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A Human Engineering Approach To The Design of Man - Operated Continuous Control Systems.

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A BASIC PRINCIPLE OF CONTROL DESIGN

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FOREWORD

The cardinal purpose of this report is to discuss a principle of control system design based upon considerations of human engineering. This principle will be found to advocate design practices for man-machine systems similar to those customarily employed by engineers with fully automatic systems. Admittedly, the reasoning leading to the principle is largely speculative, but successes have been attained in following it which would seem to warrant a hopeful attitude toward its future usefulness.

Part 1 is intended to be fully self-contained and to carry the complete argument for the principle, as well as engineering suggestions as to its accomplishment. In this part, both engineering and psychological terminology are employed, but the message is phrased primarily for the engineer rather than for the psychologist.

Quite the contrary is true for Part 2 of the report. In this part, the design principle, which initially was stated in terms of a continuous mathematical model, is restated in terms of the essential discontinuities of stimulus-response psychology. Though this may hold no immediate interest for the engineer, it should serve to provide the psychologist with a better understanding of whatever efficacy the design principle may be shown to possess. Furthermore, since many psychologists tend to think and structure their research around stimulus-response concepts, Part 2 may provide an avenue by means of which the findings of psychological laboratories can contribute materially to control engineering.

It is too much to expect that the design principle set forth in this paper will long stand without elaboration or correction. The fact that it is possible to accommodate the principle within the structure of two different, and to some extent antinomic, models points to increased specificity as one direction in which modification would be desirable. Future research will, no doubt, make necessary other and perhaps more important changes. However, if in spite of its ultimate inadequacy, the approach described in this report directly furthers control engineering by a small amount and, indirectly, leads others to develop more sophisticated and fruitful principles, this effort will not have been wasted.

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ABSTRACT

Empirical evidence suggests that, at least for short periods of activity, the simpler the tasks imposed upon the human operator of a control system the more precise and less variable become his responses. This leads to the view that optimal man-machine control system performance can be obtained only when the mechanical components of the system are designed so that the human need act only as a simple amplifier. Ways and means are described for achieving such design through "unburdening" (relieving the operator of the task of acting as an integrator) and "quickening" (providing the operator with immediate knowledge of the effects of his own responses). Aided tracking and other efforts to improve the stability of man machine systems by modifying the display circuitry are shown to be examples of these two processes.

In Part 2, a "stimulus-response" analysis is made of the concepts of unburdening and quickening. It is argued that in those man-machine system arrangements which require that the operator behave as nothing more complicated than a simple amplifier, a condition of "stimulus response integrity" may be said to exist. Only under this condition do the responses which the man is called upon to make bear an invariant and proportional relationship to the instantaneous amplitude values of the visual error (stimuli). It is suggested that the choice of a pursuit or compensatory type display is contingent upon the extent to which stimulus-response integrity has been achieved in the system under consideration

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

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A HUMAN ENGINEERING APPROACH TO THE DESIGN OF MAN-OPERATED CONTINUOUS CONTROL SYSTEMS

PART 1

THE SUBSTITUTION OF MECHANICAL FUNCTIONS FOR ELEMENTS OF THE HUMAN OPERATOR'S TASK

THE MAN-MACHINE SYSTEM

In many control systems the human acts as the error detector. Men play such a role in piloting aircraft, in steering ships, in controlling submarines in heading and depth, in driving tanks and automobiles, and in tracking with gun and missile directors. During the last decade it has become evident that, in order to develop control systems with maximum precision and stability, human response characteristics have to be taken into account. Accordingly, the new discipline of engineering psychology was created to undertake the study of man from an engineering point of view.

One of the by-products of engineering psychology is the conceptualization of the human operator and the machine which he controls as the two parts of one over-all man-machine system Figure 1 shows a paradigm of this concept.

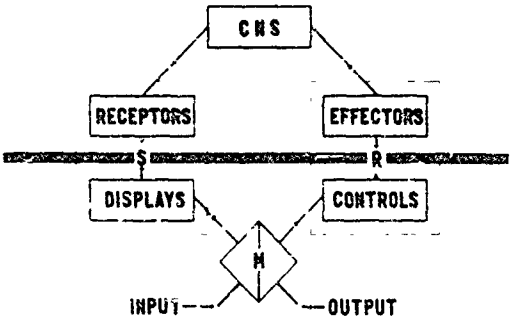

Figure 1 - The man-machine system

The man is schematized by the boxes shown above the heavy black line, while components of the machine are blocked in below. In the human, three sets of organs or functions are important to man-machine system operation, these are the receptors, the central nervous system (CNS), and the effectors.

The receptors consist of the sense organs of the body; for example, special cells in the retina of the eye, the organs of Corti in the ear, and the proprioceptors in the muscles, tendons, and joints. It is through the receptor organs that changes in energy in the external environment take effect upon the human organism. Such energy changes which excite receptor cells are called stimuli (S).

But not only is the organism acted upon by the environment—in turn the man modifies the external world through responses (R) of the effector organs. In the human, the effectors consist of muscles and glands, though only the former are directly involved in man-machine system function.

Between the receptors and effectors is shown the central nervous system, which consists of the brain and spinal cord. It is through the activity of this nervous system that thought, judgment, and decision-making arise and learning takes place.

Connecting the three uppermost boxes are lines which represent the peripheral nervous system, with the sensory nerves connecting the receptors to the central nervous system and with the effectors being supplied by the motor nerves. The upper portion of the diagram may be interpreted as indicating that stimulation from the outside leads to nerve impulses going to the central nervous system, where they are rerouted along the motor nerves to the muscles. The latter respond, moving the body or applying force to some object and thus altering in some degree the state of the external world.

The only part of man's environment represented in the diagram is the machine, which is shown in the lower half of the figure. It is through the controls, the levers, knobs, handwheels, and switches that human response takes its effect upon the mechanism. On the other hand, it is through the displays, the dials, light panels, cathode ray tubes, horns, buzzers, and cross-pointer indicators that the operator is presented with information concerning the activities of the mechanism, which is represented in the schema by the box labelled M. Within the box are the vacuum tubes, the amplifiers, the special circuits, the servo motors, the electronic or mechanical computers, and the power drives—in short, those parts of the system which are traditionally of greatest interest to the engineer.

At the very bottom of the paradigm are shown the input and the output of the system. The nature of these two quantities depends, of course, upon the particular man-machine system under consideration. In an automobile-driver system the input consists of successive positions along the twisting roadway, as visually apprehended, while the output is the progress of the car along the highway. In an antiaircraft system, the input is the spatial course of the enemy aircraft sensed through optics or radar. The output, in this case, consists of voltages which position the guns so that the bullets will pass close to the target.

If the complete man-machine system is assumed to be a gun pointing device, the informational flow is as follows: the position of the enemy aircraft is sensed, let us say, by radar. This information is processed at M and displayed to the operator. The display might be such as to present the target as a dot on a cathode ray tube, seen against a centered cross line. The operator, having been instructed to track the target, observes the misalignment and manipulates a control to move the target onto the reticle. The control motion, when transformed by M, (1) changes the system output (it repositions the guns), (2) if the human's response has been adequate, reduces the misalignment between the [illegible] However, since the input will continue to change, the [illegible] continually to make control adjustments if he is to keep the misalignment [illegible] This will have the effect of insuring that the output of the system [illegible]

remains more or less appropriate to the input, i.e., that the guns will shoot in the general direction of the target. In the case of airplanes, tanks, radars, sonars, and the like, different inputs and outputs are involved, but the diagram fits equally well.

In general, it is the task of the engineering psychologist to assist the engineer in designing the displays, controls, and intervening mechanism so that the output of the man-machine system is optimized, while the human operator requirements in regard to native ability and training are minimized. Specifically, this report will be confined to recommendations concerning the design of the circuits and equipments which define the task of the operator in a continuous control loop.

HUMAN CHARACTERISTICS RELEVANT TO CONTROL ENGINEERING

Vision—Man's Basic Input Channel

Though, theoretically, several of the human senses could be made to serve as information channels through which the man could detect changes in the state of a controlled quantity, only vision and hearing have been utilized to any extent as primary inputs in control engineering. Furthermore, of the two senses, only vision has been employed frequently. This is principally the result of the fact that only the sense of sight permits both the direct and accurate apprehension of geometrical space as it extends outward beyond the confines of the body. This spatial quality underlies three of the following four properties of the visual sense which are frequently exploited by control engineers:

Acuity - Though there are many different measures of visual acuity, those most relevant to continuous control and tracking tasks indicate that an operator with normal eyesight would have no difficulty in detecting a visual error of 0.3 mil real field (22). If the target is viewed through an optical telescope, a magnification of only six power is needed to increase the visual resolution to 0.05 mil real field. Although loss of light through the lenses will attenuate this figure somewhat, the acuity will still be very high for control devices.

Form Perception - The ability to perceive visually and react to spatial configurations is found only in higher living organisms. For certain tasks requiring landmark or target recognition, the selection and tracking of one of many targets, and/or the direct identification of friend or foe, there is no adequate substitute for the human eye.

