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THE HUMAN OPERATOR IN CONTROL SYSTEMS

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PREFACE

This report presents a tutorial introduction to the design of manual control systems. The material will be published as a chapter in the book "Psychological Factors in Systems", edited by K. B. DeGreene, to be published by McGraw-Hill Book Co., 1969.

MAN-MACHINE CONTROL SYSTEMS

1 Introduction

The purpose of this chapter is to survey the role of man as an element in a control system. Examples of such systems are found in the steering of an automobile, manual attitude control of a spacecraft, the control of piloted aircraft, manual process control, air traffic control, and, in certain cases, man-computer systems. In all these systems the human element provides certain inputs to a group of machines, devices or other fixed elements (sometimes known collectively as"the plant") and he receives feedback information regarding the state of the system. In general, a control system involves the manipulation of certain variables in order to achieve desired or reference values. Such a reference value may be fixed, as for instance the "set point" in the control of a furnace or chemical reactor, or it may be variable, as in the pursuit of an evasive target by means of an adjustable set of crosshairs. In general, the fundamental man-machine control system can be viewed by means of the block diagram of Figure 1, where inputs to the plant are provided by means of a set of controls and feedback is obtained by means of displays. The man's receptors provide a sensory inputs to the central nervous system from which a response (R) originates. Thus, from a system point of view, man can be viewed as an information processing device. He converts sensory inputs into appropriately coded muscular outputs. A complete analysis of man as an element in the system of Figure 1 requires an understanding of the characteristic of the receptors and effectors, the nature of the information processing in the central

