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Knowledge-Based Load Leveling and Task Allocation in Human-Machine Systems

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ABSTRACT

Conventional human-machine systems use task allocation policies which are based on the premise of a flexible human operator. This individual is most often required to compensate for and augment the capabilities of the machine. The development of artificial intelligence and improved technologies have allowed for a wider range of task allocation strategies. In response to these issues a Knowledge-Based Adaptive Mechanism (KBAM) is proposed for assigning tasks to human and machine in real time, using a load leveling policy. This mechanism employs an online workload assessment and compensation system which is responsive to variations in load through an intelligent interface. This interface consists of a loading strategy reasoner which has access to information about the current status of the human-machine system as well as a database of admissible human/machine loading strategies. Difficulties standing in the way of successful implementation of the load leveling strategy are examined.

Introduction

Since the industrial revolution, human-machine systems of increasing complexity have been developed. Initially, machine capability was both limited and inflexible and human operators were required to adapt themselves to the needs of the machine, often carrying out boring and repetitive tasks in cramped quarters and under hazardous conditions. The development of a human factors orientation, coupled with advances in technology, has improved working conditions and human-machine performance. As human-machine systems become more complex, however, the division of labor between human and machine becomes less clear-cut. Ideally, tasks should be allocated to the system component best suited to perform them. Machines tend to be superior in calculation, rote memory and coordination of simultaneous activities while humans excel in creative problem solving, pattern recognition, and decision making under uncertainty.

The resolution of the task allocaction problem is not always straightforward. While many tasks as yet can be performed satisfactorily only by humans, advances in machine intelligence and automated systems have increased the number of tasks which may be performed both by human and machine. Consider the task of regulating the speed of an automobile. On an open freeway, control might be passed to an automated system (cruise control), whereas the human operator (the driver) should be operating the accelerator and brake in city traffic. Changing task definition and environment may necessitate a revision of the task allocation policy. This policy will also be affected by changes in the state of the individual. When the operator is fatigued, under stress, or overloaded there is a tendency to focus on restricted elements of the task as exhibited by attentional narrowing (Hancock & Dirkin, 1983). To continue with the automobile example, part of a cab driver's task might involve carrying out a conversation with the passenger, but the driver may avoid this when fatigued or overloaded (Brown, 1967). The task of entertaining and informing might then be carried out by the radio, although perhaps not as well as by a talkative cab driver.

In complex systems where both task definitions and system capabilities vary over time, task allocation should be viewed as a dynamic rather than static process. Adaptive mechanisms are required which can diagnose the state of the machine and operator in order to reallocate subtasks accordingly and thereby optimize performance. This paper will consider how these adaptive mechanisms can be designed and implemented and will discuss some of the problems which may be encountered.

Human-Machine Cooperation

Conventional views of human-machine systems have the human controlling, or being controlled by, the machine component. In machine-paced assembly, for instance, the human is effectively controlled by the machine, whereas in driving a car, the human appears to be in control, at least under normal operating conditions. We follow an alternative perspective of human-machine systems in regarding them as a cooperative enterprise. In this view, human and machine work together to ensure successful system performance and the satisfaction of task demands. The assumption of a synergistic and cooperative relationship between the components of a human-machine system leads to a new type of system design. Firstly, cooperation presupposes communication between intelligent entities. Expert system consultants (Hayes-Roth, Waterman, & Lenat, 1983) provide low-level examples of this communication. Secondly, an interface (translation process) is required for the communication of needs, requests and ideas between the entities.

Early human-machine systems forced the human to fit in with the requirements of the machine, i.e., the human bent while the machine was straight. Human factors engineers designed machines and tools which fitted human capabilities, in keeping with the maxim "bend the tool, not the person" (McCormick & Sanders, 1982, Chapter 10). The ideal situation would be one where both the person and the machine stood straight (i.e., performed according to their design principles) while a translating interface adapted inputs and outputs so as to render them compatible.

Task Structuring

The type of adaptive interface necessary for genuine human-machine cooperation would be capable of restructuring the task in accordance with system goals and environmental constraints, and of reallocating task components between human and machine for a given task structure.

