EVALUATING OPERATOR LOADING DURING SYSTEM DESIGN

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ABSTRACT

The Canadian Defence and Civil Institute of Environmental Medicine (DCIEM), Systems Modelling Group sponsored the development of a new human performance modeling approach based on an Information Processing and Perceptual Control Theory model. The approach combines Hierarchical Goal Analysis with simulation to predict a human "operator loading, performance and error production" versus the classic analytic approach of predicting performance under simulated "task loading". This paper will describe the implementation of the theoretical approach within a task network simulator called the Integrated Performance Modelling Environment (IPME) and discusses its intended use and benefits.

ABOUT THE AUTHORS

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INTRODUCTION

Over the past ten years, the importance of human-centered design within the Systems Engineering process has been increasingly recognized. A key component of this approach is the ability of designers to predict human performance as a function of system design. The use of simulation to account for human variability is an established methodology to support these predictions. There have been a variety of different approaches taken to accurately portray human performance and workload; few can claim a strong theoretical basis.

The Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) recognized the need for theoretically based tools to help evaluate operator performance in systems design. As a result, they sponsored the development of a new discrete event simulation scheduler that attempts to predict human performance, operator workload, and error production as a function of the predicted task demand. The new scheduler is theoretically based on classic Information Processing (IP) theory and knowledge of how humans allocate their attention in situations involving competing concurrent demands. This new scheduler is implemented within the Integrated Performance Modelling Environment (IPME), a commercial discrete event modeling and simulation environment in use by Canada, the UK, Holland, Australia, the US, and others for helping to predict human performance during the feasibility and concept development phases of system designs.

Using task network simulation to predict operator performance and workload is a common analytic approach to early complex system designs. Simulation environments allow human task parameters to vary with various network states allowing behaviors to be modeled. Task network simulation extends traditional time-line analysis methods by introducing non-deterministic task characteristics such as dynamic operator assignments, task completion times, sequences, and outcomes. The output from this form of analysis is a simulated time-line of modeled activities or task loading of operators. In general, this is neither a measure of system performance nor operator workload. To provide this measure, a time-based metric of system performance or some model of the human information processor (HIP) is required from which load, and eventually performance can be inferred.

The IP/ Perceptual Control Theory (PCT) scheduler provides a theoretically based model of the Human Information Processor (HIP) for making these inferences. A unique and innovative capability of using the IP scheduler within IPME is that analysts can use the modeled behaviors to predict operator loading which represents the subset of assigned tasks performed by an individual operator. The operator loading represents what can actually be performed when considering physical resource constraints, cognitive capacity constraints, and time criterion constraints.

What is IP/PCT?

The IP/PCT model combines a simple information-processing paradigm (Hendy, Liao, and Milgram, 1997) with concepts from perceptual control theory or PCT (Powers, 1973). The combined IP/PCT model provides a unifying framework that integrates knowledge about operator workload, performance, and error production with concepts such as situation awareness. Significantly, the IP/PCT model traces the dependencies that link these constructs (Hendy, East and Farrell, 2000).

The IP/PCT model makes the claim that the fundamental stressor determining operator performance, error production, and judgments of workload, is time pressure. Time pressure is defined formally in terms of the ratio between the amount of time required to process information to the time available before a decision has to be actioned.

More specifically, it is claimed that all factors that affect operator workload can be reduced to their effect on this variable. Hence, time pressure is claimed to be the principal stressor in the human information-processing context. However, the IP/PCT model also incorporates the more global effects of various psychological and physiological stressors that act diffusely on the arousal and activation mechanisms. Within the IP model are embedded notions of multiple task interference (due to both structural effects – you can't look in two directions at once - and interference within shared IP structures) and IP strategy changes under time stress.

On the other hand, PCT drives systems analysis towards a hierarchical decomposition by goal rather than function (Hendy, Beevis, Lichacz, and Edwards, 2000). All goals from the highest to the lowest level become candidates for allocation to intelligent agents (humans or machines) within the system. PCT concepts can also be used to derive task performance modification functions that model the effect of excessive time pressure on task performance and strategy changes (Hendy and Farrell, 1997)

What is IPME?