Invulnerability to Confusion - As a result of the high acuity and the ability to discriminate form, the visual sense is immune to certain confusions which affect radar performance deleteriously. Whereas to the eye, an aircraft is recognizably different from a cloud or rainstorm, this is not always so with radar.

Invulnerability to Electronic Jamming - Though direct vision is limited to moderate ranges and to conditions of clear daytime visibility, it is immune to all forms of electronic jamming. This feature gains importance as electronic sophistication increases on the part of prospective foes.

Human Output

The Application of Force - All human responses which are directly necessary to the functioning of man-machine systems are brought about through the synergetic contraction and relaxation of muscles attached to the skeleton in such a fashion that force is applied to one or more controls. Though man is one of the weakest of the higher animals, he can apply several hundred pounds of force with leg and back muscles for short periods of time [illegible] to so. The strength of the arms is considerably less, but even [illegible]

this case more than 50 pounds of pull can be applied with the arms in bursts without fear of over-taxing the organism (23). Less is known about man's ability to graduate his force applications with precision than about the limits of his strength. However, evidence is available which shows that the absolute variability of an operator in reproducing pressures with aircraft-type controls increases as the pressures increase from one through 40 pounds, but that the relative variability decreases from one through 10 pounds and thereafter remains fairly constant (12). Inferences from early lifted-weight experiments suggest that below one pound the precision of force control deteriorates very rapidly (27).

The Action of Force on Different Controls - Analysis discloses that different controls, when acted upon by physical force, respond in ways which require different mathematical characterizations. Thus, if force is applied by whatever means to a spring-centered joystick, the angle through which the joystick is displaced is directly proportional to the magnitude of the applied force. This is true whether the restraining springs are relatively weak or so stiff that they permit practically no motion of the control, as is the case with a pressure joystick. With the latter, however, gain is markedly reduced from that which obtains when more motion is permitted.

In contrast to the action of a spring-centered control, a viscously damped joystick will respond to applied force by moving with an angular velocity proportional to the magnitude of the force. This means that, with this type of control, joystick displacement is proportional to the time integral of force.

Finally, if the damper is removed, inertia added, and force applied, the joystick will exhibit an angular acceleration which will be proportional to the magnitude of applied force With this control arrangement, joystick displacement becomes proportional to the second integral of force.

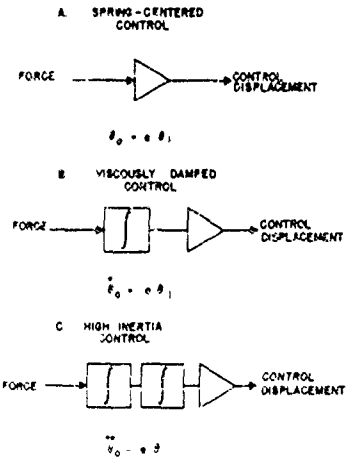

Fig. 2 - The action of force upon three types of manual controls

It is true, then, that zero, one, or two integrations can be accomplished by the physical interaction between force and the control, depending upon whether spring-centering, viscous damping, or inertia is the dominant characteristic of the control. Furthermore, the gain factors can be modified by adjusting (a) the sensitivity of the control pickoff and (o) the amount of spring-centering in the first case, damping in the second, and inertia in the third. In Fig. 2 are shown the block diagrams and equations for the responses to applied force of the three types of joystick.

In the equations, θ_0 is to be taken as the amplitude of joystick displacement while θ_1 represents the amplitude of the force input as functions of time. One dot over a term indicates the first derivative with respect to time, and two dots the second derivative of the term. The a represents a constant which may change in value from one equation to the next In Fig 2 the triangles represent amplifiers of adjustable gain, and the square boxes labelled $\int$ represent integrators.

Force as Man's Output - Introspective analysis suggests that the human regards his own basic output as limb displacement, at least for most situations. However, this cannot usefully be taken to be his output in the case where the control which he is manipulating is so tightly spring-restrained that it moves only a millimeter or two under maximal pressure. Under such circumstances it is convenient to take applied force as man's output. As a matter of fact, it seems reasonable to take applied force as the fundamental human output in all control systems, since, as Hick (1948) (8) and Hick and Bates (1950) (10) point out in their important papers, force must be applied to every control regardless of the particular transfer properties involved in any one situation. Accordingly, human output will be equated with force throughout this report. This is done without any necessary implication that force is more "real" than displacement or that this particular way of looking at human behavior will be especially productive if transferred from human engineering to theoretical psychology.

Kinesthetic Feedback - It should be pointed out that different control arrangements not only integrate force a varying number of times, but that they also affect qualitatively and quantitatively the information fed back from the kinesthetic receptors in the tissues of the active limb. When a pressure joystick is being employed, the kinesthetic feedback contains only information relating to force or pressure, since no displacement is permitted by the control. However, with a moving joystick, the feedback pattern contains information about the displacement of the limb and, perhaps, even about the rate of displacement as well as stretch or pressure specifications. This might lead one to conclude that control with a pressure stick would be less accurate than with a joystick which moved.

But quite the opposite conclusion has been reached by Gibbs (7) who finds pressure control to be superior to displacement control. In explanation of this, he adduces physiological evidence to show that the proprioceptive information available during pressure control is greater in amount, more rapidly conducted, and more directly related to applied tension than that arising from the manipulation of a displacement control. It would seem, however, that more evidence concerning these matters is still required before the issue of the absolute superiority of one type of control over another can be closed. This matter will be mentioned again later in this report.

Central Processes

Intermittency - Whenever the human is called upon to respond to some transient in his sensory environment, a period of time elapses before any response is initiated. This pause before the starting of a response is called the reaction time, and though it varies widely from moment to moment, it averages around 250 milliseconds if any "choice" is required.

There are several different sources of evidence (2, 4, 5, 9, 25) which suggest that, as a consequence of the reaction time delay and other factors, human response is intermittent rather than continuous. It would seem that if any type of servo motor could be taken as an analogue of human behavior, it would have to be an intermittently sampling servo, instead of a continuous follower. The available evidence points to a periodicity in man of about two responses per second, with a single response cycle taking 500 milliseconds or more and with this time fairly equally divided between the reaction time and the movement time. It appears that the organism utilizes the reaction time to "organize" the response which, once triggered, runs off to completion without direct voluntary control.

Bandpass - If the evidence on human response intermittency is accepted, it is possible to infer the highest input frequency which the man can successfully follow. Practical experience indicates that at least four samples per cycle are required to reproduce the waveform of the input with reasonable fidelity. If this is taken as a minimal figure, it follows that the human, responding on an average of twice per second, will be able to follow with some success frequencies no higher than 0.5 cycle per second. Of course, the lower the input

frequency, the more samples per cycle will be obtained, with the result that the fidelity of reproduction will increase as the input frequencies drop.

Translating cycles per second into radians per second, our inferences lead to the specification of the human bandpass as the region between zero and three radians per second

The Human Transfer Function - It would be convenient for engineers if it were possible to write an equation which would represent the transfer function of the human in a man-machine system. With this transfer function available, it would then be possible, at least theoretically, to design the remainder of the system to complement the man's characteristics in such a way as to achieve high system precision and stability. Accordingly, several studies have been run in the attempt to characterize human tracking performance in mathematical terms. Perhaps the best known of these were carried out by Phillips (11), Tustin (24), and Raggazini (17).

Two difficulties stand in the way of obtaining any single useful equation representing man's input-output relationships. The first relates to the difficulty of providing an adequate mathematical treatment for an intermittent system, such as the human appears to be. Though it is possible to deal with a discontinuously sampling system in terms of nonlinear mathematics, it is extremely awkward and tedious to do so (21). It is customary, therefore, to treat such intermittent systems in terms of the nearest linear approximation. This is done in the hope that, although the model chosen is recognized as being an imperfect analogy, it is still sufficiently appropriate to be useful. In fact, all expressions of the human transfer function to date have had the form of linear differential equations and, no doubt, this practice will continue. The final judgment as to the fruitfulness of thus approximating the intermittent by means of a continuous model must await the analysis of future experimental and pragmatic evidence.

But even more fundamental to the problem of writing an equation to express human input-output relationships is the fact that man appears to have many transfer functions. Evidence (18) suggests that, through learning, the human operator modifies his transfer function and alters his gains to suit the control task with which he is confronted. If the task requires an integration, he soon starts acting as an integrator, or if differentiation is called for, that also will be supplied. In short, the man alters his transfer properties in the direction of optimizing the performance of the man-machine system as it is communicated to him through the displays.

This adaptability on the part of the man is, of course, a great boon to the control designer, since he can rely upon the human to make the most of any control system, no matter how inadequate. It is this which probably constitutes the most important single reason for using men in control loops. Yet, this very adjustability renders any specific mathematical expression describing human behavior in one particular control loop quite invalid for another man-machine arrangement. This suggests strongly that "the human transfer function" is a scientific ignis fatuus which can lure the control system designer into a fruitless and interminable quest.

It would be better to recognize man's propensity for adaptation and to consider whether the human operator is equally precise when he adopts one transfer function as when he assumes different transmission properties. If it should turn out that this is not the case, it would then seem desirable to design the nonhuman elements of the control system so as to use the man in the role in which he is most competent.