Figure 1 shows the overall control structure for such an adaptive interface. Task structuring would be carried out by a task definition supervisor. As technology advances and human-machine systems develop, the task will no longer be set as a fixed entity. Instead, the definition of the task will change in accordance with the higher level goals set by some external agency and with changes in the number and type of environmental constraints acting on the human-machine system. Given a particular definition of the task, allocation of tasks to human and machine would be carried out by an intelligent interface.

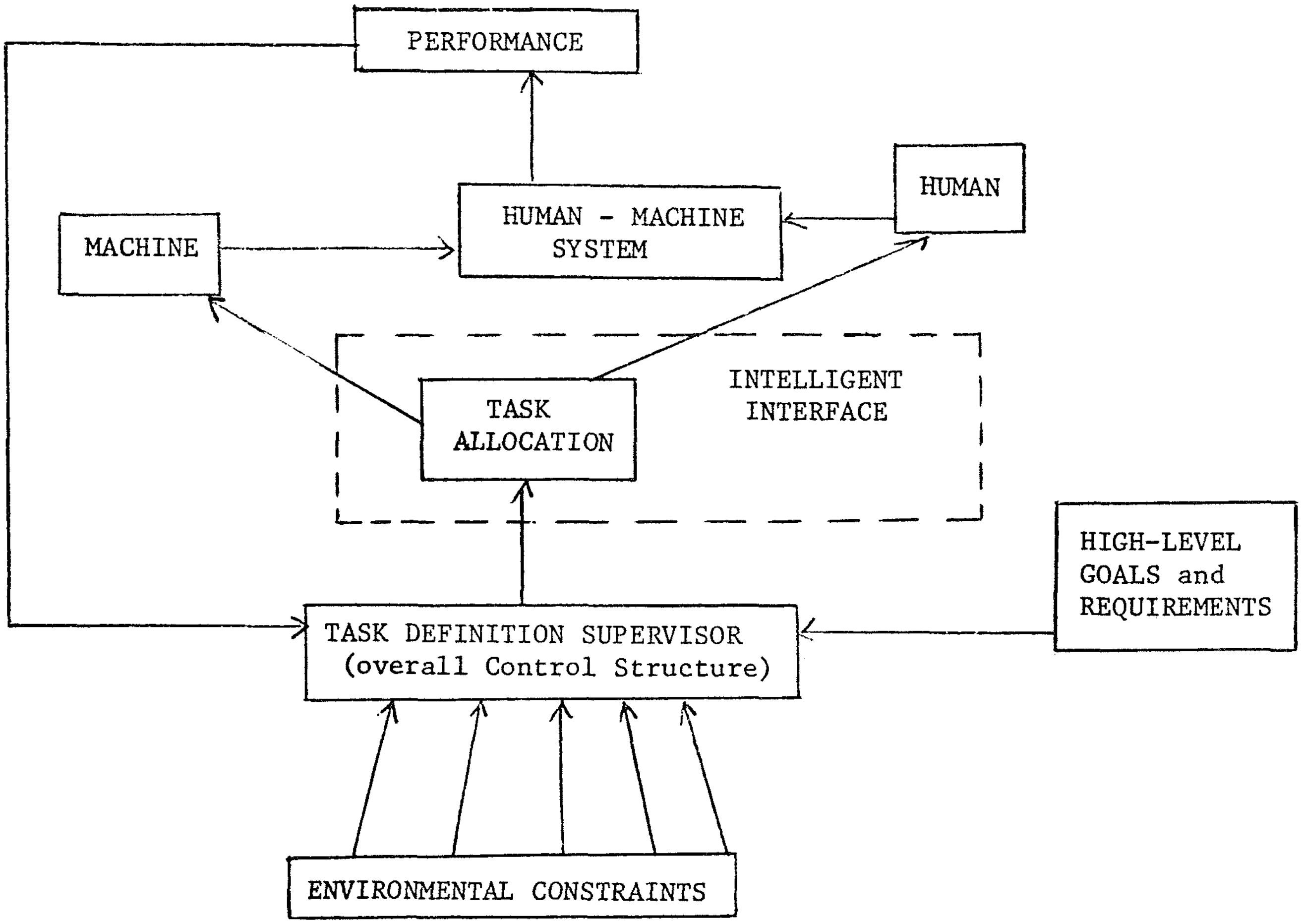

Figure 1. An overall control structure for a human-machine system which allow flexible restructuring and reallocation of tasks.

