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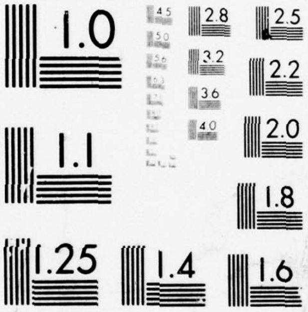

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SURVEY OF HUMAN OPERATOR MODELING TECHNIQUES FOR MEASUREMENT APPLICATIONS

By

Patricia A. Knoop

ADVANCED SYSTEMS DIVISION
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The purpose of this study was to review existing human operator modeling techniques and evaluate their potential utility for performance measurement applications. The major human operator characteristics that ought to be accounted for by a useful model were identified. Then existing models were categorized, surveyed, and summarized. Models in each category were evaluated based on the extent to which they represent the identified human operator characteristics as well as other aspects of their general validity for performance measurement applications. Results are that none of the models implement more than a few of the human operator characteristics; many are based on assumptions which are unacceptable for measurement applications; and others have not been developed far enough to justify their use as a point of departure for measurement. It is concluded that existing

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models are not sufficiently representative of known characteristics of human behavior to be useful for general applications in performance measurement.

SUMMARY

Problem

Existing performance measurement techniques do not have the capability to support the type of flight simulation research that entails accounting for the perception and utilization of various cues. In addition, the many efforts to derive more suitable measures have further complicated the problem by developing more and more measures from which to choose but with little regard for the effects of an improper choice. They have also been misdirected in their emphasis on system performance rather than on human behavior. A new measurement approach is required which minimizes the number of measures that must be considered, computed, and interpreted; and which produces measures that characterize behavior succinctly and are sensitive to those aspects of human behavior that directly involve cue perception and utilization.

Approach

Often, the most concise way to represent a set of data is to model the process that generated it. If modeling techniques were applied to human performance measurement, it is conceivable that an optimally concise set of measures could be produced from the model itself. If the model were carefully formulated and validated, measures derived from it would characterize human behavior rather than the effect of that behavior on system response; and they could be made to include the impact of various cues and the way they are perceived, interpreted, and applied. The purpose of this study was to determine which, if any, of the existing human operator models might be useful in this regard for performance measurement applications. Since model validity is particularly important in the case of the envisioned measurement applications, the first task of the study was to identify the major human operator characteristics that ought to be accounted for. Then existing models were categorized into six types. A survey was made of models in each category by reviewing the literature and summarizing the various modeling studies. Models in each category were evaluated based on the extent to which they represent the identified human operator characteristics as well as other aspects of their general validity for performance measurement applications.

Results

Several human operator characteristics were identified which ought to be included in or otherwise accounted for by models to be used for measurement applications. The categories of models surveyed include describing functions, optimal control model, discrete and finite state methods, adaptive techniques, preview models, and other nonlinear approaches. Results of the evaluation are that none of the models reviewed implement more than a few of the identified human operator characteristics. Those which have attempted to incorporate known or theorized information about the human are either based on associated assumptions which are unacceptable for measurement applications or have not been developed far enough to justify their use as a point of departure for measurement.

Conclusions

Existing human operator models are not sufficiently representative of known characteristics of human behavior to be useful for general performance measurement applications. It appears, too, that modeling studies of the past have emphasized matching the response of the average operator at the expense of modeling the behavior of the individual. For the particular application area of performance measurement, this is unacceptable. Studies are required to develop modeling techniques specifically for measurement uses, and these studies should be based on valid assumptions about the human that are supported by the body of related knowledge that presently exists. Finally, it should be noted that the fact that existing models are considered unsuitable for measurement applications should not be interpreted as meaning that they are necessarily viewed as bad models in general. When used for the purposes for which originally intended and within the confines of the related underlying assumptions, some existing models appear quite useful and have been applied successfully for many difficult tasks involving the prediction or analysis of killed performance.

PREFACE

This study was conducted under project 6114, Simulation Techniques for Aerospace Crew Training; task 611420, Advanced Instructional Features, with the author serving as both project and task scientist. Thanks is given to Dr. Lawrence E. Reed, AFHRL/ASR, Wright-Patterson AFB, Ohio, for his assistance in locating relevant literature and his constructive review of this report.

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SURVEY OF HUMAN OPERATOR MODELING TECHNIQUES FOR MEASUREMENT APPLICATIONS

I. INTRODUCTION

This report describes the results of a survey effort to assess the applicability of human operator modeling techniques to performance measurement. Specific objectives were to determine the state-of-the-art of human operator modeling; identify human operator characteristics that should be considered in models to be used for measuring performance; assess the existing models on the basis of their inclusion of known or theorized human performance characteristics; and develop a general prognosis of satisfying requirements for sensitive performance measurement using existing human operator models as a foundation.

Background and Problem

The lack of sensitive and objective measures of human performance for many complex continuous tracking tasks has been a persistent problem for many years. This problem has been particularly important and noticeable in the area of flight simulation research, where methods are required for developing and evaluating techniques of generating and sustaining the cues required for effective training. This includes distinguishing between the cues that are essential to training and those that are just expensive cosmetics; and determining the effects on performance, training, and skill retention of providing the required cues in various ways. Obviously, for this type of research, measures are needed which are objective, valid, reliable, and most important, sensitive to changes in the way cues are perceived and used in the development and learning of perceptual/motor skills.

Existing measures do not have the necessary characteristics to support the type of flight simulation research that entails accounting for the perception and utilization of cues. In various attempts to develop suitable technology over the past two decades, there has been a proliferation of different measures from which to choose, but little headway in achieving the breakthrough that the problem demands. In a way, much of this activity has probably created a false sense of security. As a result, not enough research has been conducted on measures specifically oriented toward research applications.

Associated with the generation of too many measures has been a general lack of appreciation of the deleterious effects of choosing the wrong measures for a given research application. Obermayer, Swartz, and Muckler, (1962) provides an excellent illustration of this by demonstrating the effect on study results of selecting various performance measures. The subject studied was the interaction effects of displays with system dynamics and course frequency in continuous tracking tasks. Both pursuit and compensatory displays were used with three levels of course frequency and position, rate, and acceleration control dynamics. Seven measures were computed, among which were average error (AE), average absolute error (AAE), root mean square error (RMS), and time on target (TOT). Results show that if AE had been selected as a single measure, the conclusion would have had to be that none of the experimental variables had a significant effect on performance. In contrast, AAE, RMS, and TOT all indicated significant effects for course frequency and dynamics. Further, the three-way interaction effect of displays, frequencies, and dynamics was significant (.01) using AAE and RMS but nonsignificant (.05) using both AE and TOT. One can only speculate about the number of past and contemporary studies which would yield similar discordant findings if subjected to analysis. As the authors surmise:

> Obviously, the interpretations of these data are critically dependent upon the particular measure, and the analysis has been presented with this fact in mind. However, one might speculate on past display studies where a single measure was selected and wonder if radically different results and conclusions might not be drawn if another conventional measure had been selected. It has been apparent to many for some time

> that the methodology of human continuous performance measurement is in serious difficulty and both theoretical and methodological studies in performance measurement are urgently needed. (Obermayer et al., 1962, p. 212)

Myers presents another enlightening example of the differing results that alternative measures can produce (Myers, 1972). In this case, the example hinges upon the fact that while two measures may be equally valid for assessing some skill, they may not be equally suitable for actual application within the constraints of a given experimental design. Both response time and its reciprocal, response speed, were used in an analysis of variance. In the case of response time, the computed F-ratio was 2.87, which was not significant at .05. The F-ratio using response speed was 13.56, which was significant at .01. These diverse results were a consequence of the fact that the response time measure revealed interaction effects more clearly and reduced the power of the F-test. Thus, the appropriateness of commonly used measures must be evaluated in light of the experimental design to be applied as well as the skills to be assessed.

There is some evidence that many of our efforts to derive suitable measures have been misdirected in that the wrong type of measure has been sought. A distinction may be made between measures of system performance, through which it is hoped that something may be inferred about human performance, and measures of human behavior, of which human performance is a derivative. System performance measures are confounded by variances whose sources are not confined to the human operator. As a result these measures, which are commonly applied in flight and simulation training and research, are often unreliable indicators of human performance. In what has become a classic illustration, Taylor and Birmingham (1959) showed how several instances of the same human operator behavior can be misinterpreted as different behaviors by using system performance measures. This was done by using a single servomechansim model to generate outputs to various control dynamics and demonstrating the differences in system measures that resulted. Not only can these measures effect behavior misrepresentation through the incorrect assertion that it is different when it is not, but system measures, which are generally of the integrated or average "summary" variety, can mask important changes in behavior. This was nicely demonstrated in a study of the differences in performance when controlling or monitoring several systems rather than just one (Jackson, 1958). It was shown that mean error as a measure merely indicated that errors increased as the number of systems (dials) increased. However, more elementary measures of behavior showed that the operator did a lot to try to prevent an increase in errors. He made quicker control movements, made quicker switches from one control to another, and anticipated coming events. It was concluded that overall measures of performance conceal rather than expose the details of behavior.