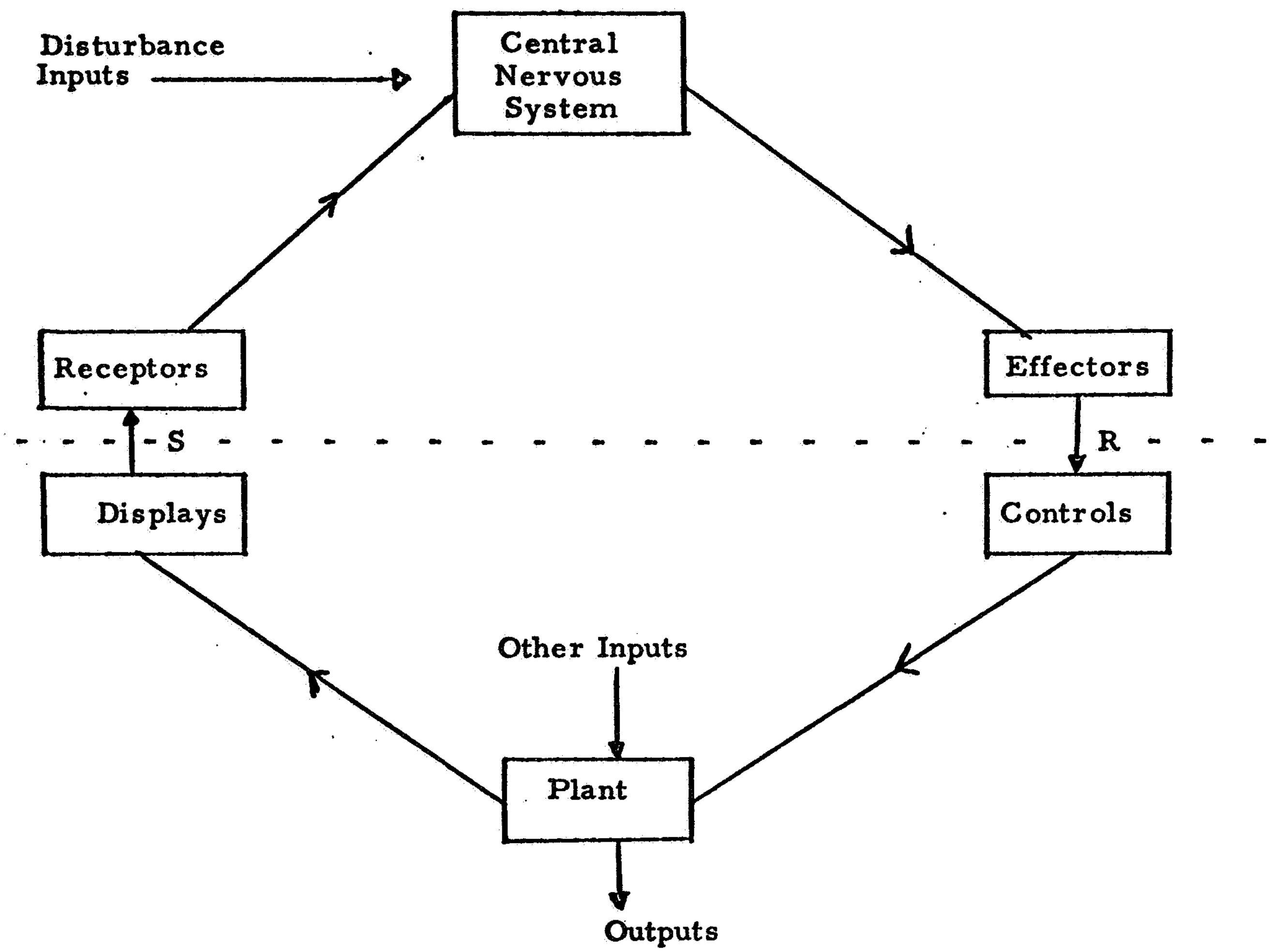

Figure 1

Structure of Man-Machine Control System

nervous system, the psycho-physical relationships existing between displays and receptors on the one hand and effectors and controls on the other, as well as an understanding of the nature of the plant or controlled process. These will be reviewed briefly in the following pages.

Much basic study has gone into understanding the interaction between man and machine. Nevertheless, it is probably fair to say that, except in certain simple cases, it is not possible at the present time to obtain a clear quantitative measure of the usefulness of man as a system element, in contrast with an automatic control device. Man excels in environmental adaptibility, versatility, ability to discern signals in the presence of noise and his presence makes a control system adaptive and self-optimizing, within certain limits. However, the relative importance of these factors is hard to assess. The optimum selection of a control strategy for a proposed system involves a wide range of disciplines, including psychology, physiology, control systems theory, mechanics, and simulation techniques. In this chapter, a brief survey of some of the aspects of such an evaluation will be provided.

The material presented in the following sections will first introduce the subject of man-machine systems and indicate some of the input-output characteristics of man. The psychological and engineering approaches to the description of man as a control element are then discussed. Display and control factors are reviewed briefly, with some examples of actual and proposed systems. The engineering approach to control systems is then indicated, and some mathematical models of the human operator's function are presented. Finally, simulation of manned systems is examined briefly, indicating the considerations of stimuli, experimental design, and evaluation criteria.

2 Design ot Man-Machine Systems

The design of man-machine systems, such as a manually controlled spacecraft, requires an understanding of man's characteristics. The effects of these characteristics, notably of the input channels (the senses) and the output channels (largely limb movements and speech) must be analyzed on the basis of their influence on overall system response. This section contains a brief review of these essential properties. Further details may be found in the references [1-6].

2.1 Major Considerations in Man-Machine System Design

(a) Variability

Human performance is subject to statistical variability from trial to trial of the same task and from operator to operator. This variation is a primary design consideration. It can be approached by designing on the basis of the statistics of selected populations: e.g., the height of an instrument panel in an aircraft should be based on average heights of pilots and not of housewives. In other cases, the design needs to be based on the accommodation of 99 percent of large populations, or it may be "worst case" design.

(b) The physiological limitations of input and output channels (such as bandwidth or muscular power available) must be considered in each design. A visual stimulus, for example, needs to bo present for a sufficiently long time and at a sufficient level of intensity to be perceived.

(c) Psychophysical relationships must be observed. These include the relationship of the objective stimulus to its perceived intensity and the relation of the threshold of noticeable change (j.n.d.) in a stimulus to its intensity.

(d) System characteristics of human operators, such as limited bandwidth (or channel capacity), memory (including short-term and long-term storage, etc.)

(e) Engineering limitations on the design of the machine part of the system. Thus, the operator's task could be simplified in many systems at the expense of much greater engineering complexity which may or may not be desirable.

2.2 Portions of the Design Problem

The design of man-machine systems must consider at least the following areas:

(a) Allocation of functions to man and machine

This is a very complex problem, which in many cases includes non-technical factors (such as Government policy, for example) in addition to an evaluation of capabilities.