Task Allocation

It is clear that optimal allocation of task functions between operator and system requires a knowledge of human versus machine capabilities. Some of the task functions will not be involved in the allocation decision because they are clearly suited only for the machine or only for the human component of the system. Allocation will be relevant for tasks which can be switched between human and machine without having a detrimental impact on overall performance (Figure 2).

Price (1985) has developed a method for allocating functions between humans and machines which requires human designers to construct a preset and fixed task allocation. The optimal allocation will not be fixed (see above), however, but will be conditional on the task definition, working environment, and current capabilities of system components. Given a particular task definition and system with currently specified capabilities, optimal task allocation requires a detailed understanding of human cognition and capability. At present, knowledge about the human abilities that are relevant to the performance of various tasks is incomplete, but there are several major characteristics which should be taken into account These include human sensitivity to relative rather than absolute change, limitations in attention and memory, compatibility of various input/output modalities for different tasks, performance variability, error correction capabilities, fatigue and reactions under stress (Chignell & Hancock, 1985, Hancock & Chignell, 1985).

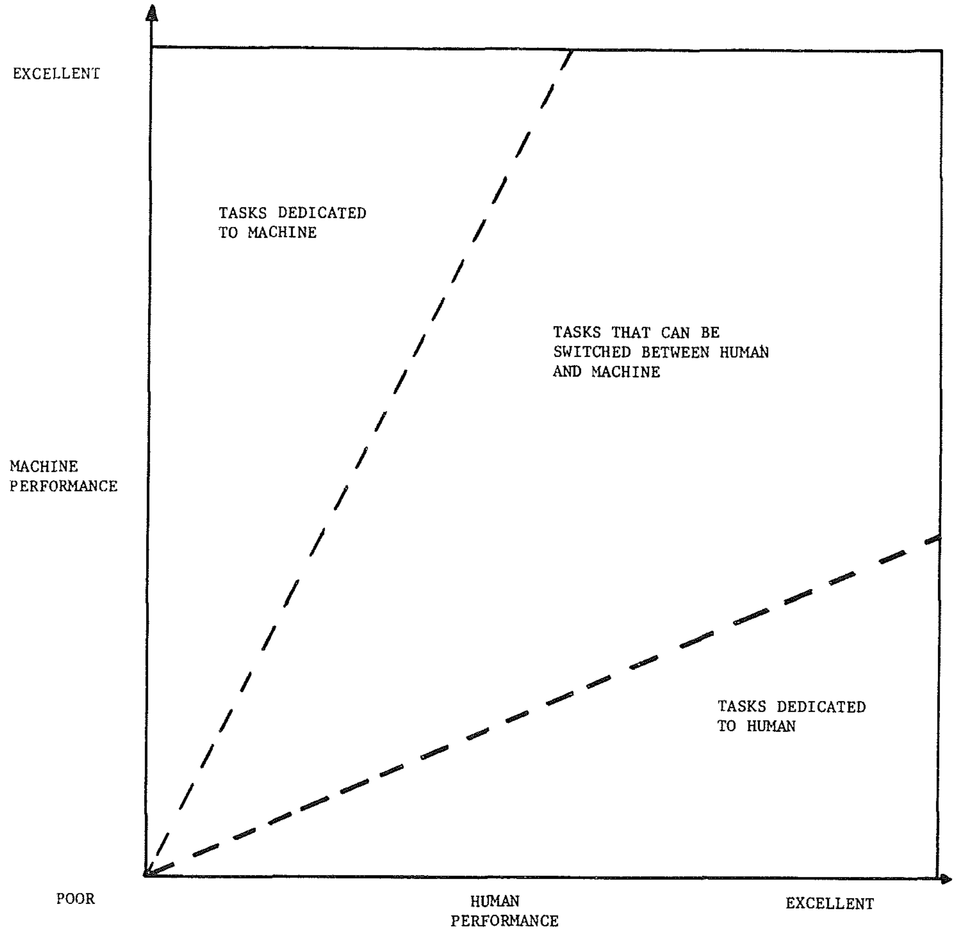

Figure 2. Decision space for allocation of tasks within a human-machine system.