It seems, then, that there is a two-part problem. First, existing measures are not adequate for simulation research applications. Second, the many efforts to derive more suitable measures have (a) further complicated the problem by developing more and more measures from which to choose with little regard for the effects of an improper choice and (b) probably been misdirected in their emphasis on measures of system performance rather than measures of human behavior. Based on these observations, a solution to the problem must be built around a new approach that, first of all, does not merely add to the already overpopulated group of system performance measures. Instead, it must minimize the set of measures that need to be considered, computed, and interpreted. Secondly, the approach must produce measures that characterize behavior succinctly and are sensitive to changes in those aspects of behavior that directly involve cue perception and utilization.

Often, the most concise way to represent a set of data is to model the process that generated it. If modeling techniques were applied to human performance measurement, it is conceivable that an optimally concise set of measures could be produced from the model itself. If the model was carefully formulated and validated, measures derived from it would characterize human behavior rather than the effect of that behavior on system response, and they could be made to include the impact of various cues and the way they are perceived, interpreted, and applied. The potential of dynamic, mathematical models for this application is nicely stated by McRuer and Krendel (1974):

> Skill, for example, is a concept which has been described in such intuitive terms as "sequence of deftly timed responses" and "the outstanding character of rapid adaptation." The availability of dynamic descriptions of human control actions enable us to quantify "deftly timed" in a fashion not otherwise possible. Similarly, the human ability to adapt can be reduced to readily quantifiable changes in the mathematical form of the description of the control actions. (McRuer & Krendel, 1974, p. 17)

Another indication of the potential of modeling techniques for measurement is provided by Pew and Rupp (1971). They fit a describing function model to the compensatory tracking data of the 4th, 7th, and 10th graders on each of several successive trials and examined the change in coefficient values across trials. The two coefficients, K and TAU, represent the gain or response amplitude and time delay, respectively. Besides demonstrating a learning effect, these coefficients provided a direct explanation of how and why learning occurred for each grade-group. The example is impressive because of the great deal of insight into behavior that the use of such a simple model can provide. As the authors so aptly state:

> . . .it emphasizes the point that K and TAU are two derived measures that permit some inference about the behavior of S himself in the tracking task. It is not necessary to believe that S carries differential equations around in his head but rather to think of K and TAU as two performance measures that are in some sense more analytic than the error score alone. It is easy to show changes in error scores, but it takes an ingenious E to design a tracking experiment, particularly one concerned with developmental questions, in which changes in error scores alone provide a degree of analytic insight into the nature of the skilled performance that goes beyond the statement that manipulation of a particular independent variable produced a change in performance. (Pew & Rupp, 1971, pp. 5–6)

Purpose and Approach

The purpose of the work being reported was to determine which, if any, of the existing human operator models might be useful for performance measurement applications. This involved a review of work dating from as early as 1944 on advancing the state-of-the-art of human operator modeling (Young & Stark, 1965). The large number of available references made organization of notes and materials difficult. The approach that seemed to work the best, and the one which has been applied in organizing this report, was to group the material according to type of model as follows:

1. Describing Functions
2. Optimal Control Model
3. Discrete and Finite State Methods
4. Adaptive Techniques
5. Preview Models
6. Other Nonlinear Approaches

The above categories are not mutually exclusive, e.g., it is possible to modify a model that is basically a describing function to outfit it with adaptive capabilities. The classification rule-of-thumb that was applied was to assign a model to that category which best distinguished it from its predecessors.

The literature survey began with a review of all proceedings of the Annual Conferences on Manual Control and branched from there to the references cited therein. A Defense Documentation Center (DDC) bibliographic search and several very good survey reports (most notably Costello & Higgins, 1966; Kelley, 1968a; Summers & Ziedman, 1964; Young & Stark, 1965) quickly provided an inundation of sources. The remaining references were located through scanning the indexes of journals (e.g., Journal of Experimental Psychology, Human Factors, Psychological Bulletin, IEEE Transactions, Automatica, and Journal of Motor Behavior) and through helpful tips and the loan of well-marked copies of favorite papers from interested colleagues. In preparing this report, those documents judged to be the best sources of information were used as references, with alternative sources and those containing supplementary information relegated to the Bibliography.

The results of this activity have included accomplishment of the original objective to assess the potential of existing models for performance measurement applications. In addition, a substantial library and a heightened appreciation for the body of knowledge in manual control modeling have been acquired. Finally, a plan has been formulated to guide research efforts in the development and application of modeling concepts for use in performance measurement.

II. HUMAN OPERATOR CHARACTERISTICS

When a model is to be used to analyze and assess its object, it is especially important that it be valid. In particular, predictive validity is required, since the intent is to fit the model to a specific set of data but use it to predict or infer general behavioral attributes. To insure predictive validity, it is not enough to merely demonstrate a close match between model and human output for a few selected test cases, and it is impractical to extend the testing over all conceivable conditions. Instead, the best approach is to build content validity into the model. This means that the constructs of the model and the assumptions on which it is based must be in full accord with the body of knowledge that exists regarding the object being modeled.

In the case of human operator modeling, the intended application in the area of performance measurement requires that the model does not violate accepted behavioral principles by virtue of its constructs or assumptions. In addition, it should incorporate these principles wherever possible. In this way, stratified testing is only necessary to provide empirical evidence of the validity that was already embedded in the model at its inception.

Over the years, a great deal of knowledge has been accumulated, largely through psychological research, about human operator characteristics. Some of these characteristics are well supported by empirical evidence and are generally accepted as factual; others are more controversial, offering possible but not exclusive explanations for observed behavior. Whichever the case, they should be considered, if not included, in human operator modeling efforts where content validity is important. Following is a discussion of the major human operator characteristics that merit consideration.

Operator Intermittency

Theories and studies about operator intermittency have a long history in psychology, dating at least as far back as 1913 (Kelley, 1968a). One reason the topic continues to generate debates today is not because of a disagreement about the existence of intermittencies in response data, but because there is a disagreement about their cause. In addition, the source of intermittencies is still unknown. They may originate in the input receptor systems, in central processing, or in the motor output systems. Finally, there has been no consistent definition of operator intermittency. This was recognized by Summers and Ziedman who proposed a liberal definition of an intermittent process as ". . .one in which information is received, processed, and transmitted at discrete intervals or instants of time" (Summers & Ziedman, 1964, p. 6). Between these intervals, new information cannot be used by the system, and processing must rely on previous samples. This definition does not involve notions about periodicity in responses as assumed by many of the earlier investigators (e.g., Craik, 1947).

The original intermittency hypothesis was developed by Craik in 1945 and was prepared posthumously for publication by his student, Margaret Vince, in 1947. Bertelson (1966) provides a concise and insightful review of the early work in this area, and much of the immediately following information is taken from his paper. Craik's thesis was that man behaves as an intermittent correction servo. Evidence for this intermittency was the jerky characteristics of tracking records. Craik's studies, as well as those of Vince (1948a), suggested that there is a period of about 0.5 second following a stimulus during which (a) some response is selected and executed and (b) no response to a second stimulus can occur. To this period, Craik followed the lead of an earlier investigator (Telford, 1931) and attached the name "refractory phase," which was long before known to exist at the level of simple physiological systems.[1]

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[1] Bertelson points out that the analogy between the refractory periods of Craik and the physiologists is a loose one, and that Craik's acceptance of the term is unfortunate. During the physiological refractory phase, the tissue does not respond to a new stimulus; however, during the psychological refractory period, a response to a new stimulus of equal intensity can be elicited, but with a greater latency.

Following Craik's death, there were two important developments. One was the completion and publication of experiments by Vince (1948b) which involved tracking of a target which changed position at discrete intervals. This permitted direct measurement of movement and reaction times and proved that when two step inputs occur at intervals shorter than 0.5 second, the reaction to the second step has greater latency.

The other development was that of the single channel hypothesis, promoted concurrently by Hick (1948) and Welford (1952) but most clearly formalized by the latter. This hypothesis was a direct outgrowth of the work of Craik and Vince. It proposed that the delay in responding to a second stimulus is due to the inability of central processes to deal with two stimuli simultaneously. Instead, a second stimulus must be stored until processing associated with the first stimulus has been completed. According to Bertelson, the importance of this work was mainly in the adoption of reaction time to a second stimulus as an estimate of the time during which processing of the first stimulus was still taking place. Later, when interstimulus intervals greater than a single reaction time were also found to produce greater response latencies, revisions of the hypothesis were suggested. For example, one suggested by Hick was that refractoriness (i.e., the occupation of central processing mechanisms) may also be caused by the subject's attention to his own response (Hick, 1948).

Bertelson observes that a major impact of intermittency research has been to suggest a way of analyzing complex activities by breaking them into basic decision units, during each of which a choice is made of a reaction for a particular sample of sensory inputs. The size of these decision units is a fundamental parameter of any intermittency model but, except for Craik, few investigators have addressed this issue. Investigation of unit sizes and the associated grouping of stimuli has been, in Bertelson's opinion, "the most serious missing link in the study of intermittency" (Bertelson, 1966, p. 157).

The jerkiness in tracking records observed by Craik was exhibited largely by novice performers. More experienced performers often demonstrate long periods of smooth response in continuous tracking (Adams, 1961). This has not served as grounds for seriously challenging the intermittency hypothesis, although Adams believes that it should. Instead, the smooth responses are explained by Craik (1947) and others as emanating from an acquired ability by subjects to predict input sequences and overlay a smoothing effect on what is otherwise a series of intermittent movements. This contention, which was an *ad hoc* analysis on the part of Craik, was supported by the work of Navas (1963), who found evidence of intermittency using unpredictable inputs but not using predictable inputs.

