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THE INTERACTION OF LIFE SCIENCES AND ENGINEERING TECHNOLOGIES
IN MAN/SYSTEM INTEGRATION

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ABSTRACT

Advancing technology has led to increasingly sophisticated systems, requiring cooperative interdisciplinary solutions to achieve optimal man/system integration. The life sciences and engineering have started to exchange ideas, techniques, and approaches to this common problem area. The difficulties encountered in such relationships are largely a matter of tradition and the absence of dialogue rather than any basic technical incompatibility. A basis for resolving these differences and the results of such endeavors are discussed.

INTRODUCTION

An outgrowth of the rapid technological advances of the past several decades has been the steady progression of man-machine systems toward greater levels of complexity. This forward thrust has imposed new requirements for a much higher degree of sophistication in effectively defining, measuring, and integrating the capabilities of both the man and the machine into an efficiently operating system. In striving for optimal compatibility between the animate and inanimate system components, new areas of cooperative effort between the life sciences and engineering have developed, more from necessity than by design. In some instances new technologies have emerged, with their specialized interests reflected in such names as bionics, bio-engineering, human factors, etc. In other cases, however, the parent disciplines, while retaining their individual identities, are finding themselves engaged in interdisciplinary efforts in which the solutions to certain problems are being approached through exchange and cross-fertilization of ideas, techniques, and approaches.

One of the difficulties which has impaired the full growth of these efforts has been a lack of adequate communication between life scientists and engineers. This can, in large part, be attributed to differences in the scientific maturity and technical languages of the respective disciplines. Engineering, as an application of the physical sciences, is deeply rooted in the traditional methods of these so-called "hard sciences". The life sciences or "soft sciences" on the other hand are relative scientific infants considered by some to be an artisan's montage rather than a group of true empirical sciences.

Both engineering and the life sciences, however, continually aspire to the advancement of the scientific method and to the development of empirical quantitative methods, and are committed to the investigation and understanding of physical phenomena, although sometimes at varying levels of observation and inference. As such, there is a genuine basis for the commonality of goals and the

establishment of a common language. The independent variables of mutual interest are the energies and forces of the natural environment, with their dimensions of frequency, intensity, duration, etc. Intervening variables are likewise common "vehicles" used to infer or explain processes, conditions, or states. It is the dependent variables which basically differentiate the respective areas of interest and cause different approaches and orientations to a particular problem. The engineer is concerned with the relatively static mechanical elements while the life sciences are interested in the responses of highly dynamic, living components. Hence, whether it be an engineer's concern for lighting in a system, a physiologist's examination of visual processes in the retina, or a psychologist's investigation of color perception, they are all concerned with the same physical energy source specified in terms of wavelength, intensity, purity, duration, and location. Thus, a rose may be red, or 675 millimicrons, or an on-off optic nerve firing, but by any other name it is still a rose. Only the operational definition of terms allows the commonality of the various approaches to become clearly evident.

A simple conceptual scheme, shown in Figure 1, presents the basic man-machine system elements and their interrelationships. Implicit in this concept is the fact that in an integrated man-machine system, all components are synergistic and therefore depend on the interplay, one with the other. It is only when the requirements and performance characteristics of each element are understood individually and at various levels of interaction can each discipline contribute in an optimal manner to overall systems integration.

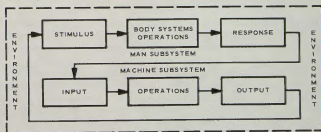


Figure 1. Man-Machine Concept

Although a significant trend has been established in the joining of forces between engineering and the life sciences, the ratio of verbage to accomplishment is still relatively high; a phenomena typical of an emerging scientific endeavor. The remaining portion of this paper will present several examples of this interdisciplinary approach to both reinforce the basic theme of this paper as well as

point out benefits that can be realized by sharing techniques and approaches toward a common problem solution.

HUMAN TRANSFER FUNCTIONS

In the area of man/system modeling, a working relationship has developed between the psychologist and the engineer as they have collaborated in attempts to develop reliable and valid human transfer functions. Each has made his own unique and distinctive contributions.

The union of these two disciplines has been one of necessity. The traditional stimulus-response approach of the psychologist is not well adapted to continuous type tasks often found in complex system operations. However, the engineering techniques for analyzing continuous time-series data from complex response functions have served to enhance the development of a quantitative expression of man's role in complex systems. The role of the psychologist in this relationship has primarily been to critique the specific models developed to insure that they are consistent with certain behavioral principles which have been established in laboratory studies.