Optimal, or close to optimal, task allocation will require a sophisticated reasoning process based on models of human and machine capability and a detailed analysis of the current operating environment. The previous discussion has outlined an ideal approach to synergistic and cooperative human-machine systems. This approach presupposes an intelligent interface which will allow communication between human and machine. The interface will then act in much the same way as an intermediary helps the user communicate with an online information retrieval system or as an interpreter translates the communications of two people who speak different languages. Intelligent systems are a powerful tool for improving the cooperation between human and machine. Building such systems into the machine allows it to function as an intelligent entity. Designing the interface as an intelligent system allows effective communication between human and machine. For a given system, it becomes debatable as to whether the intelligence resides in the machine or the interface. In this paper we shall focus on augmentation of the interface.

Static task allocation policies ignore intrinsic variability in the nature of the task and the human-machine system's response. Taking the human's point of view, the perceived difficulty of the task is a reflection of the mismatch between task demands and available resources (capacity). This mismatch will vary over time, as illustrated in Figure 3, with the human tolerating the variation in most cases. At times, however, the mismatch may be so great as to produce inadmissible overload or underload with consequent decrements in performance.

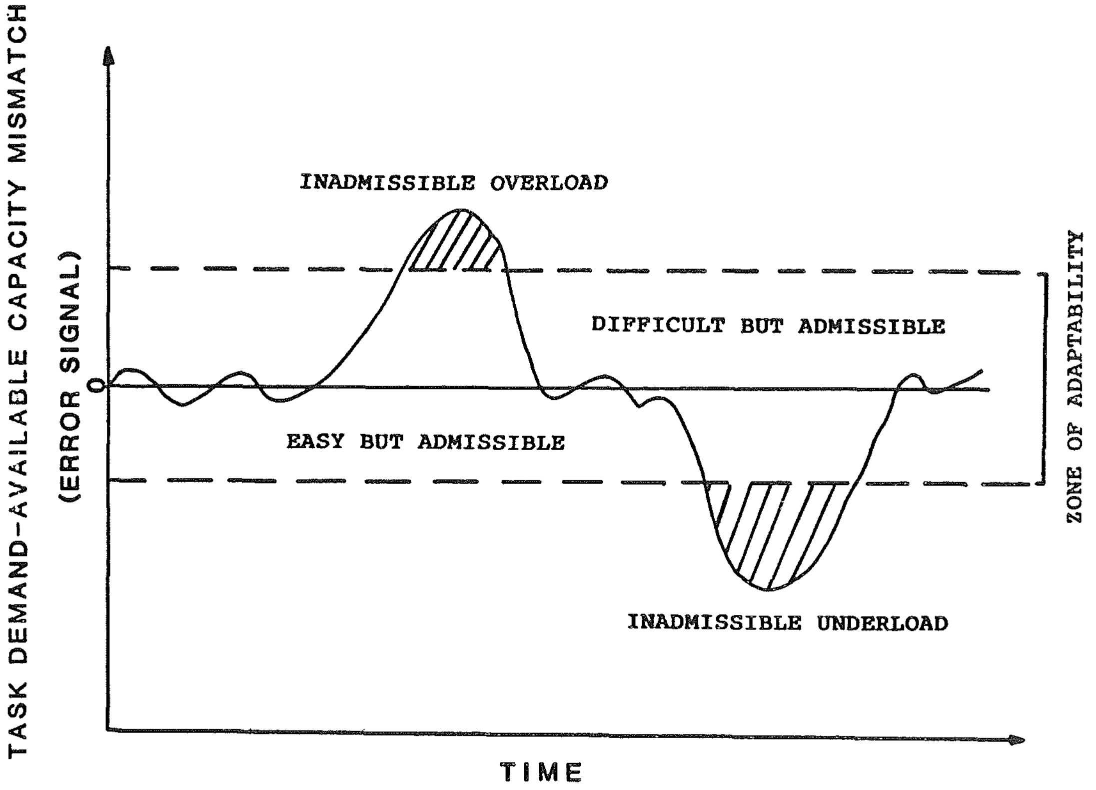

Figure 3. Schematic representation of the time-varying mismatch between task demands and available capacity. Shaded regions indicate inadmissible loading conditions.

In order to achieve a consistently high level of performance, the human-machine system will need to cope with large task and person fluctuations. In many cases, humans will be able to adapt to mismatches between current task demands and their available capacity. In some situations, however, the mismatch between task demands and available capacity will be so great as to preclude sufficient adaptation by the human operator. In such cases, return to the zone of adaptability to the task demand-resource mismatch (see Figure 3) requires dynamic reallocation of the task components, and possible, restructuring of the task. The process of dynamic reallocation requires an adaptive interface which is outlined below.