Unfortunately, no direct scientific evidence is available to furnish guidance in this matter However, empirical observations suggest that there are wide variations in man's ability to satisfy different equations and that, speaking mathematically, he is best when

doing least. It becomes, therefore, a fundamental assumption of this paper that the more complex the human task, the less precise and the more variable becomes the man.[1] It is assumed that, within limits, the higher the number of integrations and/or differentiations required of the man the poorer will he perform. Conversely, it is hypothesized that the more the human operator is freed from the tasks of integration and differentiation the more regular and precise will become the human output. Human control behavior, it is asserted, reaches the optimum when the man becomes the analogue of a simple amplifier as shown in the following equation:

$$\theta_o (t + \tau) = \theta_i (t) \qquad (1)$$

where t represents a value in time, and τ equals the human reaction time.

A BASIC PRINCIPLE OF CONTROL DESIGN

In contrast to the poor performance of complex tasks hypothesized for the human operator is the fact that machines can be built to perform intricate computations with remarkably high precision and low variability. It is true that stability and accuracy are not obtained without effort, but for such tasks as double or triple integration and/or differentiation it seems unquestionable that electronic or mechanical components can be made to be more precise and repeatable than man.

If this is the case, and if precision is required, it follows that when a man-machine system must integrate, differentiate, or perform other higher-order computations, these should be supplied by the nonhuman components of the system whenever possible. This is tantamount to saying that the human should be required to do no more than operate as a simple amplifier. Broadening this somewhat, adding to it a statement as to human bandwidth, and phrasing it as a general design principle, the following emerges: Design the man-machine system so that (1) the bandpass required of the man never exceeds three radians per second and (2) the transfer function required of the man is, mathematically, always as simple as possible, and, wherever practicable, no more complex than that of a simple amplifier.

The remainder of this paper will consist of illustrations of ways of utilizing this principle, together with explanations of its efficacy in human engineering terms. However, two matters require general comment at this early point in the discussion. First of all, it is essential to describe a basic condition which must be observed if the ultimate intent of the design principle is to be achieved. Second, it is necessary to answer the obvious question of why, after designing the system so that only amplification is required of the man, one should not take the final step of dispensing with him entirely by substituting an actual amplifier in his place.

As to the first, in order to obtain optimum performance from the control system, it is necessary, not only to design the system so that amplification is all that is required of the operator, but it is also necessary to insure that the operator adopts this, and no other, mode of response. It appears that when placed in a control loop, the human goes through a trial-and-error process wherein he varies his transfer function until he achieves a condition of minimum average error as it is reflected to him via the display. It follows from this that to insure the adoption by the operator of a mode of action equivalent to simple

[1] This assumption and all others to be stated in Part 1 of this report are made in relation to tracking and control systems employing "compensatory" type displays since these are used preponderantly in practical man-machine systems. It is anticipated that some of these assumptions will require elaboration when they are applied to systems such as may be constructed for laboratory use where a pursuit (match the pointer) display can be [illegible]. This matter will be discussed briefly in Part [illegible].

amplification, it is necessary to so design the nonhuman components that the operator will achieve minimum error at the display when he acts as an amplifier. If, through inadvertence, the design of the control loop permits the operator to reduce the displayed error more by acting as an integrator, differentiator, or a combination of one or more of these than as an amplifier, then, most certainly, he will do so.

In regard to the question of why the design principle does not lead logically to employing an amplifier to supercede the man, one can only say that it does lead to precisely that—whenever it is feasible. Under some circumstances the best man-machine system design will demand the removal of the human from the system. But in many other circumstances it would be impractical to automatize completely.

For example, in cases where the operator tracks targets optically, his removal would require the substitution of radar, infrared, or some other electronic sensing mechanism. In other situations, even though it might be quite possible to remove the man from the control loop, it would be deemed inadvisable to do so for safety reasons. It can be argued that whenever a man must be present as a monitor he should be used as a controller so as to make unnecessary the extra cost, added weight, and increased maintenance load which complete automatization would entail.

Finally, in many situations, it is not feasible to simplify the operator's task to the point of requiring of him only simple amplification. In some systems the man is used precisely because he can do more in a tracking loop than amplify. In these circumstances it would be self-defeating to attempt to carry the simplification process too far. This would be true, for example, in the case of handlebar tracking systems which utilize the man, not only as an error detector and analogue computer, but as the power drives as well. In such cases, complete redesign of the system would be required if one sought to supplant the human element entirely. In these cases, one must be satisfied with the more modest, yet still very appreciable, improvements to be brought about through task simplifications which stop short of the ultimate.

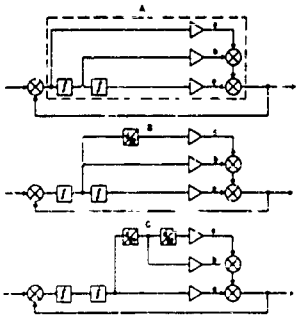

Figure 3 - Three equivalent follow up systems

APPLICATION OF THE PRINCIPLE TO THE DESIGN OF MANUAL TRACKING SYSTEMS

The simplest, practical tracking system known which can be made to follow with precision a constant velocity input is represented in Fig. 3A.[2] In this figure the circles containing crosses represent mechanical or electrical differentials which add algebraically. The system is shown to consist of two cascaded integrators with feed-forward loops around both. Path c represents the position component; path b, the velocity component; and path a, the acceleration component.

[2] Actually, the position pathway is not required for stability if there is no time lag in the system. It can be shown practically, however, that the position component is required for stability if there is a time delay in the system of the order of the human reaction time. Since the arguments which will be made requires the transfer properties of the tracking system to be sufficiently general to permit the human to be a part of the tracking loop, the position component must be included. All statements concerning stability are to be read with this factor in mind.

The transfer properties of the part of the system enclosed within the broken line are expressed in the following equation:

$$\ddot{\theta}_o = a\,\theta_i + b\,\dot{\theta}_i + c\,\ddot{\theta}_i \qquad (2)$$

This is the "open loop" equation for the system.

Figures 3B and 3C represent alternative ways of achieving the same input-output relationships obtaining in 3A. In both of these figures the process of differentiation is symbolized by a square box containing the ratio d/dt. In Fig. 3B, the output of the first integrator is the rate component, while position is obtained by differentiating this rate. In Fig. 3C, a double differentiation of the double integration provides the component of position, while rate is obtained by differentiating only once the output of the two cascaded integrators. Other ways of structuring the block diagram will be apparent, but these will suffice for the purposes of this paper.

To achieve stability with any one of the three equivalent devices shown in Fig. 3, care must be exercised in properly adjusting the gains of the three pathways. A slight error in setting, if it were in the right direction would cause the tracking device to become prone to oscillation, and the total removal of the position and velocity pathways would result in pronounced instability.

On the other hand, the removal of the integrators would result in a lag error. If only one integrator was removed, a constant lag error would result, which would be proportional in amplitude to the input velocity. If both integrators were removed, the tracking device would exhibit a lag error which would change in amplitude at a constant rate proportional to input velocity. Obviously, none of these conditions is tolerable in a tracking device.

The transfer properties of the tracking system described above are general, in the sense that they do not specify the precise nature of the mechanisms accomplishing the various functions. Thus, the integrations and feed-forwards required may be performed mechanically, electronically, or even through human behavior. Furthermore, there is nothing to prevent certain of the functions being carried out (say) mechanically while the remainder are supplied by the behavior of the man.

Such a situation is diagrammed in Fig. 4. The block diagram represents the human operator as responding to displayed error through the movement of a damped joystick. The figure shows the complete system as consisting of three basic parts—the man, the control, and the mechanism. In the diagram, the damped joystick control is shown as acting as a single integrator in accordance with the earlier discussion. The box in the diagram labeled MECHANISM is represented as performing no function other than amplification.

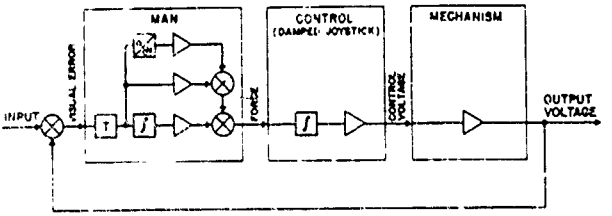

Figure 4 Tracking system with a damped joystick control and no aiding

If it is assumed that the input-output relationship of the man-operated system is a close statistical approximation of that represented in Fig. 3, and if the control element and mechanism element together provide only the function of one integration, it follows that the functions of the second integration and the two feed-forward loops must be supplied by the man. Consequently, in Fig. 4 the man is shown as acting analogously to a differentiator, an amplifier, an integrator, and two algebraic adders, all in combination. The square box labeled T is included in the figure as a representation of the human reaction time.

From what has gone before, it would be predicted that the precision of the tracking system would be enhanced if the operator were relieved of the necessity of acting in such a complex fashion. Furthermore, it has been hypothesized that the tracking would be improved most if the man were required to act only as a simple amplifier.

One might accomplish this, leaving the control unchanged, by introducing circuitry into the mechanism which would carry out the required integrations, differentiations, and feed-forwards. If this were done, it would be expected that the operator would adjust rapidly to the changed requirements by simplifying his mode of action to a level analogous to simple amplification. All this is tantamount to interchanging the functions of the man and the mechanism as represented in the diagram. In Fig. 5 this interchange has been accomplished.