IPME is a task networked-based modeling and simulation environment intended to provide an authorable simulation capability to predict human performance under future operational conditions. IPME focuses on the simulation of human operators under their operational conditions. Modelers use IPME through a set of integrated models that can represent a complete system description including the environment in which the system operates, the operators that control the system, performance modifications based on models of the operator's psychological/ physiological state (e.g. fatigue, motivation, comfort, anxiety, trust, etc.), and a flow-chart layout of human procedures and system (hardware, software) tasks. The integrated models are intended to help the human factors practitioner analyze human-system performance by providing a more realistic representation of humans in complex environments (Dahn, Laughery, and Belyavin, 1997).

The heart of IPME is the task network diagram (Figure 1) that provides a graphical view of the goals (networks or functions) and sub-goals (tasks). This graphical view provides the analyst with the spatial interdependencies between different goal states, and procedural sub-goals that must be achieved to satisfy a higher level goal.

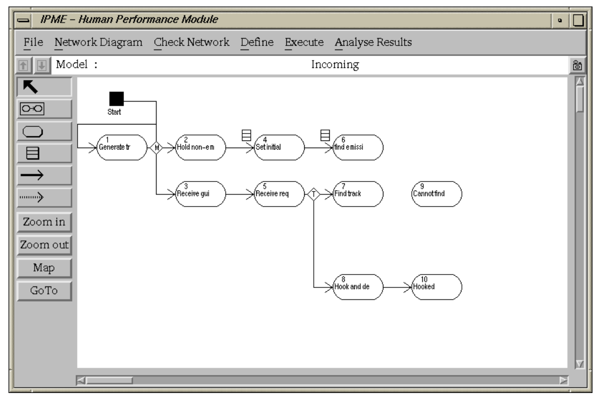

Figure 1: IPME Network View

IPME contains different scheduling engines to facilitate different types of systems analysis. The first is a standard Monte Carlo scheduler that is very effective in establishing initial model structure and parameters or provides the task load view of a system. The next is the IP/PCT scheduler that simulates operator load. That is, it establishes time criterions for tasks within the model and dynamically calculates a time pressure variable that represents what a real operator would perceive as time pressure. This metric is used to facilitate changes in goal strategy (actual performance of tasks). IPME output may be used in queuing analysis, decisions on operators in complex situations, task failure and hierarchical representation of tasks.

BASIS OF APPROACH

To effectively evaluate operator loading during system design, one must first be able to make predictions about the overall system performance. The system consists of the human, hardware, and software needed to achieve the goal or function of that particular system.

To perform the analysis an analyst will employ a systems engineering approach that consists of data collection and analysis, building executable models of the system, validating the model against a baseline or known performance data (to the extent possible), and evaluating the output metrics to predict system performance.

The data collection approach has generally consisted of a function and task analysis that defines what a system needs to do. However, this approach often overlooks supervisory and control tasks not explicitly defined in process descriptions. In addition, there are often multi-controlled system conditions that cause conflicts or unstable control conditions within a system – thus leading to system instability. Hierarchical Goal Analysis helps correct these deficiencies (Hendy et al., 2000a). HGA comes directly from the application of PCT concepts.

Hierarchical Goal Analysis

HGA combines what has traditionally been done under function and task analysis with a goal oriented structure that defines the state the human or system must achieve as a consequence of performing a task or function.

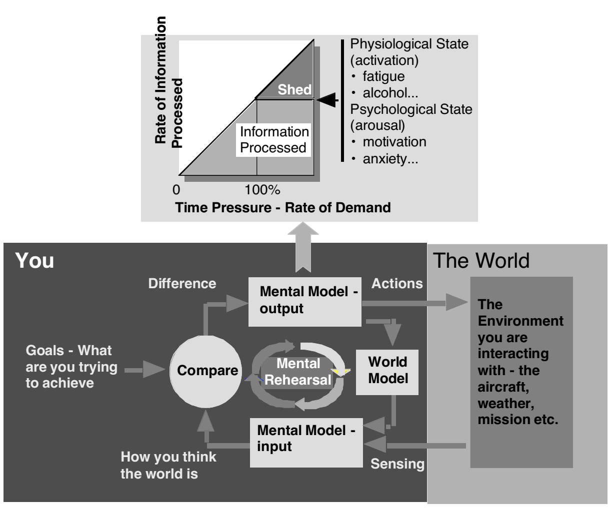

Figure 2: The IP/PCT Model at a single level of abstraction.