A Knowledge-Based Adaptive Mechanism (KBAM)

Although the concept of an adaptive interface has been discussed (e.g., Edmonds, 1981; Morris, Rouse & Ward, 1984), adaptive interfaces which allocate tasks dynamically have yet to be implemented. Part of the reason is that adaptive interfaces will be useful only with certain types of task. Firstly, the task must be performed by a human-machine system and, secondly, the task must be of moderate complexity, being neither so difficult as to tax the system as a whole, nor so easy as to allow the system to perform adequately whatever allocation policy is adopted, as depicted in Figure 4. In general, there will be some combination of task complexity and variability where an adaptive reallocation policy will improve performance significantly. Personnel training and selection will tend to shift the boundaries of the region upwards, as shown in Figure 4.

Adaptive interfaces have also been conspicuously absent in the past because the technology was not available. Recent developments in computer hardware, mental workload assessment (MWL) and artificial intelligence now make dynamic task reallocation technically feasible, although difficult to implement.

Dynamic task reallocation requires an adaptive mechanism which can assess the mismatch between task demands and available capacity (Figure 3) and redefine the task so as to reduce this mismatch. This adaptive mechanism will represent more than a simple reflexive action (e.g., table lookup) in many cases, since the complexities of human capabilities, task flexibility (i.e., the extent to which, and conditions under which, it can be redefined) and physiological variability will require some degree of knowledge-based reasoning.

The first step in developing the knowledge-based adaptive mechanism (KBAM) for load-leveling is the identification of the error signal representing the mismatch between the current task demands and the available capacity of the human operator. Task demands can be assessed either by examining task characteristics directly, or indirectly through assessment of MWL. MWL assessment will be necessary in many situations because of variability in response to specific task characteristics, both within and between individuals. Theoretically, the error signal can be expressed 1), as a mismatch between global attentional capacity and task requirements (cf. Kahneman, 1973), or 2), as a mismatch involving multiple attentional resources (Wickens, 1980).