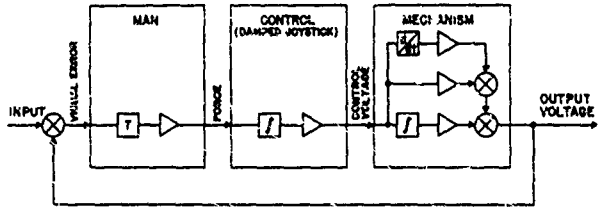

Figure 5 - Tracking system with a damped joystick control and perfect aiding

Aided Tracking

Aiding with Different Types of Controls - Though no direct test of this system design is known ever to have been made, it is interesting to note that an arrangement otherwise identical to that shown in Fig. 5, with the exception that the derivative term is not included, has been used for many years in gun fire control devices under the name of "rate aiding." Much experimental and pragmatic evidence exists to indicate that aiding of this type improves tracking considerably. Tests will be run in the future to check the additional improvement predicted to occur when the derivative term is added to the aiding circuitry.

At least in theory, it is quite possible to restructure the tracking system for the use of controls other than a damped joystick and still permit the human operator to perform as a simple amplifier. However, to do this, it is necessary to alter the circuitry within the mechanism each time the control is changed in such a fashion as to hold constant the overall transfer function of both elements acting in combination. Thus, in Fig. 6 may be seen the block diagram of the tracking system arranged for an undamped, high inertia joystick, while Fig. 7 displays the system designed with a pressure joystick as the operator's control.

It is shown in Fig. 6 that the two integrations are supplied by the action of force on the high inertia control, whereas the mechanism is represented as supplying stabilization

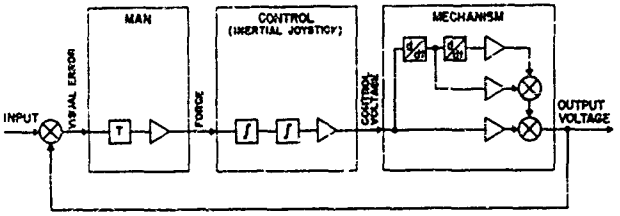

Figure 6 - Tracking system with an inertial joystick and perfect aiding

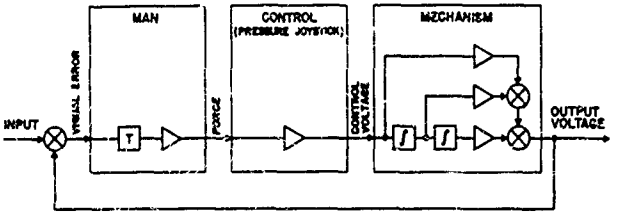

Figure 7 - Tracking system with a pressure joystick and perfect aiding

through two feed-forward loops supplying position and velocity components to the final output. "Perfect" aiding in this case is obtained through cascading properly two differentiating circuits and a simple amplifier.

Quite different from this is the case in Fig. 7 wherein the tracking control in a pressure joystick. With such a system, the action of force upon the control introduces no integrations, with the result that integrators must be inserted, along with feed-forward loops, within the mechanism. Thus, it should be clear that the circuit requirements for "perfect" aiding vary with the nature of the manual control in use, and that discussions of aided tracking become fully meaningful only when the nature of the control is specified.

Although, reasoning mathematically, there is nothing to permit a choice among the systems shown in Figs. 5, 6, and 7, since they are all equivalent, it is to be expected that some differences will emerge under test. Such differences might be expected to arise from the different kinesthetic patterns set up by the application of force to the three different controls, though at present it is not possible to guess which arrangement would be superior. The reasoning underlying the basic principle enunciated earlier in this report, would lead only to the assertion that all three of the systems would be more precise than any other arrangements which required more of the man than simple amplification.

The Aiding Required to Track Maneuvering Targets - Up to now, the discussion has involved manually operated tracking systems designed to follow constant velocity courses. One is naturally led to wonder what recommendations can be made concerning the design control systems intended to be used against targets maneuvering realistically. Such target courses contain important amounts of acceleration and rate of change of

ratio of 1 to 2 to 8 proved to be slightly superior to the predicted optimum. This single discrepancy is not at all surprising in view of the multiplicity of factors involved in determining optimum time constants of this variety.

Even though an interplay of many processes determines optimum aiding ratios, it is possible to give a very general statement of what is accomplished when the sensitivity values of the various components are proportioned correctly. It appears that the proper aiding constants for any manually operated control system are such that the correction of the position error simultaneously reduces to zero any concommitant errors in rate, acceleration, or the higher derivatives. When such a condition prevails, continuously sustained actions are made unnecessary and the man can track accurately by acting as a simple amplifier.

It is true, of course, that since human reaction time varies from person to person and from moment to moment, the best aiding ratios are correct only on the average. This means that the operator will be free to act as an amplifier only in a statistical or average sense. To the extent that the man samples irregularly rather than periodically, it will be necessary for him to add to his basic process of amplification—at one time, integration, at another, differentiation. However, it is assumed that on the average, the transfer function of the adept tracker will approximate that of a simple amplifier if the sensitivities of the various feed-forward loops are adjusted properly.

The Relative Difficulty of Mental Integration and Differentiation

Up to now, no mention has been made of the relative difficulties to the human operator of performing the psychological processes which are analogues of integration, differentiation, feed-forward, and algebraic addition. It has only been asserted that all of these mental functions are difficult, and that steps should be taken to relieve the operator of the need for performing as many of them as possible. It would be highly desirable if, in addition to the basic design principle, it were possible to present quantitative information about the increase in variability and reduction in precision expected to occur as the man takes on additional analogue integrations or differentiations. If such information were available, the control engineer would have a basis for determining the amount of improvement which could be expected from altering the design in a certain fashion. Furthermore, if circumstances prevented him from attaining the ultimate simplification of the operator's task, he would be able to choose the best possible compromise.

Unfortunately, only the most indirect evidence exists as to the man's relative and absolute ability to perform different analogue mathematical processes. One example of the kind of evidence that is available concerns the relative precision of the human when performing mental tasks analogous to integration and differentiation. The evidence is provided by two similar tracking studies, one done in England by Gibbs and Clutton-Baker (6), and one by Birmingham at the Naval Research Laboratory (3). In both of these experiments, tracking accuracy with a pressure joystick was compared to that obtained with a damped joystick. The two studies agreed in finding that the pressure stick was superior to the damped control.

The most important difference between the two experiments involved the circuitry interposed between the control and the display. In Gibbs study a single integrator was employed in the mechanism to provide "rate" tracking with both the pressure stick and the displacement control. In the NRL study, both joysticks were utilized with "acceleration aiding" circuitry. In Fig. 6 the two tracking systems tested at NRL are shown in block diagrams.

acceleration and perhaps even higher terms. Certainly, the tracking systems outlined above would have to be modified to handle adequately such inputs. However, it is believed that the reasoning remains the same regardless of the nature of the input. In order to make the system, previously discussed, adequate for tracking courses containing higher derivatives, it is thought necessary to modify them only to the extent of inserting additional integrators with feed-forward loops around them and properly adjusting the gains.

Though no rule is available to indicate precisely how many integrators, with associated feed-forward loops, should be employed for courses of different characteristics, it is thought that little or no improvement would result from the addition of more than four or five. Searle (19) found a definite improvement in system performance when two integrations rather than one were incorporated in an aided tracking circuit. Since he employed a damped joystick, the total number of integrations taking place between the hand and the system output were three in the case of the best arrangement, and two for the other. Unfortunately, neither he nor anyone else has reported systematic tests of aiding arrangements incorporating more than three integrations.

The control designer's task of choosing the proper number of integrations, with associated feed-forward loops, is made less critical by the fact that if more integrations are provided than are needed at any moment, the superfluous integrations do no harm as long as stability and transient problems have been handled adequately. The unnecessary integrating devices merely fail to contribute significantly to the output under these circumstances and, thus, at worst, only a waste of circuitry is involved. Because of this, it would seem prudent to build aided tracking systems which are intended to handle a variety of inputs with a sufficient number of integrating circuits to provide for the more complex target courses expected. By this means, maximum tracking precision will be assured at all times regardless of the complexity of the tracking task.

Aiding Ratios - It has been pointed out that the purpose of aided tracking is to remove from the operator the burden of integration, differentiation, feed-forward, and analogue addition and multiplication, and to permit him to operate as a simple amplifier. To approach this ideal as closely as possible, it is necessary, not only to insert the proper components into the mechanism, but also to adjust the various gains correctly.

It is known that the optimum relationship between the gains of the various feed-forward loops varies with the time delays in the system and with the number of components being combined. Because of this, tests of the optimum "time constant" (position sensitivity divided by rate sensitivity) give values which vary from 0.25 to 5.0 seconds (17). It appears, however, that for continuous tracking tasks where the loop is tight and where the display is such as to permit fine resolution, the optimum time constant lies between 0.3 and 0.5 second.