(b) Display design

Based on feasibility and state-of-the-art related to a study of human sensory inputs.

(c) Control design

Based on human output capability.

(d) Display-control compatibility

Many early designs violated this basic concept by such designs as relating a clockwise needle movement to a counterclockwise controller movement.

(e) Environmental control

(f) Size, shape and arrangement of controls and workspace

(g) Maintainability of equipment

(h) Verification of design

Ultimately, a design can only be verified by actual operation. However, preliminary designs can be studied using mathematical models of human performance and simulation techniques. In all such verification studies the problems of statistical variation of human operators must be considered.

Some of the above topics are treated in other chapters of this book. Some, such as item (a) through (d),are discussed later in this chapter. Consider now the question of allocation of functions to man and machine.

2.3 Allocation of Functions

The proper allocation of sensing and operating function in man-machine system requires a study of the functional advantages and dis-advantages of man and machine in typical system tasks. A careful comparison is presented in Table I below.

TABLE I

FUNCTIONAL ADVANTAGES AND DISADVANTAGES OF MEN AND MACHINES*

Data Sensing

Man	Machines
Can monitor low probability events for which, because of the number possible, automatic systems would not be feasible.	Program complexity and alternatives limited so that unexpected events cannot be adequately handled.
Under favorable conitions absolute thresholds of sensitivity in various modes are very low.	Generally not as low as human thresholds.
Can detect masked signals effectively in an overlapping noise spectrum on displays such as radar and sonar.	When noise spectra overlap detection of signal not good.
Able to acquire and report information incidental to primary activity.	Discovery and selection of incidental intelligence not feasible in present designs.
Not subject to jamming by ordinary methods.	Generally subject to disruption by various interference and noise sources.

Data Processing

Man	Machines
Able to recognize and use the information, redundancy (pattern) of the real world to simplify complex situations, e.g. recognition of airport through stages of ground contact, approach and landing.	Little or no perceptual constancy or ability to recognize similarity of pattern in either the spatial or temporal domain.
Reasonable reliability in which the same purpose can be accomplished by different approach (corollary of reprogramming ability)	May have high reliability at increase in cost and complexity. Particularly reliable for routine repetitive functioning.
Can make inductive decisions in situations not previously encountered; can generalize from few data.	Virtually no capacity for creative or inductive functions.

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*Adapted from "The Human Component" by J. Lyman and L. J. Fogel, Chapter 2, Vol. 3, Handbook of Automation, Computation and Control, edited by E. M. Grabbe, S. Ramo and D. E. Wooldrige, Wiley, 1961.

Data Processing (continued)	
Computation is weak and relatively inaccurate; optimal theory of games strategy cannot be routinely expected.	Can be programmed to use optimum strategy for high-probability situations.
Channel capacity limited to relatively small information through-put rates.	Channel capacity can be made as large as necessary for task.
Can handle variety of transient overloads and some permanent overloads without disruption.	Transient and permanent overloads may lead to disruption of system.
Short term memory relatively poor.	Short term memory and access times excellent.
Data Transmitting	
Can tolerate only relatively low imposed forces and generate relatively low forces for short time periods.	Can withstand very large forces and generate them for prolonged periods.
Generally not good at tracking though may be satisfactory where situation requires frequent reprogramming; can change to meet situation. Is best at position tracking where changes are under 3 radians per second.	Good tracking characteristics may be obtained over limited set of requirements.
Performance may deteriorate with time because of boredom, fatigue, distraction, etc.; usually recovers with rest.	Behavior decrement relatively small with time; wear maintenance and product quality control necessary.
Relatively high response latency.	Arbitrarily low response latencies possible.
Economic Properties	
Relatively inexpensive for available complexity and in good supply; must be trained.	Complexity and supply limited by cost and time; performance built in.
Light in weight and small in size for function achieved; low power requirement, less than 100 watts.	Equivalent complexity and function would require radically heavier components and enormous power and cooling resources.

Easy to maintain with minimum of "in task"extras.	Maintenance problem becomes disproportionately serious as complexity increases.
Non-expendable and interested in personal survival; emotional.	Expendable and unconscious of personal existence; will perform without distraction from problems arising outside of task.