HGA supports the concept that humans appear to function as a closed loop hierarchical perceptual control system, whether they are tracking the centerline of the road, hitting a tennis ball, regulating their heart rate, or making tactical decisions. As shown in Figure 2, humans sense the world through eyes, ears, and sense of touch, taste, and smell. This sensory information, coupled with their past experience, form the perception of what the information means. A human then compares that perception to their internal goals, and responds to any resultant error by selecting some response that that is intended to affect the world state.
The combination of all the knowledge one can draw on, in making the transformations from sensation to perception, and error to action, can be called the mental model. It consists of both the long term declarative knowledge (how things work, standard operating procedures, etc.) and short term, transient, situation specific knowledge (this is the what's happening now knowledge, and is often called situational awareness).

Systems analysis involves the hierarchical decomposition of system goals (human) and objectives (machine). Top-level goals/objectives generally represent the system at a functional level, whereas lower levels are usually thought of as task analysis. A fundamental difference is that the designer must make a decision, at each level of abstraction, as to what loops are going to be controlled. This means that goals/objectives may be assigned at all levels from the highest to the lowest. Any goal/objective not assigned is not controlled. Generally higher-level loops are satisfied by some combination of lower loop activity (e.g., a logical sum of lower loop states). If feedback is broken at any level, there is no control. If a loop is not controlled there is no error correction.

Humans and machines communicate with each other (human-human and machine-human) via their influence on various variables in the environment. Just as humans have goals that determine the set point of various control loops, machines have various references or programmed objectives that represent the goals of the system designers. Hence, the general structure of the PCT model applies to machines as well as human controllers. The control representation can be extended to systems of humans and machines of any size. This potential sharing of influenced variables between teams of human and automated systems defines a multi-controller system with all the potential for unstable behavior.

All control loops involve one or more variables that are influenced by the loop action. For example: the temperature of a room, the altitude of the aircraft, the rotational speed of a propeller etc. If there is a goal/objective there must be an influenced variable. For humans these variables can be either internal (not directly observable by a third party) or external and therefore observable. While the same can be said for the machine, human controllers can only know about those variables that are observable in the environment. Part of the HGA approach is to assign a controller, human or system, to these controlled variables.

In any system both human and machines are exerting an influence ("control") over these external variables. Depending on the division of control at any point in time (shared or segregated), the commonality of goals /references, and the compatibility of the transformation functions that shape input and output signals, the system might be either stable of unstable. This arrangement puts human and machine control side by side. It should be possible to look for the existence of potential instabilities between human-human and human-machine control.

Since we have identified who or what can modify a particular controlled variable, a database search through the data can quickly identify where multiple controllers are assigned that can modify these controlled variables leading to different system goal states. The analyst can then use this knowledge to better define user and system interfaces to eliminate these potentially unstable system conditions. At all levels of abstraction, human activities will be directed to satisfying a hierarchical set of goals.

IP/PCT in the IPME Environment

The IP/PCT scheduler within the task network framework establishes a method to predict human performance based upon concepts introduced in the IP/PCT Model. The simulator attempts to predict human performance response based on information processing theory by using a measure of time-pressure, a model of human attention, cognitive limits, and physical resource limits (Figure 3).

In making the bridge from the theoretical framework of the IP/PCT Model to the implementation of a workload/performance prediction model within a task network environment, two important constraints were considered. First, there are a restricted number of parameters available in task network simulation to capture the essence of the IP/PCT Model. These reduce to task inventories, task sequences, task attributes, task completion times, tasks serviced and task shed (see also Hendy, Koberski, and Youngson, 1992). With these limited degrees of freedom, the IP/PCT Model can be approximated only.

Second, there is no reliable method for computing either the human's actual channel capacity or the amount of information to be processed in most decisions. Nor is it necessary to do this for the application of the IP/PCT Model in a task network environment. Decision time (the outcome of these two parameters) can be observed or predicted. The relationship between decision time and the amount of information to be processed is linear according to the IP/PCT Model; hence, decision time is a surrogate for the amount of information to be processed. The realization of the IP/PCT Model within the IPME IP/PCT scheduler was made with these constraints in mind.