As to time constants for discontinuous tracking tasks, Mechler, Russell, and Preston (14) developed an equation for the optimum aiding ratio to be used with PPI presentations where the target appears intermittently. They concluded that the optimum time constant in such use always equalled the number of seconds between "paints" on the radar screen. They also pointed out that their result was consistent with a time constant of about one half second for continuous tracking if the man is assumed to respond intermittently at intervals of 0.5 second.

Searle (19), assuming that the addition of an acceleration component to position and rate would improve system performance for continuous tracking tasks, undertook a series of tests of aided tracking. Accepting the assumption of intermittent sampling by the operator at a frequency of two per second, and carrying over the reasoning of Mechler, Russell, and Preston to include acceleration, Searle predicted that the optimum ratios of component sensitivities would be 1 to 4 to 8 for position, rate, and acceleration, respectively. This prediction was confirmed in two of three experiments which he ran. In a third test an aiding

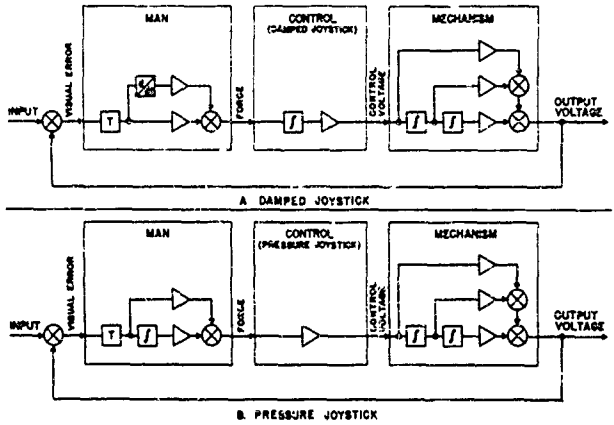

Figure 8 - Flow charts showing the different human tasks posed by a damped joystick and a pressure control

In these diagrams, it is assumed that three integrations with associated feed-forward loops are required in order for the whole system to function adequately. This is not a critical assumtpion, however, for the argument to be presented is the same no matter how many integrators, beyond two, are needed. It is apparent from Fig. 8 that the man is required to act as a simple amplifier and a differentiator when tracking with the damped joystick, whereas he must act analogously to an integrator plus a simple amplifier when using the pressure joystick. Thus, with either system, the operator is called on to perform two mental tasks, with one of them—amplification—being common to the two situations, and with the second task being differentiation in one case and integration in the other.

In the British study, the human operator was required to act in a more complex fashion with both the pressure joystick and the damped control. However, in this experiment like that of NRL, the only difference in the operator's mental activity in the two tracking systems was that when tracking with the pressure stick, in addition to other mental tasks, he was required to act like an integrator, whereas with the damped joystick system, the task of differentiation was substituted for that of integration.

Since both studies agreed in showing that the system was more precise with the pressure control than with the damped joystick, it may follow that the human is able to carry out analogue integration better than analogue differentiation. However, since the two tasks compared in the studies differed, not only in regard to the analogue computation required, but also, as Gibbs (7) points out, in respect to the nature of the kinesthetic feedback patterns evoked in applying force to the joysticks, any conclusion from the results must be regarded as highly tentative. Only when a comparison of the human's proficiency in integrating and differentiating is run in an uncontaminated test, can a conclusion be reached which is better than an informed guess.

APPLICATION OF THE PRINCIPLE TO THE DESIGN OF SPECIAL CONTROL SYSTEM DISPLAYS

Unburdening and Quickening

An analysis of the manner in which aiding enhances system performance uncovers two processes which act simultaneously but in quite different ways to simplify the human operator's task and to better system operation. One of these has the effect of relieving the man of the necessity of applying force continuously or in some time-sequenced pattern. In the systems discussed, relief has been provided by inserting integrators in the mechanical portions of the system. This process of easing the human's task by reducing the required effort may be termed "unburdening," since it has this effect on the man. Because in some practical instances, unburdening is accomplished by regenerative computers considerably more complex than simple integrators, the term appears to be generic and to apply in many situations not hitherto discussed.

A second process, of equal importance, may also be distinguished as contributing to the enhancement of system performance brought about through aiding. This process may be termed "quickening," since one of its effects is to provide the operator with immediate knowledge of the results of his own actions. In aiding, quickening is accomplished by feed-forward loops which add position, rate, and other necessary higher components to the output of the integrators which are performing the unburdening operation. Since the system output is continuously fed back and displayed to the operator, he is made instantaneously aware of the early effects of his own actions if quickening is adequate.

In the tracking systems discussed up to now the two processes complement one another, with unburdening making it unnecessary for the operator to supply integrations, and with quickening relieving the human of the necessity of differentiating. Both processes meliorate system precision, the former by reducing human effort and removing lag errors, the latter by providing stability.

In all of the systems met with so far, unburdening and quickening have a direct effect on the system output as well as a secondary, indirect effect resulting from the operator's responses to these changes. Though it would seem that the very nature of unburdening was such that it could not be achieved without direct modification of the output, this is not true of quickening. In certain circumstances the latter can be accomplished through altering the nature of the information fed back and displayed to the man, without changing in any direct fashion the output of the system. This fact is extremely important since it means that the benefits of quickening can be achieved even in those systems where, for one reason or another, the output is inaccessible to direct manipulation. Thus, in such man-machine control systems as those of ships and airplanes, where the outputs are determined in large part by immutable hydrodynamic or aerodynamic force relationships, enhanced stability and precision are still attainable through the quickening of the information displayed to the human operator. This corresponds closely to the use of certain types of equalization networks to stabilize fully automatic systems in similar situations.

A Quickened Display

An example of a case requiring display quickening is provided by a control system block diagrammed in Fig. 9. This device is intended to operate on a course input which consists only of step function position changes, so spaced that the full correction of any one step may be achieved before the next requires action. The time constants of the four integrators are long, and this, coupled with the fact that the integrators shift the phase of the input through 360 degrees, causes the system to be quite unstable.

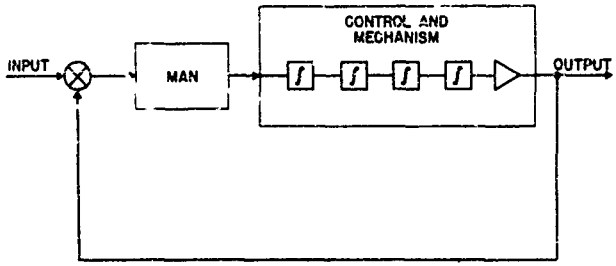

Figure 9 - A control system requiring quickening

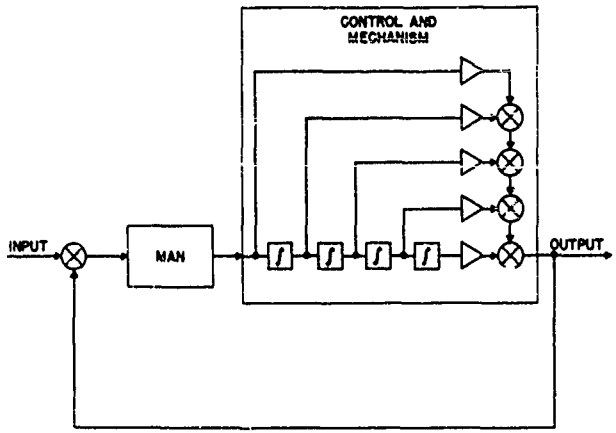

Figure 10 - The control system with quickening taking effect on output

The quickening of this device presents an intriguing problem since the obvious solution diagrammed in Fig. 10 is ruled out by circumstances which prevent making changes which affect directly the output of the control system. The problem may be solved, however, by picking off the components of position, rate, acceleration, and the first derivative of acceleration, amplifying them properly and adding them algebraically in the feedback loop going to the display (Fig. 10). The display may take the form of a double-pointer dial, with one pointer corresponding to ordered input and with the other being controlled by the quickened feedback. With this arrangement, the man has only to operate his control so that the follow-up pointer matches the input pointer at all times. Tests run with such a device have indicated that instability may be completely eliminated by this means of quickening.

Two other examples of quickened displays similar to this are provided in aircraft instrument developments. The first, and probably the best known, example of display quickening is furnished by an instrument known as "The Sperry Zero Reader" (13, 15).

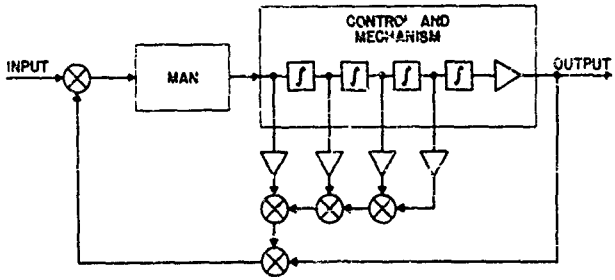

Figure 11 - The control system with quickening taking effect on display

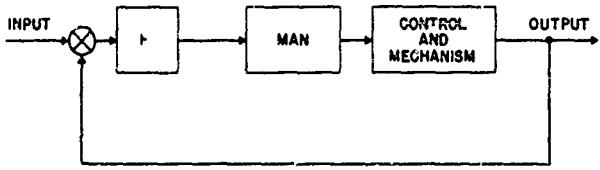

Figure 12 - A control system with filter in loop

The other example is the "Instrument Approach System Steering Computer" described by Anderson and Fritze (1) Both of these developments incorporate circuits which effect a partial tightening of the loop around the pilot by giving him more immediate knowledge of the results of his responses.