3 Characteristics of Human Input and Output Channels

The major input channels useful in system operation are vision and audition, but other senses such as the kinesthetic sense and the perception of acceleration forces are extremely important in many cases. The major output channels are those requiring muscular movement by activation of hand controllers, levers, pedals and similar devices. In addition, the human voice is an important output channel as well. This section presents a review of the major characteristics of man's input and output channels.

3.1 Input Channels

a. Vision

Major dimensions: brightness discrimination, color discrimination, spatial and time discrimination.

Brightness sensitivity:

Minimum: approx. 2×10^{-10} ergs

Maximum: approx. equal to min. $\times 10^{9}$

Brightness discrimination:

Relative: approx. 570 levels can be distinguished

Absolute: 3 to 5 brightness levels

Spatial discrimination:

Excellent: This is one of the outstanding features of the visual channel.

Major properties: visual acuity; depth, form and movement sensitivity

Typically, spatial discrimination accuracy depends on exposure time. Threshold levels also depend on exposure time.

Temporal discrimination:

0.04 to 0.4 seconds at the retina

Importance of above features:

Displays can be coded by color and shape

Brightness sensitivity is used in display design

Vision is major input sense in man-machine systems

b. Audition

Major dimensions: frequency (pitch), loudness, (intensity), duration

Pitch discrimination:

Range: approx. 20 to 20,000 cps

Intensity range:

Minimum: approx. 1×10^{-9} ergs/cm^2

Maximum: approx. equal to min. x 10^{14}

Duration

Spatial localization

Poor compared to eyes. Binaural effect versus binocular effect.

Time discrimination between sounds is one of audition's best features.

c. Mechanical vibration

Threshold at fingertips: 0.00025 mm

Pain at about 40 db above threshold

d. Kinesthetic sense

An important sensory function in man-machine systems is that provided by the specialized receptors in muscles and joints known as proprioceptors, which provide feedback information regarding limb movement, its duration and, to some extent, the applied force. Joint movements of 0.2 to 0.7° can be detected at a minimum rate of 10° per minute. Kinesthetic feedback is transmitted by afferent nerve fibers from the muscles to the central nervous system.

e. Other senses

Some of the other senses available to man are:

Touch pressure

Smell

Taste

Temperature

Angular acceleration

Linear acceleration

Smell and temperature senses are used mainly as alarm detectors, rather than for fine control. The sense of touch is incorporated in control systems mainly by the shape coding of knobs and other control devices. However, it may be interesting to note, that questions of tactile feedback are important in connection with remote planetary exploration. It may in fact be desirable to transmit back to earth signals which can be interpreted by earthbound observers as tactile stimuli regarding the nature of the surface of rocks or other planetary objects.

Angular and linear acceleration senses are of considerable importance in the design of aerospace vehicles. They are responsible in part for "seat of the pants" impressions regarding the movement of a vehicle. On the other hand, they also impose design limits on the acceleration rates of such vehicles, in order to avoid vertigo and consequent disorientation and loss of control.

h. Complex "senses"

The ability of human controllers to be aware of the passage of time, and to detect the probability distribution of random events can also be considered as senses. Quantitative data regarding these "senses" is lacking, except under carefully controlled circumstances.

g. Lacking senses

It is also significant to note that the human element completely lacks a sensor for ionizing radiation. The detection of x-rays, of lethal but odorless gases, certain radioactive particles and so forth requires the use of specialized detection devices.

3.2 Problems with Sensory Inputs

a. Interaction

In many cases there is "crosstalk" between different dimensions of the same sense (such as brightness and color in vision) and between different sense modalities. For example, the effect of strong auditory stimuli on pain thresholds is well known. From a systems viewpoint, such interaction makes it difficult to isolate particular stimulus-response relationships for mathematical analysis. This is particularly so in a complex system in which the human operator receives stimuli simultaneously through a number of sense modalities, e. g. in a space vehicle where strong visual stimuli occurs simultaneously with auditory alarms and violent pitching and rolling movements of the vehicle.

b. Nonlinearity

All the sensors are nonlinear. The following nonlinearities are of particular importance:

(1) Threshold phenomena which are present in all sense modalities, but depend on a number of other variables, such as vigilance, interaction from other senses, etc.;

(2) Saturation: there is a maximum signal which any particular sense is capable of receiving. Stimulation at a level higher then this maximum will produce organic damage or simply no additional change in the receptor output.