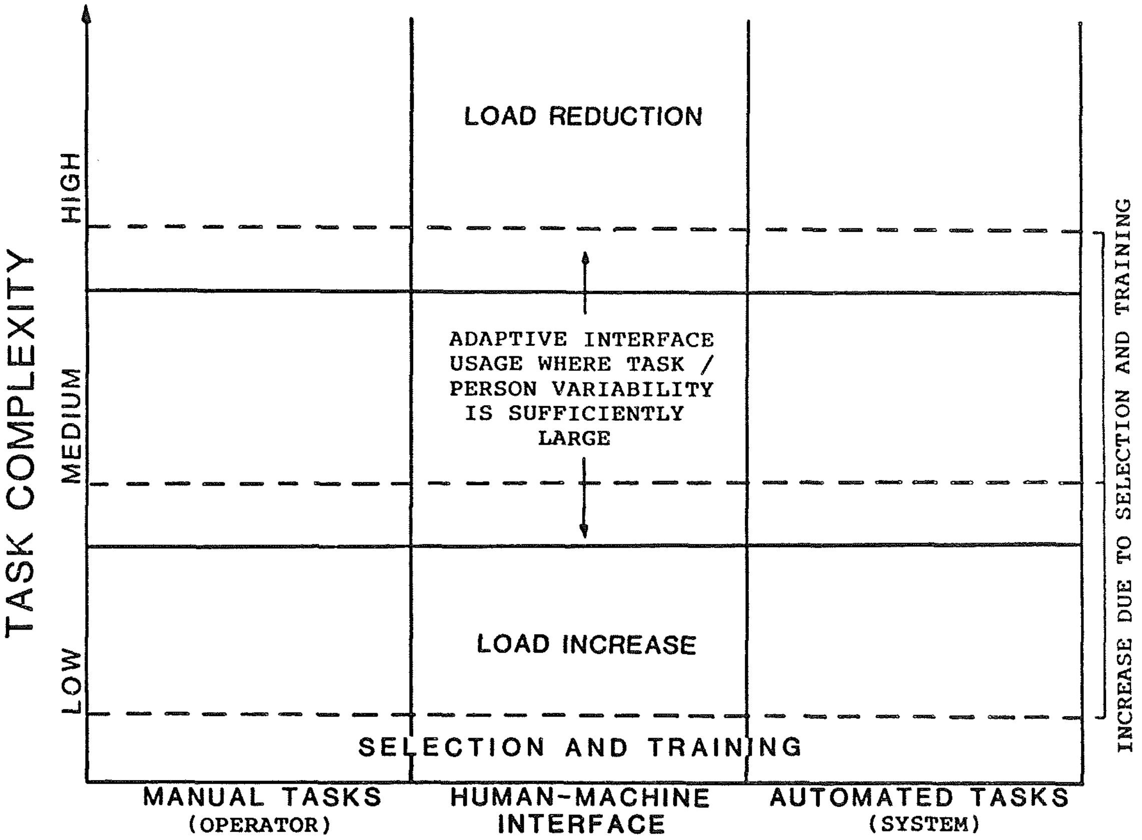

Figure 4. The effects of task complexity and degree of automation on the applicability of adaptive interfaces.

The formation of the error signal is problematic. MWL measures may be used to derive the error signal directly, but they are likely to be confounded by a number of factors, not the least of which is emotional response to the task situation and performance feedback. Ideally, the error signal would be based on a theory of attentional resource utilization and the various relationships between task demands, workload and physiological response (see Hancock, Meshkati, & Robertson, 1985). At present, we favor redundancy in error signal derivation. Direct measurement of the error signal via MWL assessment would be augmented by calculations of the mismatch between task demands and attentional resources. Indirect assessment of the mismatch by calculation requires an understanding of the demands generated by different tasks and estimates of resource capacity based, possibly, on performance measures. Specification of how the error signal should be derived under different circumstances is a subject that is being investigated in our laboratory.

Once the error signal is derived, it is input to the adaptive mechanism. Models of the task, system, and person then allow prediction of the effect of alternative task redefinitions, while lookup of a database of admissible loading strategies will enable a quick check of whether or not a proposed strategy violates guidelines relating to minimum task performance and imposed safety standards. Only tasks which can be switched reasonably between the human and machine components of the system (Figure 1) will be considered for reallocation, except under emergency conditions which demand continued performance, with the result of system failure having fatal consequences.

The output of the adaptive mechanism will be a reallocation and, possibly, restructuring of the task which alters (where necessary) the loading of task components between the human and machine so as to reduce the error signal. Thus a human-machine interface is developed which acts as a servomechanism minimizing the difference between current demands and available capacity. The overall structure of this interface is shown in Figure 5. It is referred to as an intelligent interface because of the extensive use of knowledge and reasoning in formulating the load leveling strategy. Central to the reasoning process is a knowledge base containing information about all the facts deemed to be relevant to the performance of the task. Figure 5 shows only one of a number of ways in which a KBAM might be designed, although we expect any variation to contain the components identified here, albeit in different configurations.