Quickening a Filtered Display

The insertion of a filter into a control loop often results in system instability A tracking system degraded in this fashion is pictured in Fig. 12. In this diagram, the filter is shown as taking effect on error, which in this case, is the algebraic sum of the input and the output. Tests of such a tracking system show that, with moderate or long time constants of the filter, the output tends to oscillate. This is the result of the fact that the operator perpetually over- and undershoots in his corrections, since the filter distorts and delays information about the effects of his own behavior. Quickening is required to overcome this lag between what the man does and what he sees himself do.

To explain the means whereby this quickening can be accomplished, it is first necessary to redraw the block diagram to show a system mathematically equivalent to that diagrammed in Fig. 12. In the restructured diagram. Fig. 13, the single filter has been removed and two filters, identical with the original, have been substituted. With one of these acting directly upon the input and with the other filtering the fed back output, the transfer characteristics of the restructured system are identical with those of the original, shown in Fig 12 The only difference between the two arrangements is that filtering of the input and fed back output occurs after they are added together, in the one case, and before addition, in the other

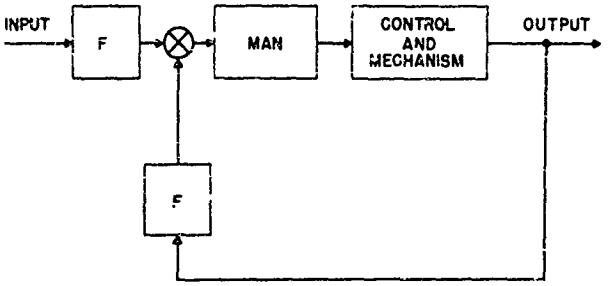

Figure 13 - Filtering equivalent to that shown in Figure 12

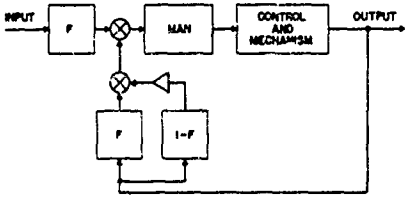

Figure 14 - The introduction of a complementary filter in the feedback loop

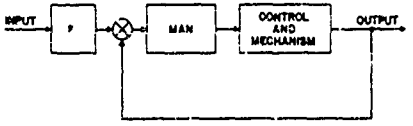

Figure 15 - The effect of the filtering shown in Figure 14

To quicken the system as it is represented in Fig. 13 it is necessary to nullify the effect of the filter in the feedback loop. This can be done by inserting a complementary filter in a loop around the original filter as in Fig. 14. If this complementary filter has the characteristic symbolized as 1-F, where F is the characteristic of each of the original filters, the effect will be to remove all filtering from the fed back output. The system may now be pictured as having the functions shown in Fig. 15. The quickening is perfect, and the operator is given immediate knowledge of the results of his actions.

However, though the quickening has improved the response characteristics of the system as far as the human's tracking is concerned, in this instance it has also introduced a sizeable dynamic error into the man-machine system output. This can be seen by referring to Fig. 16, and comparing the system input with the system output. The sinusoids appearing at various places in this figure symbolize the response of the system at these points to the input frequencies. The high frequency "noise" superimposed on the basic low frequency component in c and d is generated by the human attempting to maintain zero error.[3]

The system output (c) differs from the system input (a) in amplitude and phase because the fed back system output (d) does not match the input, but rather the input after filtering (b). To overcome this attenuation and phase shift and, at the same time, to permit quickening, it is somehow necessary to cause the low frequencies to be filtered in the feedback as well as in the input and, yet, to let the operator's high frequency correction motions come through unfiltered. This can be done by adding to the 1-F circuit of Fig. 14 an appropriate high-pass, "antibias" filter as shown in Fig. 17. When this is done, the tracker's high frequency corrective responses pass through the filter combination in the feedback loop and are displayed essentially unmodified. However, the low target course frequencies are prevented by the antibias filter from passing through the 1-F circuit, though they do pass through F, and are thereby attenuated and delayed by an amount equal to that achieved by F acting on the input. This is to say that with respect to the low target frequencies, the system shown in Fig. 17 is similar to the systems represented in Figs. 12 and 13, in that no bias develops. On the other hand, with respect to the human's high tracking frequencies, the system of Fig. 17 is similar to that shown in Figs. 14 and 15, in that the operator receives immediate indication of his corrections.

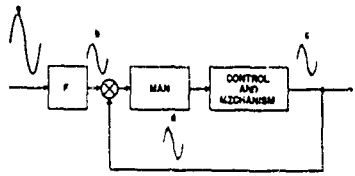

Figure 16 - Output bias resulting from complementary filtering

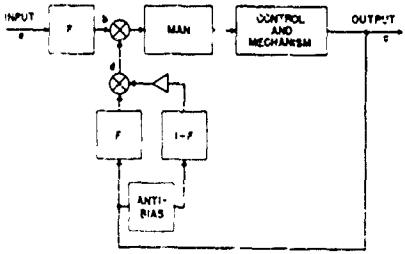

Figure 17 - An antibias network combined with a complementary filter

[3]For reasons of simplicity and clarity the sinusoids representing system response are pictured as differing only in amplitude. In actuality the phase shifts which are correlated with attenuation are of paramount importance in the development of the bias

In this way, by combining complementary and antibias filters, quickening is achieved and stability is obtained without introducing a degrading bias. The conjoint use of these two types of filter is sometimes termed "treatment." Figure 18 is operationally equivalent to Fig. 17 and shows the treatment circuits applied to the system as it was originally diagrammed in Fig. 12.

A simulator was set up at NRL to act as an analogue of this system. Human operators tracked a sinusoidal course with the device and the system output was recorded. Three conditions were compared. In one-third of the trials the operators tracked with no filters and no treatment circuits in the system (Condition 1). Another third of the trials were run with the filter in, but with no treatment (Condition 2). This condition is represented in Fig. 12. The remainder of the trials were run with the filter in and with treatment also incorporated in the system (Condition 3). The results of this experiment are shown in Fig. 19. It is clear that the quickening produced by treatment was efficacious in reducing the tracking error almost to the level obtaining in Condition 1. Thus, the degrading effects of the original filter are almost completely removed by the treatment networks.

An analysis of the control system described earlier and diagrammed in Figs. 9, 10, and 11 indicates that had the input to the system been anything other than a series of step function position changes, an antibias network would have been required when the quickening was performed as in Fig. 11. In fact, it is probably true that most efforts to quicken a display without affecting the system output directly will result in a system bias unless some form of antibias network is included in the quickening circuitry. At present, the design of these antibias circuits is a relatively undeveloped, but highly promising field.

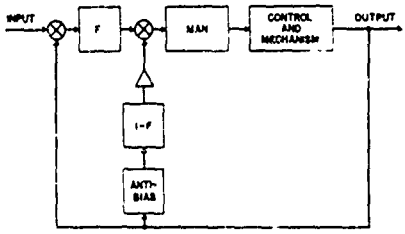

Figure 18 - An antibias network combined with a complementary filter as actually applied

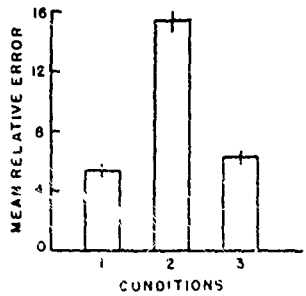

Figure 19 - The effect of filtering and treatment upon tracking error

PART 2

A STIMULUS-RESPONSE ANALYSIS OF THE SIMPLIFICATION PRINCIPLE

STIMULUS-RESPONSE INTEGRITY

In the first part of this report, a human engineering principle of control design was stated and explained. The principle asserted that man-machine continuous control systems should be designed so that the task of the operator is as simple, mathematically, as possible, and whenever feasible, no more complex than that of analogue amplification. This principle follows from the assumption that the simpler the mathematical characterization of his task, the more precise and the less variable becomes the operator.

It is recognized that there is very little experimental evidence yet available to support this assumption and, certainly, it cannot be held that the supposition is self-obvious on logical grounds. Yet, it is believed that the assumption rests on a basis more solid than pure speculation. It is the major purpose of the second part of this report to attempt to show that the design principle itself and the conjectures upon which it is based are entirely in accord with the relevant facts of psychology. Toward this end, a start may be made by discussing the process of amplification and describing the stimulus-response relationships that prevail when the design principle has been followed to the end.

With a simple, linear amplifier the amplitude of the output is directly proportional to the amplitude of the input. More or less the same relationship will hold for a human acting analogously to an amplifier in a control system. If it is assumed that force is the human output and that the direction and amplitude of the visual error is the input, then, were the man to act as a simple amplifier, he would hold force at all times proportional to the magnitude of the visual misalignment.

That he cannot do this, however, in any strict sense is attested to by considerable evidence, cited earlier, indicating that the human is an intermittent rather than a continuous responder. As has been suggested before, it seems reasonable to suppose that the operator of a system responds to the visual error now and then rather than all the time, and further, that once a response is under way, it runs its course unguided by visual events.