(3) Psychophysical Nonlinearities: even assuming that over the range between threshold and saturation stimuli a given sensor behaves as a linear transducer, this stimulus and the resulting subjective sensation are not linearly related. In some cases the stimulus level P can be related to the sensation level S by means of approximate laws such as the Weber-Fencher law, $S = k_1 \log P$ or the Stevens power law, $S = k_2 P^n$, where k_1, k_2, and n are constants which depend on the sense modality involved and the type of continuum being observed [7].

3.3 Output Channels

a. Muscular Output

In most control systems the human controller's input to the machine is obtained from the contraction of skeletal muscles. In manual control systems this involves such devices as toggle switches, buttons, knobs, levers, joy sticks, cranks, steering wheels, etc. Footpedals are used as control devices in both aircraft and automobile applications. In extreme cases, other muscles have been used for control purposes. For example, tongue control has been used as a control output by quadruplegics at the Rancho Los Amigos Hospital [8]. Ear movement has been used as a control output for the movement of artificial arms in experiments at the Case Institute of Technology [9]. In general, muscular movement is of low accuracy unless monitored by appropriate feedback (usually visual) in both force and position. The accuracy of movement is dependent upon a number of factors, such as the muscles involved, the limb position and support, the amplitude and direction of motion, and the force required. Small movements tend to merge into involuntary tremors. Large movements tend to undershoot while small movements tend to overshoot the desired position.

b. Voice

The human voice is a control output of increasing importance. An aircraft which is "talked into a landing" by the control tower is evidently being controlled by a speech channel. In addition, and of growing significance is the availability of equipment which converts voice into digital code, which is then used directly as in input to a number of control devices. It can be expected that voice control devices will assume a considerably larger share of man-machine system interaction in the next decade.

c. Other Human Outputs

Among other outputs available from a human operator are various electrophysical signals such as the electrocardiogram (ECG), the electroencephalogram (EEG), and the electromyogram (EMG); the galvanic skin response (GSR), eye movements, skin temperature, breathing rate, and blood pressure. Of these only a few have been used for control purposes.

EMG signals, which give an indication of muscle activity, can be detected and amplified and used as input to control devices. Eye movements can be detected by means of eye movement cameras or by means of simple bio-potential electrodes mounted on the temples and forehead as shown in Figure 2. Such electrodes can provide a useful signal proportional to the position of the eyes, as an input to a control device.

3.4 Problems with the Output Channels

From a system point of view, two major problems of the output channels become readily apparent: output rate limitations and performance deterioration due to fatigue.

a. Rate limitations

The maximum rate of tapping with the fingers can be shown to be about 8 to 10 taps per second. Similarly, the maximum rate of repeating memorized syllables is about 8 per second. However, as accuracy requirements are imposed on movements, even these relatively low rates cannot be maintained. In fact, operators can, within certain limits, trade speed for accuracy in a nearly linear relationship, thus implying a fixed information processing capacity.

b. Fatigue

It is also important to note that accurate movements and especially movements requiring considerable amounts of force cannot be maintained for long periods due to muscular fatigue.