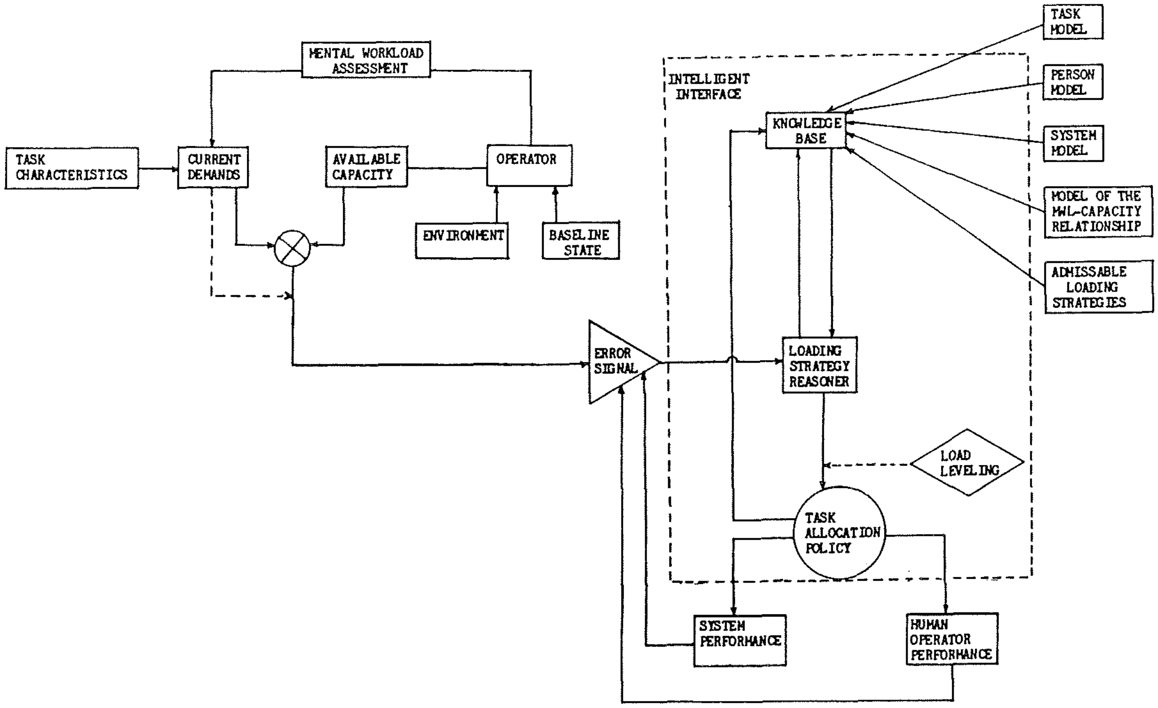

Figure 5. The overall structure of a knowledge-based adaptive mechanism that could be used as an adaptive interface for dynamic task reallocation.

Load Leveling and Task Allocation

Adaptive mechanisms of varying sophistication could be developed, differing in the amount and complexity of the reasoning used in load leveling. The simplest system would have a lookup table which assigned a loading level to each task definition. The tabulated task loading would be adjusted on the basis of the apparent effort being used by the person (measured either physiologically or as a subjective rating) in performing the task.

Additional complications would be introduced if a multivariate error signal were used, as would occur if the error signal was constructed using a multiple resource model of attentional capacity and multicomponent analysis of the task. Even so, the reasoning process might not be too complex providing that the redefinition of the task were regarded as a classification task. Conventional expert systems are well equipped to handle the classification problem and existing techniques using a well defined knowledge base and a production rule inference engine (e.g., Hayes-Roth, Waterman & Lenat, 1983) might be sufficient to accomplish this purpose.