In the study of human motor skills, for instance, the conceptual scheme of investigation has been the feedback theory of closed-loop servomechanisms. The input-output relations of servo theory are expressed in terms of physical parameters which are compatible with the stimulus-response concepts of the psychologist, hence establishing a commonality of concept and language. A servosystem analysis is concerned with the input-output relations as manifested in two domains: time and frequency. The time domain is described in terms of the time-varying characteristics of the responses, and in the frequency domain, the outputs (i.e., responses) are examined in terms of transformations of the input required to minimize error. Most of the mathematical structure of the servosystem analysis is based on the assumption of linearity which holds that the system obeys the super-position theorem, i.e., that the system's response to the sum of a set of inputs is equal to the sum of the responses made to each input separately.

This basic assumption, however, is not fully compatible with the psychological principle of intermittency which holds that human performance can be differentially affected in a non-linear fashion across time by such variables as motivation, learning, arousal, etc. Therefore, certain qualifiers and/or modifications are required to assure the transfer functions are consistent with known behavioral data. This is typically satisfied by the addition of a remnant term to the equation.

Evidence suggests that, through learning, the human operator modifies his transfer function and adjusts his responses to fit the control dynamics with which he is confronted, altering his transfer properties across time in the direction of optimizing performance in the man-machine system. What has evolved through the joint efforts of these two disciplines is an awareness that man appears to have many transfer functions.

An example of the results of these efforts can be seen in the traditional studies of motor skills acquisition in subjects engaged in tracking tasks. Typically, the psychologist has had to hand-score oscillographic records of the continuous time-varying response patterns, to determine the lead-lag index of tracking records, and to detect

shifts in these indices as response strategies change with increased practice. Hand-scoring of these records for indices of spatial and temporal accuracy has been both tedious and time-consuming. The engineer with the use of his analog computer equipment and analysis techniques offered promising alternatives to relieve some of the burden of scoring and data reduction in studying continuous response outputs. In such tracking studies, where the response records have been submitted to analysis by an analog correlator and analog frequency analyzer, they have yielded outputs from the correlator which can be converted to a lead-lag score with greater accuracy than the hand-scoring indices and with dramatic reductions in analysis time. Unexpected residual benefits, however, have been derived from the frequency analyses of the target inputs and the response outputs. The ratio of the response spectrum to the target spectrum has provided transfer function elements which depicted differential response patterns among subjects. A harmonic analysis of the responses has also indicated that the better performing subjects have greater energy output at the first several odd harmonics than do the poor trackers. This information, undetected in the hand-scoring procedure, enabled a differential expression to be added to the human transfer function which served to reduce the unknown remnant term, thus adding precision to our attempts to quantitatively describe the human performance by developing a valid transfer function.

MAN-AMPLIFIERS

Interest in the physical amplification and extension of man's skills has increased significantly over the past two decades. One of the trends that has emerged in this area is the design of anthropomorphic type man-amplifiers, e.g., remote manipulators, walking machines, etc., that respond to the natural task motion inputs of the human operator. The man-machine relationship in these systems is such that while the operator is performing a task, the machine is stimulated to amplify his motions and forces to the job at hand, while also providing the operator necessary information concerning both its position and the forces it is encountering. In essence, the operator's motions serve as a template for motions and actions of the machine's appendages or "end effectors".

Since the system must provide spatial correspondence between the operator's limbs and the machine end-effectors while not impeding the natural task motions of the operator, the engineer has turned to the life scientist for basic data, descriptive of the human controller, in such areas as biomechanics, biokinematics, and bioenergetics. In simple terms, the engineer must know the relevant performance characteristics of the man that the machine must respond to and functionally duplicate. Typical information required about man engaged in anticipated system operations includes such factors as joint mechanics and movement ranges; linear and angular velocities, accelerations, and torques about the joints; and work and power outputs for each of the major body segments, etc. The measurement techniques and anatomical information necessary to satisfy these requirements are readily accessible and need only be applied by the life scientist to the particular manual tasks to be handled by the system.

These data have many implications for the design engineer. In a hydraulic man-amplifier system, these data can provide guidelines for the design of actuators and servo valves as well as for calculation of pressures, flow

rates, areas and stroke distances that will accommodate peak and average power values. Velocity data, for instance, can provide a basis for determining flow rates, while torque values are used in the calculation of piston areas and hydraulic pressures. Also mechanical transmission systems (bell cranks, and so forth) can be designed to complement the variations in torque and velocity at various limb positions. For example, linkages designed for the inherent variability in torque and speed in normal human motions can be tailored to suit the corresponding variability in the machine joints for conditions of low torque and high speed or high torque and low speed. Finally, summation of the joint power curves provides a basis for establishing central power-pack requirements for total system motion. These power data further indicate the average power required to operate the system and can be used to determine the allowance that must be made for instantaneous peak-power outputs, all of which affords the designer the opportunity of keeping the size of the power plant to a minimum.