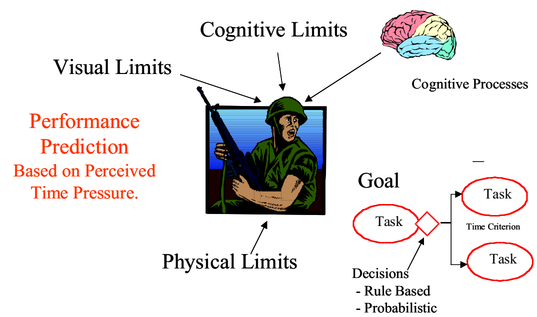

Figure 3: IP/PCT Model in IPME

The scheduler operationalizes the concept of multiple task interference and adds a basic allocation of attention rule base for scheduling concurrent task demands. The task scheduler is based on task prioritization and draws on the notion of compatibility as determined by task interference effects. The allocation of attention algorithm sets limits on the number of tasks that can be performed in concert. These aspects can be considered to be extensions to the basic IP/PCT Model. Note that the idea of concurrent task performance promoted in this scheduler consists of a combination of strictly parallel and serial time multiplexed processing of task elements (Hendy and Farrell, 1997).

The human information processing scheduler places operator tasks into the simulation event queue ordered similarly to how a human is expected to schedule tasks, such as:

1. highest priority tasks first
2. generally handling tasks in the time order they would occur
3. finishing tasks almost completed before starting new tasks (task momentum,)
4. only taking on "new" tasks that are compatible with what the operator is doing, and
5. priority is based on a sense of urgency as determined by the *perceived* time pressure.

Again, based on the IP/PCT Model, it is argued that time pressure is the best representation of the workload that operators experience. The instantaneous time pressure is the mathematical estimation of what the human is expected to perceive at a point in time, when performing a task that has a finite time criterion associated with it. The instantaneous time pressure is defined as:

$$\frac{\text{processing time remaining on task } i}{\text{time remaining to latest processing time for task } i}$$

The peak instantaneous time pressure is the maximum instantaneous time pressure across tasks performed concurrently. Peak instantaneous time pressure is averaged over recent history to estimate load.

The internal rule set can delay or shed assigned tasks based upon yhe average time pressure. The resulting delays and report of tasks shed allows the formulation of inferences regarding operator demand loading, situational awareness and potential error production. Ultimately, these inferences can be used to predict human performance. When predicted performance is sub par, analysts can select candidate procedures, processes, or other system components for redesign or automation.

Using IP/PCT for Systems Analysis

DCIEM sponsored a study of the Canadian Force's Tactical Battlefield Command and Control System (TBCS) using HGA and IP/PCT task network models implemented in IPME (Dahn and Lowdon, 2000).

Specific objectives included assessment of the applicability of the PCT protocol relative to traditional analyses, qualitative assessment of PCT implementation issues, and identification of lessons learned. The approach used for the study was to develop PCT and non-PCT network models of a single TBCS mission segment within the IP/IPME environment, and to compare the utility and relative merits of each method in achieving HFE analysis objectives.

When using HGA, we found the approach forced an analysis of the upward flow of information versus the downward flow defined from a traditional top-down functional decomposition and analysis. This upward flow of information was found to be particularly critical in identifying requirements for automation to facilitate the process of keeping high-levels informed and able to make timely and correct decisions in response to the achievement of lower-level goals.

All goals assessed as providing feedback to higher-level goals were identified. These were analyzed in detail to determine the nature of the feedback, and how it would be accommodated in the real world. This generally resulted in the need for supervisory/ control goals/ objectives being added to the network at the higher level. Frequently this also resulted in additional communication tasks being added to provide the information flow to that level. These "new" goals/objectives were incorporated in the network model and represented additional workload imposed upon the system operators that were not found in the traditional top-down approach. Thus, we found that HGA provided a more realistic view of the goal-demands that exist for each of the operators in the system.

Once the goals are modeled, several human performance metrics are inherently available within the simulation environment with the IP/PCT scheduler invoked. These include the measure of operator time pressure, prospective memory size (attentional memory), and demand load versus operator load. Built-in graphs are available in IPME to display the first two metrics. These metrics identified sections in the timeline (high time pressure or high demand) where further systems analysis was required. The analyst should consider system design intervention or task/goal reallocation to reduce the predicted stress imposed on individual operators.

Consistent with the notion that errors result from information shed, tasks that were forcibly modified from the allocation of attention module were tracked and recorded. This information was used to prepare three summary tables showing tasks shed, interrupted, and delayed along with corresponding tasks performed: shown as a proportion of 100 runs, against normalized mission time, categorized by criticality (to mission, to situation awareness etc.), and reason for event (number of attempts, priority, predecessor task, random, uninterruptible task, task hysteresis, etc).

