The Allocation of Functions in Man-Machine Systems

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Space systems as they now exist would be impossible without automated control. We have become accustomed to systems which make maximum use of computer logic to control vehicles and ground systems. In such systems, at their best, computers are able to unburden the operator, to deal with complex computations, to organize information for display, and to act with great reliability and speed. Many control problems can be solved in no other way. But automated control is no panacea. Computers cannot set objectives, and they prove to be poor substitutes for man in processes such as pattern recognition and fault diagnosis. They cannot deal with the unexpected, nor can they construct innovative solutions to an emergency condition. Sometimes computer applications create, rather than solve, problems; and in operational situations we repeatedly observe that operators or pilots elect to defeat their automated systems, so that they themselves can assume manual control.

In many of these cases the problem is an improper allocation of functions between man and machine. Allocation decisions were cast in hardware or software during design, and may now permanently limit the usability of the system. When functions are automatic the human operators may be unable to see what is happening or to exercise useful control. On the other hand, when functions are manual, the users may be forced to perform unnecessary chores or to do tasks for which humans are poorly adapted. To some extent, such design errors happen because, during design, there has been no deliberate consideration of which functions should be allocated to man and which to the machine.

An Historical Study

This problem is widely recognized in military and industrial settings, as well as in the aerospace community. Our company, BioTechnology, Inc. (BTI), recently completed a study for the Department of Defense in which we examined the R&D literature and the histories of recent systems procurements. In spite of DOD regulations which specifically require allocation of functions as a step in the design cycle, we could not find a single case in which the allocation of functions was decided, system-wide, in a systematic way. This is true, we believe, because there is no recognized methodology for allocating functions. Accordingly, BTI recommended the development of a framework and a set of methodological tools which a design team could use in allocating functions to man or machine.

Developing a Method

BTI is now developing such a framework and tools for use in nuclear power plant (NPP) design. In an effort supported by Oak Ridge National Laboratories and the Nuclear Regulatory Commission, BTI has developed a conceptual method for allocating functions (or assessing existing allocations) in NPP control rooms. The method is applicable both to earlier technology using electromechanical process control and to later technology exploiting the computer.

BTI first examined the history of technology in this perspective, and then reviewed major models and methods which have been proposed for the allocation of functions. These begin with the "listing" approach. In 1951, Fitts proposed a table listing the differing capabilities of machines and man, to be used in support of decisions about automation. Since then, more elaborate lists have been suggested, for instance by Mertes and Jenny (1974), Edwards and Lees (1974), and Swain (1980). More elaborate simulations, procedural guides, and information support systems have also been developed, including HEFAM (Connelly & Willis, 1969), CAFES (Parks & Springer, 1967), SYSSIM (Ireland, n.d.), SAINT (Workman et al., 1975), HOS (Strieb & Wherry, 1979), and the Hypothetical-Deductive Model of Price and Tabachnik (1968). Several of these have features which might be applied in determining functions for nuclear power plant control, but most of them either were never developed in an operational form, or assumed the availability of large bodies of reference data which do not yet exist. In spite of widespread concern, there appears to be no instance of a proven methodology for allocating functions to man or machine.

Findings of this research included a recommended general, iterative procedure for allocating functions in the design of NPP control rooms, and some "lessons learned":

- There has been no successful system-wide use of an allocation method.
- Most methods for allocating functions are helpful for psychomotor tasks, but *not* for the cognitive tasks which are central to nuclear and aerospace operations.
- Allocation of functions is like engineering design: it is an iterative process that requires repeated cycles of preliminary design, test, and modification.
- Engineering design depends on an institutional memory, within the profession, of past successes and failures. We need such a memory for allocation (and for other human factors) decisions.
- Allocation decisions drive related requirements for training, procedure writing, and personnel selection.
- A major need in automated systems is for man-computer communications: a means by which (1) the operators can remain aware of system states, even when computers exercise control, and (2) the computer can be informed of human interventions, including what those interventions are expected to accomplish.

BTI proceeded to (1) elaborate a practical, step-by-step, reproducible method by which allocations can be made, and (2) identify criteria sets to be used in applying the method. The method will now be fully developed and applied to a selected real case in the NPP industry.