There are several independent studies providing evidence for intermittency. Some of these are nicely summarized by Sheridan and Ferrell (1974). In studies of closed loop manual control, Bekey (1962) found a concentration of response power between 1.0 and 1.5 Hz, leading him to the conclusion that human response consists of a series of ballistic movements. Step inputs were used in another study to illustrate that responses consist of several discrete steps of, first, a ballistic response and, second, a series of discrete adjustments (Taylor & Birmingham, 1948). The work of Navas (1963) not only provided independent evidence of intermittency for unpredictable inputs, but also produced evidence that the intermittency is due to a sampling effect rather than to a quantization of the input. Finally, there is some evidence of abrupt changes in the velocity of control motion during continuous tracking. This has been interpreted as an indication of sudden, discrete changes in muscle force level (Kelley, 1968a). Other justifications for accepting the intermittency hypothesis are provided by Kelley (1968b).

There have been four main hypotheses for explaining why intermittency in responses occurs. The most popular is the existence of a psychological refractory period, as originally suggested by Craik. (This is sometimes augmented by further assumption of the single channel hypothesis.) Second is the expectancy theory which, according to Bertelson (1966), has been formulated several times (in 1950, 1955, & 1962). This theory is based on the well known fact that the reaction time to a signal varies with the probability of the occurrence of the signal as observed by the subject. If two signals are to be given in succession, the subjective probability of the second one occurring, given that it has not yet occurred, is lowest immediately after the first signal and increases thereafter. This is used to explain why second signals result in a longer response latency when they closely follow first signals. A third hypothesis for explaining intermittency is that inputs are quantized and that a subsequent response is not initiated until the input moves to a new quantum level. This theory was disputed by Navas (1963) but has been supported through the success of some models fashioned on its behalf (e.g., Costello, 1968). Finally, a fourth hypothesis is that once initiated, response movements are open-loop for a time, neither depending upon nor using continuously available feedback information (Adams, 1961; Taylor & Birmingham, 1948). Therefore, the human executes response sequences that are momentarily independent of the input and, thus, intermittent with respect to it.

Psychological Refractory Period

As indicated in the foregoing subsection, the existence of a psychological refractory period (PRP) was proposed by Craik (1947) as one possible explanation for intermittency. The PRP is found when two stimuli are closely spaced in time. Response time to the second stimulus is longer than the response time associated with a single stimulus. The only important exception to this is that when two signals occur almost simultaneously (within .05 sec. of each other), they may be handled together (Welford, 1960). Both signals are apparently responded to as a single unit in this case. However, once the human is committed to handling one stimulus and its response, he cannot handle another until he has completed the first (Fitts & Posner, 1969).

Almost as soon as it was suggested as an explanation for intermittency, the PRP was subject to question. Vince (1950) concluded that the PRP is not absolute and observed that many times when two stimuli are given in succession, the first response is suppressed or modified by the second. Since then, three distinct theories have been proposed and studied to account for the PRP effect, (Smith, M.C., 1967). The single channel theory is based on the assumption of a limited capacity channel and the related inability of man to process two stimuli simultaneously. The central refractoriness theory proposes that there is a physiological inhibitory effect of one stimulus upon a succeeding stimulus. Finally, the preparatory state theory suggests that a delay in responding to a second stimulus is primarily due to the subject's expectancy of and/or readiness for that stimulus, not to physiological characteristics or limits in processing capacity.

Each of these theories has its supporters and offers a unique explanation for certain data. For example, Poulton (1950) found that regardless of how long a subject is allowed to recover from a previous response, if he is not expecting to have to make a further response, he will have a delayed reaction time to a second stimulus. This is most easily explained by lack of preparedness on the part of the subject. According to Poulton, "If, by dividing his attention, the subject was able to prepare for his next response while making his previous one, the so-called psychological refractoriness could be completely absent" (Poulton, 1950, p. 99). In contrast, convincing evidence against the preparedness theory was provided by Davis (1965), who showed that reaction time delays can be eliminated when the first response is spontaneous rather than elicited. Finally, Creamer (1963) demonstrated that event uncertainty rather than temporal uncertainty could produce reaction time delays to the second stimulus. This represented a vote against the preparedness theory, and Creamer interpreted it as evidence for the single channel theory.

Despite continuing debates on the subject, the single channel theory seems to best account for the bulk of data and is least subject to critique (Smith, M.C., 1967). There is no physiological evidence of refractoriness in the nervous system for durations as long as have been observed; therefore, the central refractoriness theory has little support. Readiness is believed to play some role, but Smith points out that it is not an adequate explanation by itself. This is largely because there is still a reaction time delay when all uncertainty about the arrival time of the second stimulus is removed. At least some of the disagreement may be attributable to different experimenters giving different interpretations to tracking records (Poulton, 1974). (For example, when two responses follow each other closely, it is not always possible to distinguish between a preprogrammed double response and two separate responses.) In any event, it appears that we can only conclude that some type of "refractoriness" exists and that the most defendable explanation for it, so far, is the single channel theory.

Range Effect

An often demonstrated and commonly accepted aspect of human performance is the range effect. This characteristic was discovered and named by Searle and Taylor (1948), who observed that step inputs of random magnitudes elicited responses whose amplitudes tended to the mean. The range effect is sometimes called the central tendency of judgment (Poulton, 1974), since it represents the human operator's tendency to respond as if the stimulus were of average intensity. After he has tracked for awhile, the human prepares for an average input. If the actual input is smaller than expected, he overshoots; and if it is larger than expected, he undershoots. The range effect is a function of relative rather than absolute values of signals (Ellson & Wheeler, 1949) and is, therefore, not observed until after the first several trials have made available information about the values to be expected.

The range effect is asymmetrical in that the responses to small stimuli are more heavily skewed to the mean of the series of stimuli than are responses to large ones (McRuer & Krendel, 1958). In addition to applying to stimulus amplitudes, the range effect also applies to the times and directions of stimuli (Poulton, 1974). For example, after the human learns the average time interval between two steps, he will tend to respond early when the interval is long and late when it is short. Since this is true, it is possible that the range effect may accentuate characteristics of the PRP and, except at long interstimulus intervals, may not be distinguishable from it.

Frost (1972) observes that the range effect shows that the human operator responds to the total situation, not to instantaneous inputs. It is produced by conditions that let a response be based to some extent on a comparison of the present input or stimulus with previous ones. Perhaps more than any other human performance characteristic, the range effect in tracking is accepted as factual due to the frequency and consistency with which it is observed.

Inadvertent Crosscoupling

Crosscoupling can refer to a characteristic of the control system or to a characteristic of the human's control technique. When used in the former context, crosscoupling indicates that a movement of the control stick along one axis results in an effect on the system in another axis. For example, moving an aircraft control stick left or right results in a loss of altitude. In the latter context, crosscoupling indicates that the control itself was moved along several axes simultaneously.

Bekey, Meissinger, and Rose (1965) identified inadvertent crosscoupling as a human operator characteristic that must be accommodated in modeling performance on two-axis tracking tasks. This refers to an unnecessary movement of the control in one axis when activity should have been limited to control movement in another axis. Bekey identified two potential sources of this behavior. One is perceptual crosscoupling, or the inability of the human operator to distinguish motion in one axis from motion in another. The other is motor crosscoupling, or the inability of the operator to perform in one axis without inadvertent movement in the other. Based on modeling feasibility studies, Bekey showed that additional terms to account for this inadvertent crosscoupling are necessary when using describing function types of models for the separate axes in a two-axis tracking task.

Bang-Bang Control

It has been repeatedly demonstrated that when the forcing function increases in frequency, the human operator's control technique changes in a relatively predictable way (Summers & Ziedman, 1964). First, a continuous appearing, smooth control action changes to one of making discrete corrections about every .5 second as forcing function frequency rises. The operator attempts to center control at the peaks of the waveform rather than attempting to smoothly track the entire function. If the frequency is further increased, his control becomes bang-bang, which means that he moves the control from one side to the other in an attempt to follow the sign of the forcing function.

This is a nonlinear characteristic of human operator behavior that is not adequately treated by many modeling efforts that assume operator linearity.

Cue Utilization

Studies in cue utilization have been largely concentrated in two areas: (a) use of visual position, rate, and acceleration cues and (b) effect on performance of adding proprioceptive cues. In the first area, Fuchs (1962) has provided evidence that as learning proceeds and/or as task-loading decreases, the human operator relies more and more on velocity and acceleration cues and less on position cues. This would explain why highly skilled operators are better able to lead the system and predict future events (by utilizing higher-order information). While this may be true for velocity information, there is some doubt that humans are really able to use acceleration as a cue, however. It has been found, for example, that accelerations and decelerations are usually inaccurately interpreted as constant velocities (Adams, 1961).

There is additional evidence to indicate that the use of velocity versus position cues differs depending on the type of tracking task used (Briggs, 1962). In one study, for example, Walston and Warren (1953) found that velocity information was used more in pursuit than in compensatory tasks. Thus, the relative utilization of velocity versus position data is certainly task dependent as well as proficiency dependent.

