continuing education effort for established professionals. Any efforts on the part of model developers to provide user friendly interfaces for their products should be directed at this nonnaive user population.

Regardless of who the user of an HPM is, a need exists for better user interfaces to HPMs. The output of the HPM must be usable by the person who needs the product. The input should be easy to enter and guided or assisted by information embedded in the computer implementation of the HPM. The possibility of model developers providing expertise that is incorporated in inspectable knowledge in the software should be explored (i.e., expert systems to aid model application). It should be recognized that because the development of user interfaces is not a prime research interest of model developers, such efforts will have to be undertaken by those supporting model development and will certainly necessitate additional funding.

Many of the misuses of a model result from factors such as poor input data and lack of awareness as to the range of its validity. These problems can often be overcome by sensitivity analyses with the HPMs. In particular, it is recommended that model results not be accepted unless accompanied by sensitivity analyses with respect to input parameters and data. These analyses should serve to identify the range of expected performance as well as key assumptions or parameters for which highly reliable data are needed. They should also provide the guidelines and forms for follow-up, person-in-the-loop simulations. It is also recommended that the methodology for conducting such sensitivity analyses be investigated. This would provide data on the robustness of the model Because of the large number of parameters likely to be involved, it is important to perform these analyses effectively. At present, it is not dear how this can be done.

Mental Models to Account for Mental Aspects of Tasks

Issues

Advances in microprocessor and display/control technologies have altered the roles of humans in the operation of complex systems. The result is an increasing emphasis on the cognitive aspects of a task as opposed to its perceptual and psychomotor components. To continue to be useful, HPMs must be able to account for these cognitive processes.

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The exploration of mental models to account for the cognitive aspects of task performance is receiving increasing attention in both the psychology and the modeling communities. Unfortunately, the catchall term *mental models*, although popular, is not sufficiently wen defined and understood to be particularly useful for human performance modeling. There is an underlying assumption that changes in mental models lead to changes in performance. However, there are a number of difficulties involved in attempting to build a mental model of a particular system: mental models tend to be incomplete; they are dynamic (and thus unstable); they are different for different users; they include contradictory, erroneous, or unnecessary concepts; and they are context specific. These characteristics pose some critical questions that must be addressed:

- What are the requirements for identifying an operator's mental model that may be integrated into an HPM?
- How does one measure and describe the cognitive behavior or performance of the operator?

Recommendation

Efforts in describing cognitive functioning in computational terms should be supported. To be most useful cognitive models need to be developed at a concrete, operational level of representation so that they can be incorporated in existing HPMs and model behavior can be compared with measurable operator data. In addition, cognitive models that place more emphasis on psychologically valid descriptions of, rather than prescriptions for, behavior are required.

Developing and Using Knowledge-Based Models

Issues

Many developers, regardless of their primary approach, attempt to incorporate elements of the knowledge-based approach into their models. One reason for this is that the knowledge-based approach appears to be well suited for implementing the cognitive models discussed above; however, the procedures are very individualistic and the criteria for model validation are unknown at present. Therefore, for knowledge-based models to gain acceptance as a valid approach, additional research and testing are required.

The use of linear statistical models and linear control-theoretic models has benefited greatly from the availability of identification methods, as well as ways of testing the goodness of fit of such models. Current practice in knowledge-based modeling suffers from a lack of such methods, relying

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instead on subjective analysis of protocols and other knowledge-engineering methods.

Recommendation

Some initial work on identification and testing of knowledge-based models has been done. However, much more effort is recommended if this approach to human performance modeling is to achieve a reasonable level of methodological rigor.

Accounting For Individual Differences

Issues

Humans differ from one another in a number of physical, cognitive, and emotional ways. Some of these differences are easily quantified (such as visual amity or reaction time). Others, such as motivation, are more difficult to qualify. Although not all differences have an impact on the performance of person-machine systems, which differences are significant in a given circumstance it not always clear.

In general, HPMs have not focused on the effects of individual differences for several reasons. First, the problems of interest (e.g., pilot performance) have been ones in which the range of permissible human characteristics and behavior was constrained through selection and training so that the effects of individual differences on system performance, and therefore the need to model them, were minimized. Second, the relationships between model parameters and context-free, measurable individual differences are not known. Third, the relevant data on the range of values for individual characteristics often do not exist and are difficult and expensive to obtain.

As noted elsewhere in this report, the systems of current and future interest inherently allow for more operator discretion. Because of a reduced emphasis on physical ability, new systems may use a greater variety of operators. In addition, system designers are increasingly interested in tailoring their systems to individual operators as advanced automation provides the opportunity to do so. For these reasons, it is becoming increasingly important that HPMs be able to incorporate individual differences.

Recommendations

Rather than attempting to collect data on all possible individual differences in all relevant contexts, it is recommended that existing HPMs be used to assess the sensitivity of system performance to variations in

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operator characteristics. This will entail systematically manipulating the model to determine which human characteristics significantly affect system performance and to identify the range of acceptable variation for each, within which the system functions at an acceptable level Thus, HPMs can be used to define their own data requirements. A list of key characteristics would enable more economical and more feasible data collection on individual variation. It is recommended that the users of models engage in this sort of experimentation and convey their results to other practitioners for additional testing and evaluation.

CONCLUSION

Given the current state of the art in human performance modeling, is the methodology ready to be an integral part of the system design process? Although the methodology has a number of admitted weaknesses, it also has the ability to make a number of unique contributions to the process of system engineering.

By beginning modeling efforts early in the design process, a formal means is provided for considering the impact of human performance capacities and limitations on the range of design issues that must be confronted while there is still time to resolve them. An early modeling effort can provide quantitative and qualitative analyses that allow design trade-off studies to include a variety of human performance factors along with other system variables. This process forces consideration of the assumptions and design decisions which underlie assertions that the system will work with available personnel

In all, there are compelling reasons to believe that systematic human performance modeling efforts should be regularly advocated and used along with expert judgment and manned part-and full-task simulation, as a regular part of the design process for large-scale human-machine systems.

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