The task redefinition process can be viewed as one of classifying a given error signal in terms of a fixed set of task definition choices, as occurs in the table lookup methods. In the more complex versions of KBAM, however, the table lookup procedure of classification is replaced by rule based inference. The success of this strategy will depend to a large extent on the quality of the information stored in the knowledge base, i.e., whether or not the set of allowed task definitions or the specific rules are appropriate. One factor which will affect the complexity of reasoning required will be the variability of the environmental contingencies affecting the task. Tasks can be classified as open, i.e., subject to variable environmental contingencies, or closed, where environmental contingencies do not vary and task restructuring will not be required, except when satisfactory allocation is not possible within the current task structure. An example of this open/closed task distinction occurs in flying where good weather and safe flying conditions will provide a closed task, whereas poor weather and intermittent hazards will result in an open task which requires more flexible responses. In general, the more closed a task is, the easier it will be to model it and build an appropriate adaptive mechanism.

The purpose of KBAM is an allocation of task functions between human and machine which maximizes performance outcome. The process of task reallocation should not be disruptive. A large number of sudden, discrete changes might lead to a worsening, rather than an improvement, in performance. It is likely that smooth and relatively continuous changes in task definition will be preferable.

The manner in which the change in task demands is best communicated to the human operator will depend to some extent on the task being performed. One can distinguish between insidious systems which reallocate tasks without directly warning the human, and conversational systems which signal explicitly each change in the task definition and allocation. Alternatively, the adaptive interface may be consultative, suggesting a better task allocation policy, while allowing the human operator to decide whether or not the suggested task reallocation should take place. In order to minimize a variety of stresses associated with the lack of autonomy, it is suggested that the latter proposal will generally be more useful for dynamic human-machine systems.

Implementation Problems

Development of the type of adaptive mechanism outlined here entails a number of difficulties which are summarized briefly below. It is not clear what task should be used in building a KBAM prototype. A suitable task will have components which can be switched between human and machine, well defined parameters (for task definition and analysis), will test a variety of human resources, and possess continuous measures of success and failure. Flying tasks appear to be appropriate, but they are not readily amenable to experimental manipulation without access to a sophisticated ground-based simulator. Video games are likely to be among the first tasks for which a KBAM prototype is developed.

MWL assessment is a controversial topic. Since KBAM is designed to deal with complex tasks where overloading may be a problem, dual task assessment methods may not be appropriate. Similarly, reliance of subjective ratings would be unwise in situations where the person is fully occupied by the task. We favor using physiological measures in this instance, supplemented with direct assessment of performance. More research is required before MWL measures can be used with confidence in generating an error signal. The development of physiological recording systems which are unobtrusive and reliable is a technical problem that remains to be solved (Hancock, Meshkati, & Robertson, 1985).

As specified earlier, KBAM should operate in close to real time. In the prototype that we are developing, processing tasks are divided between three computers. The first computer carries out data acquisition, while the second does the automated reasoning and the third presents the task. Given current laboratory facilities, it is likely that there will be a delay of approximately half a minute between the physiological response and the resulting task reallocation, with up to 10 seconds being required for each of the three major steps in the process. This may be acceptable in a laboratory demonstration of the concept, but this lag will be excessive and impractical in applications such as flying. While improvements can be made in the speed of data acquisition and task presentation, automated reasoning is likely to remain a bottleneck for the forseeable future. Thus there will be a tradeoff between sophistication of reasoning and response latency with the hardware and techniques available now and in the immediate future.

The final difficulty considered here (although there are others) is that of putting a number of complicated components together into a working system. A working prototype is necessary to demonstrate the feasibility of the concept. Each of the components of KBAM, MWL assessment, modeling of attentional resources, task analysis, automated reasoning, and task reallocation, is a major technical challenge.

Summary

The knowledge-based adaptive mechanism (KBAM) is a powerful method for implementing dynamic reallocation of task components between human and machine. Implementation of this method requires models of attention, cognition and physiological response, as well as expert systems and related techniques. Despite potential problems, the benefits of the KBAM technology justify a large scale research and development effort. As technology advances, particularly in aerospace applications, KBAM systems may be the only way of preserving harmonious, cooperative and successful human-machine relationships.

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