But this, in no way, invalidates the design principle nor alters the general proportionality between the amplitude of the visual error input and the man's force output, when he performs as an amplifier. The intermittency sets a limit to the operator's bandwidth and reduces the proportionality of his input-output relationships from strict to approximate Except for this, however, human intermittency requires no modification in the basic thesis of this report.

The translation of the process of amplification into stimulus-response terms begins by identifying the direction and amplitude of the visual error as the primary stimulus for analogue amplification and the force output of the man as the response With stimulus and response thus denoted, it may further be pointed out that in those situations where the man is free to act as an amplifier, an invariant and proportional relationship will be found to exist between the primary stimulus and the required response This is to say that the information contained in the instantaneous amplitude value of the stimulus is sufficient to specify completely the response which will reduce that value to zero.

At first glance, this condition, which will be referred to from now on as "stimulus-response integrity," appears to be entirely commonplace and hardly worthy of note, not to mention name Yet, the occurrence of the state is far more rare than one might suppose. As a matter of fact it can be demonstrated that this one-to-one relationship between

stimulus and response holds for no control arrangement, whatsoever, other than one calling for analogue amplification on the part of the operator. In every other case the human's task is mathematically more complex and the operator must take something into account other than the amplitude of the visual error. In some situations the man must try to modify his response to the visual signal in terms of his memory of the way the error has been changing in the past. At other times he must vary his response to the visual error depending upon information supplied by kinesthetic feedback. But in all cases, except those calling for the mathematically simplest operator task, the correlation between the response and the amplitude of the primary stimulus is low, since the human output is a function of several stimulus dimensions rather than only one.

It was pointed out earlier in the report that two different processes were involved in simplifying the human's role in a control system. One of these (unburdening) involved supplying mechanical or electronic aids which would relieve the man of the necessity of applying force continuously over extended periods of time. The other (quickening) consisted of giving the operator immediate knowledge of the results of his own actions. When both of these processes are carried to completion, the goal of the design principle is achieved, and only simple amplification is required of the human operator. However, less than complete unburdening and quickening results in conditions where the man must perform tasks which are mathematically more complex than amplification. It is convenient, therefore, to organize the ensuing discussion around these two processes and to make the effort to show how they relate to stimulus-response integrity.

Incomplete Unburdening

Let it be assumed that the operator of a man-machine control system is responding by applying force to a pressure stick in response to a tracking error presented on a visual display. If the unburdening is inadequate, i.e., if an insufficient number of integrators are included in the system mechanism, the man will be required to apply force continuously for varying periods of time in order to track the target. Furthermore, it will be found that, under these conditions, the amount of force and the direction in which it must be applied bears no constant relationship to the direction and amplitude of the error as it is displayed.

Thus, if the operator must supply one integration in order to track (say) a constant velocity target moving from left to right, he will be applying a constant force in such a direction as to counter the steady input when the amplitude of the displayed error is zero. This is to say that the man must emit a sustained output with the input at zero. If the course is supplied in the opposite direction, then this time, the operator will achieve a zero error by applying force in the opposite direction. Finally, if the course input is removed, the visual error will now reduce to zero when the man applies no force to his control.

It is clear from this that the same visual stimulus (zero error) calls for a response (force output) in one direction at one time, the opposite direction at another time, and for no response at all (zero force) at a third time. In order for the operator to take correct action under all of these circumstances, it is clearly evident that more information is required than is supplied by the primary stimulus.

A similar state of affairs may be shown to exist with a tracking error of finite size. Depending upon what has been going on prior to the development of such an error, the error will call for (a) the application of force in the indicated direction, if no force is already being applied, or (b) an increase in the amount of force, if force is being applied in the indicated direction, or (c) a decrease in the amount of force, if force is already being applied in the direction opposite to that indicated

Both of these illustrations show a condition of low stimulus-response integrity, since the required response bears no invariant relationship to the instantaneous amplitude value of the stimulus. Rather, the behavior called for at any moment must be educed from properly weighted and combined data jointly supplied by the visual error amplitude and the memory of the response events immediately preceding the act. In these examples, the reduction in the integrity has been brought about by insufficient unburdening, although inadequate quickening produces a similar effect in a different way, as will now be shown.

Inadequate Quickening

In situations where there is a time delay in the control loop, the instantaneous amplitude values of the visual stimulus generally will not correspond to the required amplitude values of the response. This can be understood if one visualizes a damped joystick tracking device with only a simple amplifier in the mechanism (Fig. 4). Into this system let a long transmission delay be inserted. If now the subject perceives a visual error injected as a position step, and responds by applying force to the joystick in the appropriate direction, he will recive no visual confirmation of the fact that force has been applied until one delay-time later. If the operator has been continuing to apply force throughout the whole transmission delay in his effort to reduce the error, he soon discovers that he has overcontrolled to a marked extent.

What the operator would have had to do in order not to overcorrect would be to start out by responding to the visual error just as he did, but then, after the force had been applied for a time, to react to the unchanged visual error by reducing applied force to zero. In other words, in order to correct the error, the operator would have had to make two different responses at different times to the same stimulus. Quite obviously, this is a condition of low stimulus-response integrity. Warrick (26) has demonstrated that a transmission delay of as little as 40 milliseconds affects tracking performance adversely, though the operator is not consciously aware of the delay.

Unpublished studies done at NRL and the Aero Medical Laboratory at Wright-Patterson Air Force Base have shown that exponential-type delays in the tracking loop also degrade tracking performance by an amount related to the time constant of the delay. As is the case with the transmission lag, the exponential delays bring about disruption through reducing the stimulus-response integrity of the system. The cure with both types of time lags is the most direct form of quickening, i.e., the removal of the delay.

Quickening of a somewhat different type is required in aided tracking. Curiously enough, the chief necessity for it arises from the insertion of integrators into the tracking loop for the purposes of unburdening the operator. These integrators introduce a phase shift which, as far as the human is concerned, acts like a time lag.

To exemplify this situation, let it be assumed that an operator is tracking with a pressure stick control and with two integrators and two feed-forward loops inserted in the mechanism (Fig. 7). With such an arrangement in proper adjustment and with simple target courses the man can act like an amplifier and track with high precision, since a good correlation prevails between the instantaneous value of the visual error and the response required to reduce it to zero.

However, all this is changed when the feed-forward loops are removed. With no quickening the operator begins to overshoot and oscillate around the target. In servo terminology, the system is unstable, and if the operator's task in this unquickened situation is analyzed it can be seen why. In order for the man to know what response to make at any moment in time he must take into account (1) the instantaneous direction and amplitude of the displayed visual error, (2) the velocity at which the error position has been changing

and (3) the rate of change of the velocity of the error. Yet at any instant, only the direction and amplitude of the error are displayed directly, where as the other two quantities must be supplied by estimates based upon error values extending back in time. If the instantaneous error value is taken to be the primary stimulus, it follows, therefore, that at different times different responses are required for the same stimulus.

For example, the operator must respond to an error of a certain value by applying force in the indicated direction if the error has just been increasing at a constant or accelerating rate. However, he must respond to the same stimulus by applying force in exactly the opposite direction, if, during its recent past, the error has been diminishing at a constant or increasing rate. Finally, he may have to exert no force at all if the error is decreasing at a decreasing rate. In short, without the quickening provided by the feedforward loops, stimulus-response integrity is destroyed and the tracking system tends to become unstable.

From the foregoing it seems evident that there is a close relationship between mathematical and psychological descriptions of human control task complexity. Thus, the operator need attend only to the primary stimulus while performing the analogue of the mathematically simple task of amplification, whereas he must simultaneously take account of several channels of information when acting in the more complex mathematical roles of integration and differentiation.

It seems reasonable to expect that, in general, complex psychological processes, such as those mediating responses which are based upon information culled from several different channels, will vary more from one instant to another than will the relatively uncomplicated operation of acting on values within a single informational dimension. In other words, one would expect performance based upon simple stimulus-response bonds to be less erratic than actions evoked through the exercise of complex stimulus-response connections.

The simplification principle, which is the raison d'être of this report, stands or falls on the assumption that the condition of stimulus-response integrity is associated with reduced human variability and enhanced response precision. It is now argued that this association is produced by virtue of the fact that the condition of stimulus-response integrity provides the operator with the easiest of all possible eye-hand coordination tasks.

LEARNING

Providing the operator with a specific task, simple or complex, does not, however, insure his performance of it. A second assumption behind the design principle is that the human will learn to change his performance when the presented task is changed, i.e., he will learn to do whatever he is supposed to do in order to optimize his own performance. Thus, it is assumed that if the system is designed to require complex actions from the operator he will gradually learn to perform then, whereas, if only simple acts are called for he will adjust his "set" so as best to execute these.

There is certainly no question that the human can learn through trial-and-error in circumstances similar to those encoutered by an operator of a man-machine system. Assuming adequate motivation in the form of interest in the task and desire to perform well, there is every reason to suppose that the operator of a machine will, in time, come to adjust his response characteristics so that he is doing whatever is necessary to keep the error below some "maximal tolerable" level. True, this tolerance level will vary with conditions, if the task proves difficult, it will probably be set high, while for simple tasks it will undoubtedly be lowered. Further, the average size of the error tolerated by the operator will probably vary with the stage of his learning and the level of proficiency with

which he is capable of performing. Nevertheless, it is unlikely that anyone will seriously challenge the assertion that, given sufficient practice, the man can learn to perform control tasks representative of a wide range of mathematical and psychological difficulty.