In the second area, several studies have demonstrated that the addition of motion cues results in a change in human operator control characteristics (Ringland & Stapleford, 1971, 1972; Shirley & Young, 1968a, 1968b). Even more interesting is the evidence that early in training, spatial and visual cues are most important, but later in training kinesthetic cues become more useful (Fleishman & Rich, 1963; Summers & Ziedman, 1964). This has important implications for training as well as for human operator modeling.

Summary

Several specific characteristics of the human operator have been identified which ought to be included in or otherwise accounted for in models to be used for performance measurement. These include operator intermittency, or the processing of information at discrete intervals rather than continuously; psychological refractory period, or an interval of time following response to a stimulus when response to a second stimulus cannot be issued; range effect, or the tendency to respond as if the stimulus were of average intensity; inadvertent crosscoupling, or movement of a control in one axis when activity should have been limited to movement in another axis; bang-bang control, or the use of a pulsing control movement as the forcing function increases in frequency; and cue utilization characteristics, including the increasing use of velocity and acceleration information as learning proceeds or as task-loading decreases, the use of different control techniques when motion is added to a simulator, and the possiblity that spatial and visual cues are more important early in training, with kinesthetic cues becoming more useful later on. Some of these characteristics have more support than others in the literature. In models to be used for performance measurement, these characteristics should either be included directly (particularly those characteristics that are well substantiated) or otherwise accounted for by allowing for their existence within the scope and assumptions of the model. In addition, general consideration should be given to associated traits of the human, some of which precipitate many of these characteristics. These include the existence of observation and control errors, time variations in control strategy, threshold and saturation effects, preview and precognitive functions, variations in performance due to changes in attention and fatigue, and, generally, man's ability to remember, predict, reduce information, and make decisions.

III. MODELING APPROACHES

The previous Section reviewed many of the human operator characteristics that ought to be considered in developing a valid model. This section and the next examine the various modeling approaches from the standpoint of how well they represent these characteristics and, thus, how suitable they are for performance measurement applications.

Describing Functions

The earliest attempts at human operator modeling were based on applications of describing function methods. This approach evolved from the observation that many nonlinear systems behave like linear systems when subjected to specific, controlled inputs (McRuer & Jex, 1967). The idea then occurred that perhaps engineering analysis tools designed to study linear systems could be used to model those aspects of human operator performance for which quasi-linearity can be safely assumed.

Description and Assumptions. A describing function model is essentially a differential equation relating the human operator's output, or movement of the control, to his input. Excellent descriptions of the model are provided by Kelley (1968b) and McRuer and Krendel (1974). The model is based on the observation that in a compensatory type tracking task with simple dynamics, the human operator performs in a manner similar to a servomechanism. An observed error, following a central processing delay, gives rise to a motor command that is applied to the control in a manner which reduces the error to zero. As Wickens (1974) observes, it is because of this simplicity that man's behavior in some circumstances can be closely modelled by describing function techniques.

The describing function model is one of a class of models known as quasi-linear in type, referring to a linear model which is employed to model the behavior of nonlinear system. The basic describing function accounts for that part of the human operator's response that is linearly correlated with the input signal. Its general form is

$$\Theta_o(t) + (T_N + T_I)\,\Theta_o(t) + T_N T_I\,\ddot{\Theta}_o(t)$$
$$= K\,(\Theta_i(t-\tau) + T_L\,\dot{\Theta}_i(t-\tau))$$

where the terms are as described below:

Operator Output (Θ_o) is the actual control stick position as activated directly by the human operator.

Operator Input (Θ_i) is the stimulus to the human operator, usually consisting of some displacement of a target or cursor from a reference. The task is to minimize the displacement through appropriate control movements.

Neuromuscular Lag (T_N) is that portion of t delay between stimulus and response that [illegible] be attributed to dynamic characteristics of the limb. Nominal values are 0.1 to 0.5 second.

Low frequency Lag (T_I) is a general lag constant introduced into the operator's response when low frequency system response is important. Nominal values range from 1 to 20 seconds.

Gain (K) is the amplitude ratio of output to input and is the operator's primary adjustment coefficient.

Lead Time Constant (T_L) is the time into the future for which the operator is predicting the input and formulating an output. Nominal values vary from a fraction of a second to 1 or 2 seconds.

Delay Time Constant (τ) is proportional to the operator's reaction time delay. Nominal values are .15 to .20 second.

The component of the output that is not linearly correlated with the input is referred to as the remnant (McRuer & Krendel, 1957). The remnant reflects nonlinear aspects of operator behavior, and it is the existence of the remnant, the occasional application of the model in tasks which are not of the simple, compensatory variety, and the basic linearity assumption that have been continuing sources of criticism regarding this approach. Remnant is usually described as an insignificant portion of control behavior which is unpredictable except in a statistical sense. Yet, as Levison and Kleinman (1968) observe, this description of remnant is not valid in situations where the controller's response contains significant nonlinearities or consistent time variations. Possible sources of the remnant are errors of observation, errors of control execution, time variations in control strategy, and structural deficiencies of the model. With the describing function approach, all such model and operator variants are lumped into the remnant and are indistinguishable from one another.

The linearity assumption is that the human operator will respond to changes in the frequency of the input only, and that his response will be essentially independent of the amplitude of the input. This assumption has been made ". . .so that the mathematical procedures applicable to transfer function theory can be used. Such application has persisted in spite of the general admission that the human operator is essentially nonlinear and that his representation by a linear function is inadequate" (Beare & Kahn, 1967). Known operator nonlinearities include threshold and saturation effects, dither, range effect, preview and precognitive functions, and parameter variability due to changes in attention and fatigue (Kelley, 1968a). These nonlinearities cannot be modeled using describing functions. This led Wherry (1969) to conclude that there is really little merit in applying describing function methods to describe human operators. He states:

> It is my personal feeling that those who would have us believe that man is just a fancy servo system or that he is like an autopilot have spent too much time with machines and not enough with real operators in real systems. Even at the risk of offending some model builders, I feel compelled to say that I am singularly unimpressed with the transfer equation approach. (Wherry, 1969, pp. 2–37)

These sentiments are endorsed also by Poulton (1962), who points out that describing functions merely give an exact numerical value to those aspects of human performance that resemble the parameters of servomechanisms. However, they are not as suitable "...as simple measures are for determining the details of the ways in which human operators do *not* behave like servomechanisms; these include most of the phenomena studied by psychologists." (Poulton, 1962, p. 320)

Another assumption of the describing function approach is that the human is attempting to minimize error based on some constant, implicit error criterion (Sheridan, Fabis, & Roland, 1966). In reality, the error criterion that is applied varies with time as well as with the task. By incorrectly assuming constancy, the modeler observes these variations as changes in model parameters that are indistinguishable from changes arising from other sources. The model additionally assumes that the operator's attention to error is restricted to a single observation when, in fact, his behavior is influenced by both memory and prediction.

Applications. Despite the rather obvious shortcomings of the describing function model as a general model of human behavior, many interesting insights have nevertheless been obtained through its application to tasks for which it is best suited. Most applications have consisted of either examining parameter variations under different task conditions or developing describing functions for new tasks. In the former category are a number of efforts to examine the effect of simulator motion on control technique as characterized by the describing function model coefficients. Most studies surveyed concluded that the addition of motion cues changes the manner in which control is executed (Shirley & Young, 1968a, 1968b; Stapleford, Peters, & Alex, 1969; Ringland & Stapleford, 1971, 1972). The observed changes in the model coefficients include greater values of lead and decreased time delay when motion cues are supplied. Interestingly, and in distinct contrast, a 1967 study comparing inflight performance with fixed base simulator performance found no significant differences in model coefficients (Smith, H., 1967). Another study compared inflight performance using the real visual scene with single degree-of-freedom simulator performance using instruments and found large differences in model coefficients (Newell, 1967); unfortunately, however, the cause of the differences (different motion or different visual) cannot be determined from this study. Salmon and Gallagher (1970) found that in addition to a change in coefficients, moving base simulator performance produces more aileron and less elevator activity than its fixed base counterpart. The describing function model has also been used in studies to examine differential effects of roll and yaw motion cues (Young & Dinsdale, 1969) and visual motion cues versus those supplied proprioceptively (Junker & Price, 1976).

An extremely interesting group of studies was performed to determine whether or not the describing function coefficients change as a result of learning and, thus, whether they may be useful as measures of performance. Todosiev, Rose, and Summers (1966, 1967) found that the lead time constant increased with training and was greater in two-axis tracking than in one-axis tracking, although no significant difference was observed in tracking error per axis. This illustrates the increased sensitivity that may be expected from model-based measures as opposed to conventional system measures. These findings were substantiated in 1967 in a study which analyzed gain and time delay coefficients for three subjects over several days of training and found significant changes (Jackson, 1967). Burgett (1969) varied this experiment by computing values of gain and time delay every 20 seconds and confirmed earlier findings. In addition, he concluded that the variance of the time delay is a more sensitive measure of learning than the mean value. Finally, the work of Pew and Rupp (1971) provides excellent confirming evidence of the sensitivity of model coefficients to learning and their utility in discriminating among subjects of different ability levels for simple tracking tasks.

