A Design Philosophy for Man-Machine Control Systems*

H. P. BIRMINGHAM† MEMBER, IRE, AND F. V. TAYLOR†

Summary—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 is discussed in light of these two concepts and is related to various efforts to improve the stability of man-machine systems through the use of special equalization networks.

THE CONCEPT OF A MAN-MACHINE SYSTEM

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

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 clear 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 overall man-machine system. Fig. 1 shows a model of this concept.

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).

Not only is the organism acted upon by environment—in turn man modifies the external world through responses (R) of the effector organs. In the human, 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 re-routed 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 concern-

---

* Original manuscript received by the IRE, March 22, 1954; revised manuscript received, May 19, 1954. The opinions or assertions contained herein are the private ones of the writers and are not to be construed as official or reflecting the views of the Navy Department and the naval service at large.

† Naval Research Lab., Washington, D. C.
As the activities of the mechanism; represented in the schema by the box labelled "M." Within the box are the sensor 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 that traditionally interested the engineer most.

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 visions along the twisting roadway, as visually appreciated, while the output is the progress of the car along the highway. In an anti-aircraft system, the input is the spatial course of the enemy aircraft sensed through optics or radar. The output, in this case, consists of stages which position the guns so that the bullets will pass close to the target.

Taking the complete man-machine system to be a gunnery device, the informational flow is as follows: The vision of the enemy aircraft is sensed, let us say, by the operator. 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 center. The control motion, when transformed by M, changes the system output (it repositions the guns), and (2) if the human's response has been adequate, reduces the misalignment between the target and the cross line. However, since the input will continue to change, the operator will be forced continually to make control adjustments if he is to keep the misalignment at a minimum. This will have the effect of insuring that the output of the system at all times 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 aircraft, tanks, radars, sonars, and the like, different input and output parts 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 limited to recommendations concerning the design of sensors, circuits and equipment which define the task of the operator in a continuous control loop.

**Human Characteristics Relevant to Control Engineering**

**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 mils real field. 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 mils real field. Though 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 supply several hundred pounds of force with leg and back muscles for short periods of time when called upon to do so. The strength of the arms is considerably less, but even in this case, more than 50 pounds of pull can be applied with the arms in bursts without fear of over-taxing the organism. Less is known about man's ability to graduate his force appli-

---


cations 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 remain fairly constant.\footnote{R. S. Woodworth, "Experimental Psychology," Henry Holt and Co., New York, N.Y., p. 433; 1938.} Inferences from early lifted-weight experiments suggest that below one pound the precision of force control deteriorates very rapidly.\footnote{W. O. Jenkins, "The discrimination and reproduction of motor adjustments with varying types of aircraft controls," Amer. Jour. Psychol., vol. 60, pp. 397-406; 1947.}

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.

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 (b) 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, $\theta_0$ is to be taken as the amplitude of joystick displacement, while $\theta_1$ 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 $\alpha$ represents a constant which may change in value from one equation to the next. In the figure, the triangles represent amplifiers of adjustable gain, and the square boxes labeled ($\int$) 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 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 (1946) and Hick and Bates (1950), point out in their important papers, force must be applied to every control regardless of the particular transfer properties involved in any one situation.\footnote{W. E. Hick, “The Effect of Heavy Loads on Handwheel Tracking,” Medical Res. Council, SRI (Servo) Rep. No. 3; July 1, 1946.} 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.

![Fig. 2—The action of force upon three types of manual controls](image-url)

Kinesthetic Feedback: It should be pointed out that different control arrangements not only integrate force a varying number of times, but also affect qualitatively and quantitatively the information fed back from the kinesthetic receptors which signal the degree of activity of the moving limb’s tissues. 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' who finds pressure control to be superior to displacement control. In explanation of this, he adduces physiological evidence to show that the kinesthetic 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 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 analog 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 (1943), Tustin (1947), and Ragazzini (1948).

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. It is customary, therefore, to treat such intermittent systems in terms of the nearest linear approximation. This is done in the hope that, though the model chosen is recognized as being an imperfect analogy, it is still sufficiently appropriate to be useful. Following this convention, 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 relation-
ships is the fact that man appears to have many transfer functions. Evidence 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 adaptability 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 will-o'-the-wisp 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 he is most competent to play.

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.

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 analog of a simple amplifier as shown in the following equation:

\[ \theta(t + \tau) = \theta(t) \]  

where \( t \) represents a value in time, and \( \tau \) 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 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
supersede 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, infra-red, 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 analog computer, but as the power drives as well. In such cases, complete redesign of the system would be required if one sought entirely to supplant the human element. In these cases, one must be satisfied with the more modest, yet very appreciable, improvements to be brought about through task simplifications which stop short of the ultimate.

THE 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. 3(a).\(^{19}\) 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, \(b\) the velocity component and \(a\) the acceleration component.

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

\[ \theta_9 = a\theta + b\dot{\theta} + c\ddot{\theta}. \]  

(2)

This is the “open loop” equation for the system.