Through this effective integration of state-of-the-art techniques in the life sciences and engineering, significant technological gains have been realized in the area of man-amplifier systems as seen in such devices as the walking truck and other remote handling devices to extend man's capabilities to inner and outer space.

INFORMATION PROCESSING

A final area for consideration involves the application of the conceptual framework and language of communication theory to the quantification of higher mental processes. In dealing with the cognitive or higher mental processes of the human operator, one frequently is confronted with concepts, intervening variables, or hypothetical constructs whose physical dimensions or correlates in the physical world are not known. Information analysis is compatible with this limitation in that only a nominal scale of measurement is required. Thus, a quantitative difference between classes or even an ordering of elements is not required.

The basic tenet of information theory is that any event can be evaluated against the background of a whole class of event possibilities. Hence, in the area of human performance assessment in complex man-machine systems, one of the greatest advantages in applying information measures is that it represents a means of expressing a wide variety of tasks under a single quantitative index (i.e., bits or binary units). In such circumstances, it deals with the single behavioral process of response selection as a function of the total population of response alternatives and their relative probabilities of occurrence.

There is nothing implicit in the use of information measures which imposes a theoretical scheme on human behavior. However, through the years, there has accumulated a considerable body of empirical data from a variety of sources and psychological tasks which suggest certain behavioral characteristics in handling information flow. These data have led to certain inferences concerning human cognitive functioning (relating to information processing) which intervenes between the stimulus and the response. The most generally accepted notion is that man has a rather limited capacity for processing information. This view holds that he has only a single channel available at any one time through which information can flow to the higher processing centers, and that he must alternate

attention from one information source to another to process the various input modes. This upper limit (i.e., channel capacity) is usually found to be around two to three bits/second under normal circumstances; however, under unusual conditions involving highly skilled tasks, it may go as high as 40-50 bits/second.

Man does, however, have a considerable repertoire of behavioral strategies he can use to efficiently handle large amounts of information. If the tasks involve repetitions of the same information, he can, through learning and/or experience, recode either the stimuli or responses and, hence, facilitate the processing rate. He can also use selection processes to filter out redundant and/or irrelevant information or use a process of queuing to more evenly distribute the flow of information over time.

The methods and techniques of information theory have been successfully applied to the assessment of human performance in a number of complex man-machine systems through analysis of operational system measures. In a large system, where the role of the man covers a broad spectrum of functions ranging from simple monitoring and switching activities, through complex problem solving and decision making, to highly skilled psychomotor performance, there is a need for a single quantitative index to express the diverse domain of activities demanded of the human operator and to quantify his actual performance in the system. It is possible by means of function and task analysis and examination of the man-machine interfaces to identify selected system measures which serve as performance indices, for either real-time and/or post hoc analysis. For example, if a given task calls for a particular three-position toggle switch, located in a cluster of five similar switches on a panel, to be placed in a discrete position, in a specified time period, then that task can be quantified in terms of the number of bit of information involved in the response selection for successfully performing the task. These measures of information, when summed across an empirically derived time period can then be expressed in terms of an information processing rate.

As is evident, such a process involves the joint effort of system engineers and human factors personnel to untangle the confounding of man and machine performance factors from operational system measurements. With such cooperation and the analysis techniques of information theory, it has been possible to advance the state-of-the-art in operational performance assessment, and also to use the measures as an a priori indication of the demands on the human element in the design phase of a system.

CONCLUSION

A main key to success in each of the examples considered above has been the willingness of the various disciplines involved to translate the "special language" of their technology into communicable objectives and variables for investigation. Thus, as the cardiovascular specialist converses with the physicist, it becomes apparent that factors in blood flow, e.g., pressure, flow rate, viscous resistance, inertia, compliance, volume, etc., are typical parameters in fluid physics problems. And as the electrical engineer becomes involved, it is noted that the major variables involved in fluid dynamics can be related to the flow rate, its time derivative, and time integral and thus it is possible to establish an analogy between blood flow and electrical networks. Thus, all of the

techniques of electrical circuit analysis can be brought to bear on the problem of blood flow and, in fact, electrical networks can be constructed whose response simulates the behavior of the cardiovascular system. This simulation capability expands the knowledge of the cardiovascular specialist and significantly accelerates the time scale for its acquisition.

The results of these types of interactions, between the life sciences and engineering, offer one of the most promising and exciting areas for advancing our knowledge about man. This knowledge will likewise be reflected in the development of new machine capabilities, e.g., bionics devices, man-amplifiers, mechanical hearts, etc., to benefit man. Only a concerted effort on the part of the engineer and life scientist is required to achieve these goals — the basic need and knowledge exist today.