In another group of studies, describing functions were used to study the effects on performance of divided attention and time sharing (Gopher & Wickens, 1975a, 1975b; Wickens, 1974, 1976). It was found that gain was significantly decreased when time sharing tasks were added to a primary task and that the size of remnant increased, indicating an increase in nonlinear characteristics of performance during task loading. In addition, it was found that there is no reliable increase in time delay with the addition of a secondary task, suggesting that divided attention does not necessarily lead to an increase in the time required to process information (Gopher & Wickens, 1975a). The same type of result was found by Vinje (1971), who noted no coefficient differences as a function of audio versus visual feedback, although it is commonly accepted that aural receptor delays are shorter than visual receptor delays.

Other applications have included examining the effects of feedback on performance (Miller, 1965), the effects of predictive displays and varying amounts of preview (Dey, 1971; Reid & Drewell, 1972), and the possible reasons for performance problems in pursuit tracking (Reid, 1969). In all of the applications reviewed, it was clear that use of the describing function model greatly aided performance analysis, notwithstanding the model's known shortcomings and limitations as a general model of human performance on highly complex tasks.

Revisions and Extensions. A number of studies have been performed in attempts to correct deficiencies of describing functions or to extend them to new applications. For example, describing functions do not work well for step inputs. Thus, Phatak and Weir (1968) proposed the addition of a bang-bang control capability to handle step inputs, where the switching logic is a function of the order of the controlled element. Similarly, describing functions are not applicable to nonlinear controlled elements, and studies have been conducted to develop coefficient adjustment procedures for handling special nonlinear cases (Duggar, Mannen, & Hannen, 1969).

Another deficiency of describing functions is that they are intended only to reproduce average operator performance, and a single instance of model output does not generally appear like the output of a human. Adams (1968) developed techniques to add random noise signals to the model's output and to introduce time-varying gains in attempts to make the output appear more realistic. Comparisons of his modified model and the original model with actual human operator output show that his model appears to better replicate human data.

Finally, the describing function model was originally intended for use in single-axis tasks. Levison and Elkind (1967) performed experiments to determine its applicability to two-axis tasks. They found that two-axis performance is the same as one-axis so long as the control problems on the two axes are homogeneous and the displays for both axes can be viewed foveally. If displays for the two axes are separated, peripheral vision becomes important. They proposed a multiaxis model consisting of a simple combination of single-axis describing functions with the human operator modelled as a two-channel controller processing information obtained foveally for one channel and peripherally on the other channel.

Summary and Critique. The motivation for using describing functions to model human performance stemmed originally from (a) the desire to make use of highly developed linear systems analysis techniques and (b) the observation that for simple tracking tasks, human control is similar to the control method of a servomechanism, where an observed error produces some motor command designed to reduce the error to zero. Thus, by assuming that much of human performance is linear for the tasks to be studied, a describing function model can be formulated which relates the linear portion of the human's output to the input by means of a differential equation. That portion which is nonlinear is relegated to a remnant term in the model, with the assumption that for most tasks the remnant will be negligible and will consist only of random type components of the output that, except in a statistical sense, cannot be modeled anyway.

The describing function approach has provided a quantitative method of analyzing performance and providing insights about behavior on the simple compensatory tracking tasks to which it is applicable. However, these tasks comprise only a small percentage of the real-world tasks of interest, and the associated performance is of relatively little interest. As might be expected, the temptation to apply describing functions to more complex tasks has been irresistible, and it is here that justifiable criticism of the approach has been levied. When performing any but the simplest tracking tasks, humans are highly nonlinear in their performance. Thus, the linearity assumption upon which describing functions are based is violated and results of their application are suspect. Some of the nonlinearities which arise are observation and control errors, time variations in control strategy, threshold and saturation effects, dither, range effects, preview and precognitive functions, and variations in parameters due to changes in attention and fatigue.

When nonlinearities in the performance arise, the remnant term grows because a smaller percentage of the overall output can then be linearly related to the input. Because of this, some attention has been devoted to modeling the remnant term itself (Levison & Kleinman, 1968). While the intent here is worthwhile (i.e., accounting for more and more of the operator's output), these efforts are less than satisfactory for human operator modeling because instead of attempting to develop a flexible and accurate basis for a model, the intent is to convert an inherently limited and inaccurate model into one of merit by adding various features. This may produce an improved mathematical prediction of human response but it cannot be expected to result in a valid model of the human.

Based on the above considerations, the describing function approach appears to have little, if any, utility as a basis for performance measurement. Due to the assumptions on which it is based, it is applicable to only a small percentage of the tasks of interest in manual control. Attempts to extend it to more complex tasks give questionable results due to violation of the underlying assumptions. It is inherently inviable as a general model of human performance because of the simplistic view of behavior upon which it is founded. Attempts to improve its accuracy and extend its range of applicability are of questionable merit because they are oriented toward improving mathematical prediction capabilities with little or no regard for assuring model validity.

Optimal Control Model

An optimal controller is one which controls a given process in a way which minimizes some cost or criterion function while satisfying a set of constraints (Sheridan & Ferrell, 1974). In the early 1960's, it was discovered that the mean-square error from human tracking data approximated the mean-square error of various optimal controllers. Since then, considerable interest and research has been generated for developing an optimal control model of the human operator. As Sheridan and Ferrell (1974) observe, the idea is attractive because it is based primarily on the (sensible) assumption that if the human operator is intelligent, he will attempt to behave optimally to the best of his ability.

Description and Assumptions. An optimal control model is a computer model consisting of several distinct operations which, collectively, are designed to simulate human control behavior. Excellent technical descriptions are provided by Baron and Kleinman (1968), Kleinman, Baron, and Levison (1969), and Kleinman and Phatak (1972). The model is based on the assumption that a well-trained, highly motivated human controller behaves optimally subject to his own inherent limitations and the task requirements. Figure 1 and the following, associated description explain how the model basically works: The previous control action, μ, affects the vehicle dynamics to produce a new system state, X, which is displayed to the operator as Y. Subject to some observation errors or "noise" and a time delay, τ, the human observes the available information. He deduces the true vehicle state from the available information (the role of the Kalman estimator and the predictor). He then applies a set of gains, ℓ^*, that

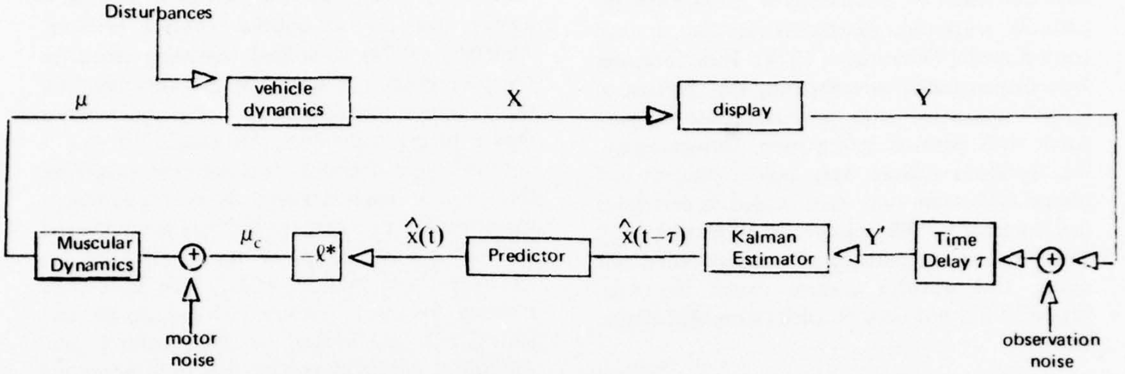

Figure 1. **Optimal control model.**

operate on the predicted state to produce a desired control resposnes, μ_c. The gains are chosen to minimize a "cost functional" which relates the human's control objectives to the task being performed. The desired control response is then acted upon by motor "noise" and neuromuscular dynamics to produce the actual control action, μ.

The major assumptions of the model are that the human behaves optimally and that he minimizes some cost functional. It is the existence and nature of the cost functional that has been the source of much criticism. One problem is that the cost functional is assumed to be some quadratic function, both for mathematical convenience and because quadratic criteria seem to work well for a broad range of problems (Sheridan & Ferrell, 1974). However, the real form is unknown. By far the more serious problem is that no one knows the nature (parameters and constants) of the cost functional (Obermayer & Muckler, 1964). While it may be true that the human is optimal for *some* criterion, determining that criterion is quite another problem.

Another source of criticism about the optimal control model is that it is not identifiable (Phatak, Weinert, Segall, & Day, 1976). This means that there are so many parameters that a unique value for each one cannot be determined. Instead, the parameters must be estimated by empirical "rules of thumb" and then iterated upon until a satisfactory fit of model predictions to actual data is obtained (Phatak & Kessler, 1975).

The model assumes that the human's observation of state variables is inaccurate due to imperfections in the visual process and various time delays. It further assumes that the operator is aware of the existence of imperfections and delays and that he attempts to compensate for them. In this respect, the model is much more sophisticated than the describing function.

Applications. The optimal control model has been applied to a variety of tasks, although not nearly so many as describing function models. What is most interesting and encouraging is that it has been used successfully to model performance on complex as well as simple tasks. For example, the model was used for a study of closed-loop performance in an air-to-air combat task, and excellent agreement resulted between model data and actual data (Harvey & Dillow, 1974). In addition, the model has been used for a variety of unique studies that could not have been conducted without great difficulty otherwise. In one effort, the model was extended to simulate the task interference that would be experienced when performing several tasks simultaneously. It was assumed that the human is a parallel processor with a fixed number of channels, and various sensory inputs were selectively contaminated with white noise. The effect of requiring the subject to perform several tasks was emulated by increasing the effective observation noise ratio associated with each component task (Levison, 1970).