Figs. 3(b) and 3(c) represent alternative ways of achieving the same input-output relationships obtaining in 3(a). In both of these figures the process of differentiation is symbolized by a square box containing the ratio \(d/dt\). In 3(b), the output of the first integrator is the rate component, while position is obtained by differentiating this rate. In 3(c), 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.

![Fig. 3—Three equivalent follow-up systems.](image)

To achieve stability with any one of the three equivalent devices shown above, 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 (next page). 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.

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.

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 over-all 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 through two feed-forward loops supplying position and velocity components to the final output.

Quite different from this is the case in Fig. 7 wherein the tracking control is 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 becomes fully meaningful only when the nature of the control is specified.

Though, 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 announced earlier in this report, would lead only to the assertion that all three of the systems would be more precise than any other arrangement 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 of control systems intended to be used against targets maneuvering realistically. Such target courses contain important amounts of acceleration and rate of change of 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 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 analog 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. 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 sec.

As to time constants for discontinuous tracking tasks, Mechel, Russell, and Preston 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 sec.

Assuming that the addition of an acceleration component to position and rate would improve system performance for continuous tracking tasks, Searle 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 Mechel, 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 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.

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

Unburdening and Quickening

An "anthropocentric" 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 improve system precision; the former process by reducing human effort and removing lag errors, the latter process 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 is an extremely important fact, since it means 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 control system requiring quickening](image)

A Quickened Display

An example of a case requiring display quickening is provided by a control system block diagrammed in Fig. 8. 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.

The quickening of this device presents an intriguing problem since the obvious solution diagrammed in Fig. 9 (facing page) is ruled out by circumstances which prevent making changes which affect directly the output of the control system. The problem may be solved, how-
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. 11. 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 under-shoots 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.

Such quickening is provided by the insertion of two special high-pass filters in the manner shown in Fig. 12. Now, the higher frequencies in the operator’s output which were absorbed by the low-pass filter of the system, as shown in Fig. 11, reach the display. The complementary IF filter and the “antibias” network act together to quicken the human’s high frequency correction motions without introducing a bias such as would occur if the IF filter were employed in isolation. The conjoint use of these two types of filter is termed “treatment.”

A simulator was set up at NRL to act as an analog 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 was run with the filter in, but with no treatment (Condition 2). This condition is represented in Fig. 11. The remainder of the trials were run with the filter in and with treatment also incorporated in the system as in Fig. 12 (Condition 3).
Fig. 13—The effect of filtering and treatment upon tracking error.

The results of this experiment are shown in Fig. 13. 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. 8, 9 and 10, indicates that had the input to the system been anything other than a series of step function position changes, an antibias network similar to that employed above would have been required if the quickening were performed as in Fig. 10. 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 anti-bias network is included in the quickening circuitry. At present, the design of these anti-bias circuits is a relatively undeveloped, but highly promising, field.

Dielectric Potentiometers *

GEORGE E. PIHL†, ASSOCIATE, IRE

Summary—The term “dielectric potentiometer” is used to designate a new type of controllable voltage divider employing a lossy liquid dielectric as the impedance medium. With proper design, the dielectric potentiometer may be operated over an extremely wide frequency range with a flat amplitude response and zero phase shift. Unlike conventional wire-wound and film type controls, the new device is readily capable of being perfectly compensated for broadband operation when operated into either resistive or capacitive loading, or a parallel combination of both. Other advantages include infinite resolution, long life, and adaptability to specific nonlinear requirements. Probable advantages such as a low noise figure and the capability of operation at high rotational speeds have yet to be experimentally investigated. Examples of designs for particular applications are given.

INTRODUCTION

WHAT APPEARS to be a new form of potentiometer or voltage divider has been discovered. This came about during an investigation of various variable impedance devices suitable for use in amplitude compression systems. The requirements included wide frequency response, large dynamic range, rapid operation, and minimum amplitude distortion. In an effort to avoid the distortion inherent to nonlinear devices commonly used for automatic amplitude control, consideration was given to mechanically-actuated voltage dividers. As a result, a miniature broadband dielectric potentiometer has been developed having a self-contained magnetically-operated rotor. Used in a high-gain, closed-loop system, the device is capable of maintaining a constant output amplitude for input voltage variations over a 35 db range without appreciable amplitude, frequency, or phase distortion for frequencies between 50 cps and 1.0 mc. The response time is of the order of 100 millisecond.

Subsequent development has led to designs for other applications where manually-operated precision controls having greater bandwidth capability than conventional wire-wound controls are necessary.

BASIC PRINCIPLES

The successful operation of a dielectric potentiometer depends upon the simultaneous variation of resistance and capacitance existing between a movable electrode and a system of fixed electrodes all immersed in a lossy liquid dielectric. To understand the operation of such a device, consider first the simple system shown in Fig. 1.

In this sketch, A and B represent metallic electrodes of arbitrary shape having connections brought out of the enclosure H through hermetic seals. If the enclosure is filled with a fluid having a particular resistivity \( \rho \) and dielectric-constant \( \varepsilon \), the impedance \( Z \) observed at the indicated pair of terminals may be expressed as a paral-

* Original manuscript received by the IRE, June 7, 1954; revised manuscript received, August 18, 1954.
† Technology Instrument Corp., Acton, Mass.