The hazard in the assumption relates to the speed of learning. If the operator learns rapidly there is no problem, but should weeks of practice be required in order for the human to change his response characteristics to those demanded by the mechanical components of the man-machine system, the design principle as stated earlier may be open to serious question. To be specific, if the operator, when called upon to do so, cannot start acting fairly quickly in a manner akin to simple amplification (i.e., start applying force roughly in proportion to the amplitude of the visual error), the simplification principle, as presently stated, no longer holds true. Experimental evidence is sorely needed on this point.

COMPENSATORY AND PURSUIT DISPLAYS

Just as the speed with which an operator can learn to change his mode of response may be critical in regard to the validity of the simplification principle, so also, may be the nature of the visual display employed in the system. Up to this point in the report, very little has been said about the manner in which information should be presented to the operator. This neglect has resulted from a preoccupation with ways and means of overcoming the necessity for presenting complex information to the man. However, it is quite likely that the nature of the display will influence system performance to an important extent. For example, it is to be expected that in those cases where it has not been possible to achieve complete stimulus-response integrity, the man will do his best only when he is provided with adequate information for the integrations and differentiations which he must carry out. On the other hand, in systems where the operator need act only as an amplifier a simpler display may be in order since less information is required.

Two fundamentally different types of display have been employed in research studies on tracking. One of these, termed a "compensatory" display, presents to the human a fixed center reference mark or reticle and a moving "target image" which responds to the difference between the input to the control system and some function of the output. With such a display, the operator's task is to center the target signal and to hold it on center as well as he can by means of appropriate responses with the control. This display presents directly to the operator only visual error in terms of direction and amplitude. No immediate inference as to the nature of the target course is permitted since the input and output of the system are mutually contaminated through being mixed together.

In contrast to this "single channel" indicator is a "pursuit" display which presents three channels of information rather than only one. Visual error is here shown as the distance between two separately actuated signal markers. One of these markers responds directly to system input, whereas the second, representing system output, may be made to pursue the first when the operator applies appropriate forces to the control.

By means of this one display, information is provided to the man which permits him to take account of the properties of the input and output independently of one another, as well as the nature of the error. Thus, if input rate is required, the pursuit display provides information which, when differentiated by the operator, furnishes this quantity. In contrast, the compensatory display does not provide this information, nor does it supply anything which the man can operate upon directly to obtain system output rate. In the pursuit indicator the latter is provided by the response of one of the two signal markers.

Up to now, the discussion in both parts of this report has assumed that a compensatory display was being employed in all man-machine systems described. This is even true for

the indicator associated with the control system discussed under the heading A Quickened Display on page 15. Though the display is described as a double-pointer dial, the nature of the system is such that during those periods in which the operator is carrying out his control task, one of the pointers remains stationary while the other is held in alignment with it through balancing responses made by the man.

Compensatory indication has been assumed throughout this report since it is far more frequently employed in existing continuous control systems than are displays of the pursuit variety. This choice is influenced by the serious practical limitations on the usefulness of pursuit displays. Perhaps one of the most troublesome of these is the restricted sensitivity of this type of indicator. If, for example, all 360 degrees of azimuth and 90 degrees of elevation had to be displayed simultaneously on the indicator, as would be required if a pursuit display were used to present tracking information in a gunfire control director, sensitivity would have to be so much reduced that precise control would be impossible. In contrast to this, very high error magnifications can be achieved by using compensatory displays.

But to return to the discussion, it would be predicted that if a pursuit display could be used it would make possible more precise human performance than would a compensatory indicator under conditions of less than perfect unburdening and quickening. This would result from the fact that the pursuit display would supply the operator with more information than would the compensatory indication. However, if the condition of perfect stimulus-response integrity had been realized, the additional information provided by the pursuit display would not be needed by the operator. Consequently, in this case, it would be expected that either no difference would be found between the two types of indicators or that the pursuit display would actually become worse than the compensatory. This would occur if the extra information presented in the pursuit display had a distracting effect on the operator. Such considerations suggest that the benefits to be derived from the use of one type of indicator over another will vary with the level of complexity of the operator's task in the system in question.

Studies by Poulton (16) and Senders and Cruzen (20) attest to the superiority of a pursuit display over a compensatory indicator in an unaided tracking system. By means of an ingenious arrangement, it was possible for Senders and Cruzen to present the subject with either a pursuit or compensatory display situation or intermediate combinations of the two. They found that the tracking improved continuously as the conditions were gradually altered from the pure compensatory arrangement to the pure pursuit condition, though the change from 50 percent to 100 percent pursuit was not statistically significant. Their findings support the contention that if the operator must act as an analogue computer in order to track proficiently, the pursuit display will furnish him with the best information.

Unfortunately, adequate evidence is lacking in regard to the hypothesis stated above that the superiority of the pursuit display over the compensatory will disappear when the system is perfectly unburdened and quickened. Research on this matter has begun at the Naval Research Laboratory.

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REFERENCES

1. Anderson, W. G., and Fritze, E. H., "Instrument approach system steering computer," Proc. I.R.E., 41:219-229 (1953)

2. Bates, J. A. V., "Some characteristics of a human operator," J. Inst. Ele. Engrs., 94 (pt. II A):298-304 (1947)

3. Birmingham, H. P., "Comparison of a pressure and moving joystick," NRL Ltr. Report 3600-330/50 rac, Oct. 9, 1950

4. Craik, K. J. W., "Theory of the human operator in control systems. I. The operator as an engineering system," Brit. J. Psychol., 36:56-61 (1948)

5. Craik, K. J. W., "Theory of the human operator in control systems. II. Man as an element in a control system," Brit. J. Psychol., 38:142-148 (1948)

6. Gibbs, C. B., and Clutton-Baker, J., "Pressure operated manual control levers," Medical Research Council, R.N.P.R.C., Operational Efficiency Sub-Committee Report No. 200, 1-12 (1951)

7. Gibbs, C. B., "The continuous regulation of skilled response by kinaesthetic feedback," Great Britain Medical Research Council, A.P.U. 190/53 March 1-13, 1953

8. Hick, W. E., "The effect of heavy loads on handwheel tracking," Great Britain Medical Research Council, Applied Psychology Research Unit SRI (Servo) Report No. 3, July 1, 1946

9. Hick, W. E., "The discontinuous functioning of the human operator in pursuit tasks," Quart. J. Exp. Psychol., 1:36-51 (1948)

10. Hick, W. E. and Bates, J. A. V., "The human operator of control mechanisms," Great Britain Ministry and Supply Permanent Records of Research and Development Monograph No. 17,204 (1950)

11. James, H. M., Nichols, N. B., and Phillips, R. S., eds. "Theory of servo-mechanisms," Radiation Lab. Series No. 25, pp. 360-368, New York: McGraw-Hill, 1947

12. Jenkins, W. O., "The discrimination and reproduction of motor adjustments with various types of aircraft controls," Amer. J. Psychol., 60:397-406 (1947)

13. Kellogg, S., and Fragola, C. F., "The Sperry zero reader," Aeronaut. Eng. Rev., 8 (No. 11):22-31 (1949)

14. Mechler, E. A., Russell, J. B., and Preston, M. G., "The basis for the optimum aided-tracking time constant," J. Franklin Inst., 248:327-334 (1949)

15. Nesbitt, F. Glen, "The Sperry zero reader," Sperryscope (The Sperry Corp., 30 Rockefeller Plaza, N. Y.), 11 (No. 9):2-3 (1949)

16. Poulton, E. C., "Perceptual anticipation in tracking with two-pointer and one-pointer displays," Brit. J. Psychol., 43:222-228 (1952)

Best available Copy 7 Feb 1986

17. Raggazini, J. R., "Engineering aspects of the hum
unpublished paper presented at 1948 meeting of Ar

18. Russell, L., "Characteristics of the human as a lin
M. S. thesis, Servomechanism Lab., M.I.T. (1951)

19. Searle, L. V., "Psychological studies of tracking b
tency hypothesis as a basis for predicting optimum
NRL Report 3872 (1951)

20. Senders, J. W., and Cruzen, M., "Tracking perform
and pursuit tasks," Wright Air Development Cente

21. Stafford, B., "Frequency analysis of some closed-
NRL Report 3910 (1952)

22. Stevens, S. S., ed., "Handbook of experimental psy
1951

23. Tufts College, "Handbook of human engineering da
Technical Report No. SDC 199-1-1, Part 1-9 ONR

24. Tustin, A., "The nature of the operator's response
tions for controller design," J. Inst. Elec. Engrs.,

25. Vince, M. A., "Corrective movements in a pursuit
1:85-103 (1948)

26. Warrick, M. J., "Effect of transmission-type contr
U. S. Air Force Technical Report No. 5916, Septem

27 Woodworth, R. S., "Experimental psychology, p. 4

• • •

Best Available Copy