In another effort, measures of pilot workload were developed by computing weighting terms for possible workload parameters in the optimal control model (Wewerinke, 1974). These measures were demonstrated by computing the "percent of effort" associated with processing rate as compared with position information. Unfortunately, the workload indices were task dependent and several calibration runs were needed to determine the operator's "full capacity." Additional work based on the computation of operator workloads using the optimal control model has been suggested but not fully pursued (Baron & Levison, 1975).

The model has been coupled with a flight simulator model to analyze maneuvering flight stability boundaries (Broussard & Stengel, 1976). Excellent agreement was obtained between actual and predicted stability boundaries as evaluated in follow-up studies involving actual flight testing (Stengel, 1976). In addition, the model has been used to analyze the utility of various cockpit displays for the DC-8 aircraft (Kleinman & Baron, 1971). Again, excellent agreement was obtained between actual and predicted data. In less successful studies, attempts were made to use the model for simulating performance of a vertical takeoff and landing (VTOL) hovering task (Baron & Kleinman, 1971; Baron, Kleinman, Miller, Levison, & Elkin, 1969). However, in this instance, poor agreement between model and actual data was obtained for various regions of control.

By far the most interesting application of the optimal control model and the theory on which it is based has been to try to determine (compute) the nature of the cost functional for a given individual or group. This has been named the "inverse optimal control problem," and its solution would have tremendous utility in studies of human behavior. In normal applications of the optimal control model, different cost functionals are selected on the basis of judgment and are tried until something which seems to work best is identified. Since the choice of the cost functional is arbitrary and subjective, it may be pointless to expend too much effort in finding a control law which can only be assumed correct in some restricted sense (Obermayer & Muckler, 1965). Instead, it may be more worthwhile to channel this effort toward discovering the true cost functional for the task and individual at hand – hence, the inverse optimal control problem. Anderson (1974) computed weighting terms for the parameters in a quadratic cost functional for many vehicle configurations using conventional model fitting techniques. He concluded that a universal cost functional does not exist, suggesting that the cost functional depends on at least vehicle dynamics and probably the task and the individual as well. This supports the contentions of Obermayer and Muckler (1965) that it may be fruitless to try to assume some universal cost functional and deduce a valid control law. Additional empirical support has been generated by showing that optimal control model parameters change for a given subject depending on his interpretation of "optimality" as influenced by verbal instructions regarding task objectives (Obermayer, Webster, & Muckler, 1966). Unfortunately, the inverse optimal control problem is mathematically nontrivial and has so far defied numerous attempts at its solution.

Revisions and Extensions. Most of the active research involving the optimal control model has centered around its direct application to new problems and not on its revision or extension. One of the few exceptions is some work to configure the model to handle the decision-making tasks of pilots (Levison, 1971). This was performed in recognition of the fact that continuous manual control is only one of the functions performed during flight. The model extension consisted of replacing the computation of gains and subsequent determination of a control action with a decision algorithm based on Bayesian-statistics. For single and double decision tasks, the model produced data that agreed fairly well with data from four subjects. However, for simultaneous control and decision-making, there was such a large subject-to-subject variance that the predictive ability of the model could not be assessed.

In another study, it was proposed that instead of attempting to minimize the total cost functional, what humans really do is to minimize the number of instances where there is an increase rather than a decrease (a) between the present position and the objective and (b) in the accumulated cost (Thomas & Tou, 1966). The proposed model revision for implementing this theory consisted of a new method for determining the correct control action based on use of a search algorithm which operates under the above minimization constraints. The work did not include actual model implementation and test.

Wierenga (1969) has contended that modelers have paid too much attention to the human as a controller at the sacrifice of adequate attention to his perceptual mechanisms. He postulated that *transformation of raw displayed information into* a useable form is performed as an optimal, time-varying Kalman filter. He implemented this theory as a revision to the optimal control model and successfully demonstrated its feasibility.

One of the most interesting efforts involving a revision of the optimal control model was one performed in 1976 for the purpose of reducing the number of parameters and thereby making the model identifiable (Phatak et al., 1976). The authors contend that the model is over-parameterized because its assumptions about the human are overly stringent. They further contend that the standard optimal control model attempts to be isomorphic to known characteristics of the human and that this, in turn, results in some effects cancelling others in the long run (e.g., time delay in observation and then prediction of true state estimates from the delayed observations). The model developed by Phatak and associates involves four simplifying modifications: (a) Assume time delay to be zero; (b) assume the human observes the displayed variables alone and not their rates; (c) assume zero motor noise; and (d) assume no control-rate term in the cost functional. For various reasons, all these modifications result in a greatly simplified model which can be identified. The authors admit that their revised model has no isomorphism to human information processing and psychophysiology but quickly point out that "isomorphic models are of no use if their parameters cannot be identified" (Phatak et al., 1976, p. 34). The identifiability of the revised model was demonstrated but extensive testing of its validity has not yet occurred.

Summary and Critique. The optimal control model is based on the assumption that the highly trained and motivated operator will behave optimally subject to his own limitations and basic task constraints. Optimality is defined as minimizing some cost functional, which is formulated to represent the "cost" of the performance in terms such as error, time, energy, etc. The model itself consists of a number of operations which are sequentially executed on a computer and which are isomorphic to known or postulated human characteristics and activities in performing a task. For example, one part of the model represents the time delays involved in visual perceptions and another represents the belief that the human predicts a best estimate of the true state of the system based on his awareness of his own imperfect perceptions and time delays.

The major criticisms of the model have concerned the existence and nature of the cost functional and the large number of parameters in the model. The form and content of the cost functional are only conjectured, and it is contended by some that it is fruitless to devote much effort to the development of a model with only restricted applicability due to uncertainty regarding this issue. The issue of over-parameterization concerns the lack of a unique solution for the parameters of the model because of their number. In practice, it is necessary to fix several parameters based on best guesses and then solve for remaining parameters, iterating on this process until what is judged as a "good" model is found.

Applications of the model have been quite successful and diverse. It has been used for air-to-air-combat modeling, pilot workload computation, determination of flight stability boundaries, and evaluation of alternative flight displays. One of the most interesting applications has been to try to experimentally determine the nature and parameters of the cost functional, alternatively known as the inverse optimal control problem. At least one investigator (Anderson, 1974) has concluded that there is no universal cost functional, supporting previous contentions that it is not a viable approach to assume some universal cost functional and expect to derive a valid control law.

Principal uses of the model have been direct applications to new problems with a minimum number of revisions and extensions. Some exceptions are efforts to extend it to decision making tasks, revisions to the bases for selecting an optimal control action, and the addition of preprocessing on the displayed signal to better simulate the human's perceptual processes. In addition, a major simplification of the model has been attempted to correct the problem of overparameterization.

The optimal control model represents a number of real or intuitively logical characteristics of the human operator. This is at the expense of identifiability, however, and in attempts to reduce the number of parameters, several of the simulated characteristics had to be omitted. Thus, it seems that to make derivation of the model's parameters completely rigorous from a mathematical standpoint means a necessary loss of essential aspects of the model's content validity.

The most serious shortcoming from the standpoint of applying the model for measurement applications lies in the cost functional and the associated assumption on which it is based. First, the model parameters are extremely sensitive to the cost functional. The fact that the nature and form of the cost functional can only be conjectured makes it impossible to place much reliance on the resulting model parameters in general measurement applications. It is possible, however, that the model may be useful in carefully controlled experiments where (a) the true cost functional is of no interest and (b) the subjects can be instructed to perform in accordance with the dictums of the assumed cost functional without compromising the results of the experiment.

In addition to the above shortcoming, the basic assumption of the model contraindicates its use in performance measurement, that is, the assumption that the highly trained and motivated operator will behave optimally. In measurement applications, the concern most of the time is with the untrained operator; there can be no assurance that he will behave optimally nor even that he will attempt to minimize the same cost functional as a trained operator will, granting that a universal cost functional for any group of operators even exists.

Thus, the optimal control model does not appear suitable for investigating behaviors for which it was not designed, such as those involved in learning. Therefore, it is not suitable for general measurement applications. Its forte lies in the study of optimal behavior of highly trained operators, but even here the computation of parameters lacks complete rigor due to overparameterization. It is possible that simplifications as proposed by Phatak et al. (1976) may be useful in solving this problem. Possibly the most interesting application of the model in the area of measurement and training is in studying the inverse optimal control problem. However, this problem is not trivial and, so far, a general solution has not been discovered.

Discrete and Finite State Methods

Most of the mathematical models discussed so far are based on the assumption that the human observes a continuum of input states and produces a continuous stream of outputs. Several investigators have taken issue with this assumption, claiming that the observations and decisions which determine successive outputs are discrete rather than continuous events. As a result, various theories have been proposed regarding issues such as the bases on which decisions are made, man as a sampled data system as opposed to a continuous regulator, and man as a finite state machine.