These tables were used to represent the comparison of demand load versus operator load. Knowing the salience of the tasks that remain unserviced to the mission requirements provided insight into the consequences of the task environment — which of course is generally the goal of the workload/ performance assessment.

These tables identified the points where the mission was subject to potential breakdown or failure. They showed conflicts on the mission timeline when the operator demand load could not be met and what tasks were in conflict. Although this analysis did not include modeled consequences as a result of the demand load not being achieved, the points in the time-line that required additional study by the analyst were identified.

The largest insight was the simulated prediction of areas in the timeline where certain operators that were preoccupied by other tasks did not attend to messages in the communications system. Each of these missed messages had the potential to generate mission critical errors.

The HGA and IP/PCT approach was found to be quite applicable to conceptual-phase system analyses, and offered benefits over the traditional human factors engineering approach. The HGA stability analysis was found to be particularly beneficial as a structured process for early identification and resolution of potential instabilities resulting from multiple control of a single variable.

VALIDATION

Evidence for the IP model comes from two related experiments involving a simulation of an Air Traffic Control task to manipulate processing load. The first experiment was designed to investigate the effects of time load and intensity load (amount of information to be processed) on operator performance, errors and perceptions of workload (Hendy et al., 1997)]. The IP model was derived from the data of this experiment. A second experiment was conducted to address some issues arising from the first. This provided additional insight into the theoretical foundation of the IP model (Hendy, et al., 2000b). As these studies are available in the literature they will not be elaborated further here.

The notion of the human as a closed loop controller is hardly new, yet direct experimental evidence for PCT is scarce. Some evidence comes from Bourbon (Bourbon, 1990, 1996), who tested PCT experimentally using a manual-tracking task. PCT is also said to be evident in systems other than human tracking, such as in genetic reorganization, self-realization, and social systems (Robertson and Powers, 1990), yet few experimental studies have attempted to validate PCT in these more complex environments.

A closed loop, negative loop gain, control system is an error correcting system. The reverse side of this statement is the assertion that all error correcting systems can be reduced to the form of a closed loop, negative loop gain, control system. If this is so then PCT, at the very least, is a normative model for human behavior. This may prove to be the most persuasive argument for the use of PCT.

NEXT STEPS

Further validation both of the concept and the IPME implementation of the IP/PCT model is required. Validation of such a complex environment is a challenging task because of the number of degrees of freedom. The current plan is to pursue laboratory studies to focus validation on specific parts of the IP model. The IP model contains a considerable number of rules and numerical coefficients; unfortunately, only a small number of these may be addressed with any given data set.

Work has recently started to represent several laboratory studies within IPME task networks then compare predicted to empirical results. Data sets from single and dual task studies were provided through international collaboration (Belyavin, Personal Communications) that will form the initial validation efforts. The tasks include: Visual Bakan, Auditory Bakan, dual-axis tracking, spatial vigilance and non-spatial vigilance (variable pitch detection). Representing the empirical tasks as task networks is itself a challenging endeavor; the appropriateness of each representation is debatable. Adjusting the task network fidelity to the sensitivity of both the IP/PCT model and the empirical results without biasing the predictions requires both creativity and objectivity.

A few simulator study results have been collected for the validation effort. These results will be used to explore the validity in a more global, subjective evaluation after the single and dual task studies have been used to validate specific aspects of the model.

CONCLUSION

The IP/PCT model

- recognizes that human behavior is goal driven and has purpose,
- is built on a large body of human performance literature,
- invokes all the rigor of control theory within a human context, and
- is a hard (quantitative) model in systems analysis terms — in contrast to the soft (descriptive) models that dominate many areas of psychology.

The IP/PCT model has not only shaped the approach to operator performance prediction within IPME but has led to a new method for systems decomposition that combines what has traditionally been done in function and task analysis into a single integrated process. Two new forms of analysis emerge from this hierarchical goal analysis that are expected to significantly improve systems requirements capture. They are: an analysis of multi-controller stability requirements; and support for the upward flow of information in the system (support to higher level goals). These forms of analysis capture supervisory tasks that are normally missed during a systems analysis, thus providing a more realistic estimate of actual demands being imposed on an operator of the system.

Finally, implementation of the IP/PCT scheduler within the IPME environment provides a human task management strategy that can show how well the operator can be expected to perform their tasks, where conflicts exist, and where the mission can potentially break-down.

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