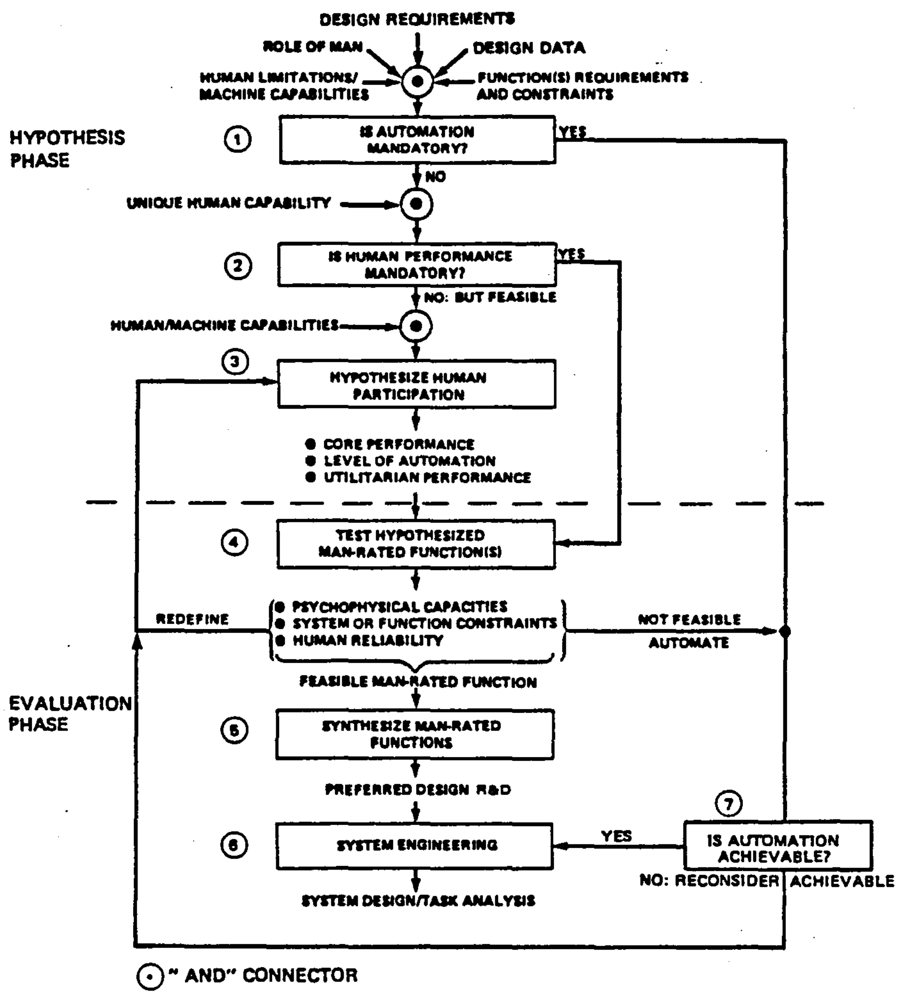
The Recommended Procedure—Hypothesis

A procedure was developed which differs from earlier schemes in at least one major feature: earlier procedures provided hypothetical solutions only. However sound they were, they provided only an untested hypothesis as to the correct allocation of functions. The BTI procedure added deductive (or empirical) tests of the hypothetical solution. Furthermore, specific tests were followed by closed feedback loops, so that the method can search heuristically toward an optimized man-machine interaction. The method is designed to be applied continuously, throughout the system design process, and to provide a series of iterative approximations approaching the goals expressed in a system requirements statement.

Exhibit 1 illustrates principal steps of the proposed method. Note the median dashed line, which separates an initial hypothetical analysis from the following evaluation phase. This second phase is called the "deductive" phase when deductive rather than empirical tests are employed, as must be the case during early (concept or preliminary) design phases.

Exhibit 1

The Allocation-of-Functions Process



In the procedure, initial decisions identify these functions which must be allocated to man or machine for obvious reasons. Such allocations must be made to automation (Step 1) for instance, when regulation or policy requires it, when hostile environments preclude the presence of man, or when the required system reaction times exceed human response limitations. Allocations to human control (Step 2) may be mandatory, for instance, when there is a requirement to develop strategies, to detect patterns or trends, or when meaning or values must be assigned to events. Additional tests are applied for economic and technical feasibility (Step 3), and in some cases a tentative decision may have to be fed back for reconsideration at the system requirements level.

Steps (1) and (2) are repeated first at the whole-system level, then for subsystems, and finally for portions of subsystems until those parts of the system which clearly must be controlled by man or computer have been partitioned off and allocated properly. Normally, this will leave substantial portions of the system, and of the operating procedure, which can reasonably be allocated *either* to man, to machine, or to some combination of the two. At Step (3), these functions are classified according to a performance taxonomy and allocated on a best-choice basis. This process is reported in detail in NUREG/CR-2623 (Price, Maisano, & Van Cott, 1982). At each point in this process decision aids are provided, but the actual decisions remain judgmental. It is suggested that the procedure be applied by a team including at least one experienced human factors engineer and one control engineer. The method provides an orderly decision procedure and a set of decision aids which includes some representative quantified human performance data. Most importantly, it provides for documentation of the decision process. This documentation makes it possible for allocations decisions to be communicated widely within the systems design organization. It provides a basis for the evaluation steps which follow. Finally, it provides a basis for iterative improvement and elaboration of detail in the man-machine relationship, and interaction with engineering design decisions as the system design evolves.

The Recommended Procedure—Evaluation

At this point in each cycle of the system design, an allocation of functions to man or machine has been hypothesized. In a design which has reached the mockup or prototype phase, an empirical test is appropriate. But a set of deductive tests are provided as well, which can be used during concept formulation and other early design phases.

First (Step 4), those functions hypothesized as "man-rated" are reviewed in detail against the known psychophysical capabilities of man, against system constraints, and against reliability requirements. If found feasible in these tests, a next step (Step 5) asks whether the human job, as it is emerging, is acceptable to an operator. Modifications are made at this point to ensure that operators will feel supported and important, that the job is coherent, and that it will fit into a reasonable authority and social structure. Finally, depending on outcomes of tests (Steps 4 and 5), elements of a preferred man-machine design are provided to systems engineering (Step 6) or are fed back to other steps of the design process.

Although the work discussed in this paper is being directed at nuclear power plant operations, the allocation-of-functions lessons learned, method, and criteria should be applicable to many design issues in space systems. In both cases, the key lesson to be learned is that man and machine should not be considered as competitors but as complementary components for achieving system performance.

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