One of the principal promoters of the theory that man acts on the basis of discrete observations and decisions was Bekey who, along with various associates, developed several novel modeling concepts. As early as 1962, Bekey proposed that the human's output in a manual control task is intermittent, consisting of a series of ballistic responses triggered at intervals of about .5 second (Bekey, 1962). Referencing the earlier work of Craik, Bekey developed a simple model based on this assumption and showed that it was capable of producing outputs more representative of real performance than contemporary linear, continuous models. Stimulated by this early work, Bekey investigated the effect of using a random sampling interval, finding it produced outputs that appeared more realistic (Bekey & Biddle, 1967). This supported the earlier efforts of Pew (1966). In associated studies, a model was proposed wherein the human is assumed to quantize his input and output into a finite number of states, and data are processed using asynchronous samples of this coarsely quantized input (Angel, 1967; Bekey & Angel, 1966). These assumptions permitted the use of the highly developed theory of finite state machines. The work was also based on the assumptions that the human changes states, depending on quantized observations of error and error rate, and that a response, once initiated, cannot be interrupted but must run to completion. This initial work consisted primarily of developing modeling rationales and proposed modeling constructs.

Experiments were conducted to study the control response amplitudes and pulse-widths in an attempt to specify a model representative of the foregoing theories (Merritt & Bekey, 1967). As a result, it was concluded that sometime near the completion of an output pulse, monitoring of error and error-rate begins. When the error trajectory enters some preselected region of the phase plane, a decision to produce a new pulse is made and, sometime later, is executed. Merritt went on to apply some of these discrete modeling concepts to visual scanning behavior (Merritt, 1968), while Angel and Bekey pursued the further development of a finite state model of manual control (Angel & Bekey, 1968). In the latter effort, the assumption was added that the human has a library of four force programs, any one of which can be triggered based on phase plane observations. Although the results of the associated modeling experiments looked promising, no comparison with actual human performance data was made, and an objective evaluation was not presented.

Other active promoters of finite state machines for modeling manual control behavior were Fogel and Moore. Their work resulted in a finite state model of human performance in flight control tasks, including a representation of reaction time delay (Fogel & Moore, 1968a). Model outputs were compared with those produced by a linear pilot model, a nonlinear model, and a human. The results were excellent. A detailed description of the model showed that input data were quantized into 64 elements and a 64-state machine was used (Fogel & Moore, 1968b). State transitions were fixed (next state is present input), and outputs were computed statistically. Thus, much of the success can be attributed to the large size of the machine, and a direct correlation could be anticipated between the number of states and the accuracy of results.

The notion of using finite state machines was also pursued to develop an adaptive gain changer in an aircraft stability augmentation system (Burgin & Walsh, 1971). Walsh had performed earlier work with Fogel and was undoubtedly influenced by previous experiences with finite state machines. The actual machine developed is only sketchily described; however, it was constructed by adjusting outputs to minimize a cost function representing the difference between real and model-computed gains.

The use of dscrete decision events in operator modeling was also proposed by Poulton to produce outputs corresponding to high frequency input components that more nearly mimic man (Poulton, 1967). He suggested that the human makes decisions about every .5 second and that there must exist two models (compensatory and pursuit) to fully represent a given performance. According to Poulton, the latter is due to the likelihood that the man's internal compensatory model is kinesthetic while his internal pursuit model is visual.

In another effort, Preyss developed a theory of human learning behavior based on a single channel assumption involving discrete response selection (Preyss, 1968). He theorized that a priori estimates of the probability that a specific response is appropriate are stored in memory. Response selection is a decision process which uses the prior estimates, and learning consists of revision of the priors based on the weighting of certain evidence. A model based on this theory was developed for performance of a relay control task. The ensuing experiments supported acceptance of the null hypothesis, but follow-up studies were not conducted.

More recent applications of discrete modeling concepts include development of a model of the helmsman of a supertanker (Veldhuyzen, Van Lunteren, & Stassen, 1972). Here, studies were conducted to determine decision rules for making discrete adjustments in the wheel position. The study revealed extensive intersubject variance on the parameters believed to be essential independent variables. Finally, other investigators have pursued the idea of using the phase plane as a medium for specifying decision criteria (Jagacinski, Burke, & Miller, 1976). This study showed that as learning proceeds on a manual control task, the decision locus in the phase plane approaches that employed by a theoretically optimum controller.

In way of critique and final comment, many good ideas have been proposed for modeling all or part of human performance as a discrete process. Much theoretical evidence and some empirical data suggest that such concepts as input quantization, response intermittency, and discrete observation and selection of output responses have merit. At least part of the problem in implementing these concepts lies in the difficulty in mathematically modeling discrete as opposed to continuous events. Attempts to use existing tools, such as finite state machines, have enjoyed some success but very large models were necessary. Studies that have been done to try to characterize the decision criteria used to govern changes in the response have been very valuable. In particular, the phase plane has been used extensively to determine the boundaries of regions in which control response or some aspect thereof remains fixed.

Adaptive Techniques

One very important human trait which models discussed so far have not addressed is adaptation. In performing complex tasks, it is unlikely that the operator selects a fixed control technique and applies it without change for the duration of the task. Instead, he adapts his technique depending on the acquisition of new knowledge about the task, instantaneous task requirements, and other concurrent jobs that compete for his attention. Studies of operator adaptation are especially relevant to performance measurement applications, because learning a control task may be viewed as a succession of adaptation processes.

Most efforts in adaptive modeling are oriented toward the control of systems having complex and/or time-varying dynamics. In one such study, the adaptive process was characterized by four phases: (a) Detection of a change in the vehicle dynamics or environment which necessitates a change in control; (b) identification of the characteristics of the new situation and stabilization of the vehicle; (c) reduction of accumulated errors; and (d) optimization of dynamics (Elkind, Kelly, & Payne, 1964). Detection was modeled as a threshold identification process based on error alone, while identification was based on an estimation of the relationship between stick movement and error position, rate, and acceleration (Elkind & Miller, 1966). An adaptive model incorporating these phases was proposed. The model also included assumptions that position and velocity are directly perceived, responses are intermittent, and both pursuit and saccadic channels exist. Some studies were performed to empirically determine how changes in control dynamics are detected (Miller & Elkind, 1967). However, full test and validation of the proposed model was not accomplished.

In another similar study, attempts were made to identify the decision process used by humans in detecting a change in control system dynamics (Phatak & Bekey, 1968; Weir & Phatak, 1966). Here, it was assumed that the human operator recognizes certain pattern features in the error versus error-rate phase plane. The phase plane was divided into regions, and studies were conducted to try to identify a valid decision process based on asking yes/no questions about the region currently active and trends of error and error-rate (Phatak & Bekey, 1969). Complete pursuit of this modeling idea through the validation phase did not occur, although some interesting concepts were developed.

In another study to develop adaptive control methods for time-varying dynamics, it was proposed that the human operator works in terms of a string of control intervals (Knoop & Fu, 1964). In attempting to track as well as possible, the human attempts to shorten his control intervals, within each of which bang-bang control is used. The amounts by which intervals are reduced are bounded below by the system delay time. It was further hypothesized that the human forms an internal model of the plant, subjects it to the same forcing functions, and uses its response to predict system response. He then compares this with actual system response to identify changes in plant dynamics. This is accomplished at the end of each control interval. Experiments were conducted to establish basic feasibility of the model and develop methods of obtaining model parameters.

It was concluded that the control intervals are relatively constant in length and that the model has potential for explaining adaptive behavior.

Other studies have been conducted on adaptive modeling methods, but most are variations or extensions of those discussed above. For example, Niemela (1974) worked to experimentally derive boundaries of regions in the phase plane where the human perceives a change in vehicle dynamics. Interestingly, another study in the same year concluded that subjects are not able to consciously detect changes in dynamics as soon as they are made, although they change their control characteristics almost immediately (Moriarty, 1974). Gould and Fu (1966) proposed a three-part adaptive model involving the process of identification, decision, and modification. However, the model was not developed and validated.

In way of summary and critique, a number of interesting concepts have been developed in attempts to make models adaptive. These concepts are of interest in performance measurement because learning can be viewed as a sequence of adaptations. Most of the adaptive modeling work has been oriented toward situations involving time-varying plant dynamics, and efforts have been concentrated on determining valid decision rules for detecting a change in dynamics. For example, attempts have been made to determine regions of the phase plane between which transitions cue the operator that plant dynamics have changed. Although some good ideas have been conceived in these efforts, none has been pursued far enough to fully validate the associated model, and only a few have been pursued past the proposal stage.

Preview Models

Conventional models such as describing functions and the optimal control model do not cope with preview and are not generally able to model performances where the operator is privy to preview information. However, preview occurs in most of the complex tasks of interest in flying training, for example, and efforts to accommodate it in a model are of considerable interest. Unfortunately, only a few studies were found where the modeling of preview behavior was of primary interest.

Sheridan and associates note that, "The human's transfer function for response to a predictor display is not amenable to conventional filter discovery analysis since his dynamic response at each instant is not determined by a single valued function of time" (Sheridan, Johnson, Bell, & Kreifeldt, 1964, p. 230). They propose that one way of accounting for preview is to assign weighting factors to each point, from the present to some realistic, observable limiting point in the future, and then use the weighted value of the input to determine the next response. In rationalizing this approach, they present an analogy of turning a car into a parking space. The initial trajectory is arbitrary but the final one is not, the error there being far more important. Still, the initial trajectory must be chosen to minimize the expected error in places where it is relevant – thus the use of independent weighting factors. The relevance of this concept to other tasks is of interest for, as Sheridan observes, "It is evident that uniformity of error importance is indeed a very unusual situation in human control tasks such as driving vehicles, walking, using tools, and most things people do" (Sheridan, 1966, p. 92).

Unfortunately, little was done in the way of validating any preview models based upon these concepts. Only a few other studies of preview control behavior were cited; these were largely thesis topics and were apparently not pursued in depth (Sheridan & Ferrell, 1974). The idea of incorporating preview control by appropriately weighting the inputs representing the preview area is novel, but identifying the best weighting function is not a trivial job and would probably be task-dependent. Therefore, considerably more research on preview modeling is necessary before it would be a serious candidate for use in performance measurement applications.

Other Nonlinear Approaches

Despite the fact that the human has long been known to be nonlinear in most behavior, surprisingly little research has been performed in developing nonlinear models. A possible reason is provided by Pitkin:

> Most likely, this is due to the fact that control engineers can deal with linear models expressible in terms of transfer functions with much greater facility than nonlinear models; that these models are fairly easily derived from experimental data

> with cross correlation techniques; and, furthermore, that in situations wherein the operator behaves in a quasi-linear fashion, the use of a linear model is a most appropriate engineering approximation. (Pitkin, 1972, p. 11)

A good example of readily observed nonlinear behavior occurs in tracking tasks involving acceleration-control. Here, it is well known that the human operator resorts to a pulsing output behavior, presumably to develop enough lead to enable control to be exerted. Linear models have attempted to account for this by using an adaptable lead-lag term. This can provide the necessary lead by properly adjusting parameters; however, it does not result in the distinctive pulse-like behavior observed consistently in the human (Pitkin, 1972).

According to Pitkin, the earliest work in nonlinear modeling was performed around 1958 by Diamantides (Diamantides, 1958). He developed a model which inserted a step function into the output each time the error crossed the zero point. The step preceded the reaction-time delay element and resulted in generation of a lead pulse. Diamantides also injected dither into the output and included a threshold on the error-plus-derivative signal.

Ten years later, Costello developed a two-mode surge model which constitutes the basic idea upon which much of the subsequent work in nonlinear modeling has been based (Costello, 1968). This model used either conventional linear control or a surge control (pulsing output) depending on the magnitude of error versus error-rate (phase plane position). This modeling concept was applied later by Johannsen (1972), who added a third control mode consisting of constant output. Comparison of the output of this model with that of a human and a describing function model clearly revealed its superiority over the describing function in predicting human response. (Johannsen, 1972). Equally promising results were achieved by Pitkin with a model based on use of a linear controller plus a threshold feedback unit, where large, negative feedback of the output resulted in initiation of a pulsing action (Pitkin, 1972).

Beyond these studies, little has been accomplished in nonlinear modeling that is of potential utility in measurement applications. Nonlinear analysis is at a stage of infancy compared with linear analysis, and perhaps this accounts for the fact that little headway has been made. The work discussed above consists of adding additional control modes to the conventional linear mode and determining which to apply on a sample-by-sample basis using error and error-rate information. Results are sufficiently promising that these techniques are worth pursuing further. However, progress so far is limited, and much work remains to be done to investigate the validity of proposed methods before they can be considered candidates for measurement applications.

IV. ASSESSMENT OF EXISTING MODELS

Several human operator characteristics have been identified which ought to be included in or otherwise accounted for by models to be used for performance measurement applications. These include operator intermittency; the existence of a psychological refractory period which is best explained by the single channel theory of behavior; range effect; inadvertent crosscoupling; bang-bang control characteristics; and differential use of various cues at various times and circumstances. Associated traits of the human, some of which precipitate many of these characteristics and which ought to be considered, are the existence of observation and control errors; time variations in control strategy; threshold and saturation effects; preview and precognitive functions; and variations in performance due to changes in attention and fatigue.

Describing function models incorporate virtually none of the above characteristics. Furthermore, they are based on assumptions of operator linearity which are in direct contradiction of several of the characteristics. Describing function models were designed to be applicable to simple compensatory tasks, but these tasks represent only a small percentage of the real-world tasks of interest. Attempts to extend these models to other applications have not been successful. Therefore, these models have no anticipated utility as a basis for general measurement applications.

The optimal control model incorporates a few selected operator characteristics, most notably the existence of observation and control errors. In addition, it is based on a viable theory of behavior of a highly trained operator. To a greater extent than any other model reviewed, the optimal control model attempts to incorporate identifiable modules which are isomorphic to reasonable hypotheses about human behavior. The most serious shortcoming of the model from the standpoint of its potential use for measurement applications lies in the optimality assumption and the related cost functional. The former is an assumption about the highly trained operator, whereas in most measurement applications the interest lies primarily in the untrained operator. The true nature of the cost functional (for the highly trained operator and certainly the untrained operator as well) is unknown, and since it influences the model parameters, its conjecture gives poor assurance of their validity and reliability. Therefore, this model is not considered suitable for general measurement applications, although it seems fairly well suited for studies involving highly trained operators in which use of a specific cost functional can be experimentally controlled.

Discrete and finite state models incorporate various human operator characteristics such as intermittency, single channel behavior, input quantization, and discrete observation and selection of output responses. Unfortunately, the related work has not yet progressed far beyond the breadboard stage in many instances, and what has been performed suggests that implementation problems may be the cause. There is a distinct difficulty in modeling discrete as opposed to continuous events, and it is possible that the necessary modeling tools are just not yet highly enough developed. Therefore, these modeling methods are not sufficiently far developed for justifiable use of any one as a point of depature for measurement applications.

Adaptive models are of considerable potential interest because learning can be viewed as a sequence of adaptations. Related modeling work has been primarily oriented toward accommodation of time-varying plant dynamics. Several good ideas have been proposed for this particular type of adaptation; however, no attempt has been made to incorporate the human operator characteristics identified in this report. In addition, few of the ideas have been pursued past the proposal stage. Therefore, these models do not appear defendable at this time for measurement applications.

Several preview and nonlinear models have incorporated a few of the identified human operator characteristics; but the associated work was not pursued far enough to give particular credence to any one model as a likely candidate for measurement applications. Very little work has been done with these two types of models. At this time, neither is considered suitable for measurement.

In summary, none of the human operator models developed to date and reviewed in this study implement more than a few of the operator characteristics that have been identified. Those which have attempted to incorporate known or theorized information about the human are either based on associated assumptions which are unacceptable for general measurement applications (as with the optimal control model) or were not far enough developed to suggest that they are desirable for use as a point of departure (as with discrete and finite state, adaptive, preview, and nonlinear models). Part of the problem appears to lie in the deficit of technology for dealing with such things as nonlinear analysis and discrete event modeling. The bulk of the problem, however, lies in the fact that existing models were not developed for measurement applications, and the attempt has been one of emulating human output rather than simulating or otherwise accounting for the intricacies of human behavior. Therefore, underlying assumptions are not based upon characteristics of human behavior to the extent desired for measurement applications.

V. REVIEW AND CONCLUSIONS

A survey has been conducted of human operator modeling technques to assess their utility for performance measurement applications. Existing measurement techniques do not have the capability to support the type of flight simulation research that entails accounting for the perception and utilization of cues. In addition, the many efforts to derive more suitable measures have further complicated the problem by developing more and more different measures from which to choose with little regard for the effects of an improper choice. They have also been somewhat misdirected in their emphasis on measures of system performance rather than measures of human behavior. A new measurement approach is required which minimizes the number of measures that must be considered, computed, and interpreted; and which produces measures that characterize behavior succinctly and are sensitive to those aspects of human behavior that directly involve cue perception and utilization. It is believed that human operator modeling techniques may provide a basis for this type of measurement.

Model validity is particularly important in the case of the envisioned measurement applications. A model used for measuring human performance should be based on assumptions that are in full accord with the body of knowledge that exists about human behavior. Therefore, the first task of this study was to identify the major human operator characteristics that ought to be accounted for by a model to be used for measurement. These characteristics were later used in evaluating the various models for this application.

Existing models were categorized by type as follows: (a) Describing Functions; (b) Optimal Control Models; (c) Discrete and Finite State Methods; (d) Adaptive Techniques; (e) Preview Models; and (f) Other Nonlinear Approaches. A survey was made of models in each category by reviewing the literature and summarizing the various modeling studies. Particular attention was devoted to modeling assumptions and whether or not any specific human operator characteristics were incorporated.

Models in each category were evaluated based on the extent to which they represent the identified *human operator characteristics* as well as other aspects of their general validity for performance measurement applications. It was found that none of the models reviewed implement more than a few of the operator characteristics; and those which do are either based on other assumptions which are unacceptable for measurement applications or have not been far enough developed to justify their use as a point of departure. The major reason for this is that existing models were not developed with measurement as an objective; and the attempt has been to emulate human output rather than simulate or otherwise account for the intricacies of human behavior.

It is concluded that existing human operator models are not sufficiently representative of known characteristics of human behavior to be useful for general performance measurement applications. It appears, too, that modeling studies of the past have emphasized matching the response of the average human operator at the expense of modeling the behavior of the individual, and for the particular application area of performance measurement, this is unacceptable. Studies are required to develop modeling techniques specifically for measurement uses, and these studies should be based on valid assumptions about the human that are supported by the body of related knowledge that presently exists. Equally important, these studies should emphasize the development of models of the behavior that generates the performance of the individual rather than models of average operator performance output with little regard for the underlying behavior.

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