The above summary of the input and output characteristics of human

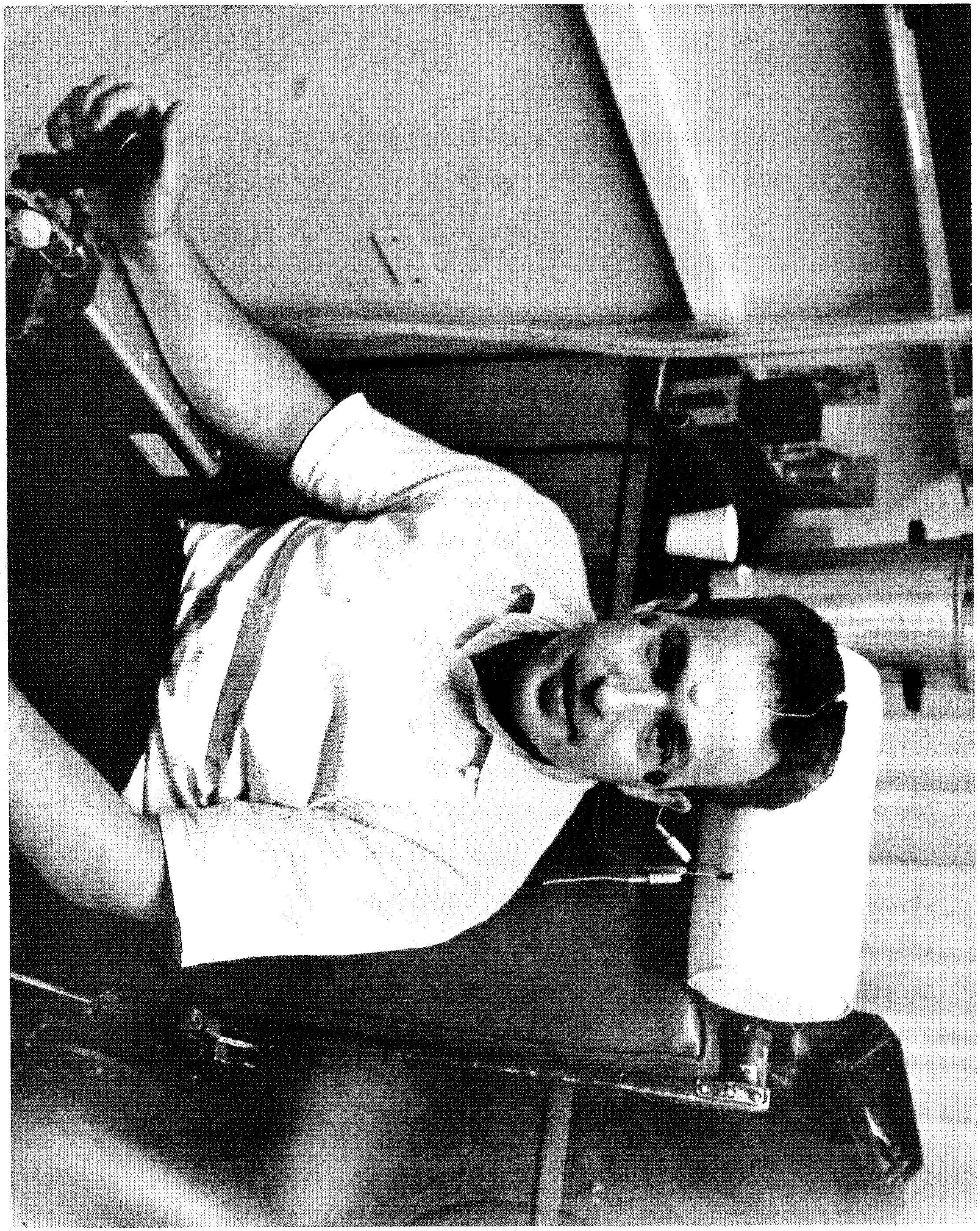


Figure 2
Measurement of Eye Movements as a Control Response

operators is necessarily very sketchy and many details have been omitted. Much more detailed discussions can be found in the references at the end of the chapter [1-6]. In the following section we will turn our attention to a study of manual control systems as representative of a large class of man-machine systems.

3.5 System Aspects

The above paragraphs provided an introduction into the physiological and psychophysiological aspects of human input and output channels. However, in a system design, the overall input-output transfer characteristics of the human element are of importance. In many cases it is very difficult to isolate the specific physiological source for the human controller's behavior as a system element. In the following section we shall examine both the psychological and engineering approaches to the overall view of man as an element in the control system.

4 The Man-Machine Control Loop

4.1 The Basic Control System

As a basis for the subsequent discussion of manual control systems, consider the block diagram of Figure 3. This figure may be considered as a representation of a tracking task, in which the human operator observes on a visual display the difference between a desired input quantity i(t) and the feedback or system response r(t) and adjusts a manipulator, joystick, hand-wheel or similar output device in such a manner that the system response agrees with the input as closely as possible. Tracking research, involving an investigation of human behavior in systems of the type of Figure 3, has been performed by both psychologists and engineers for a number of years. It was initiated in connection with problems of tank turret control and anti-

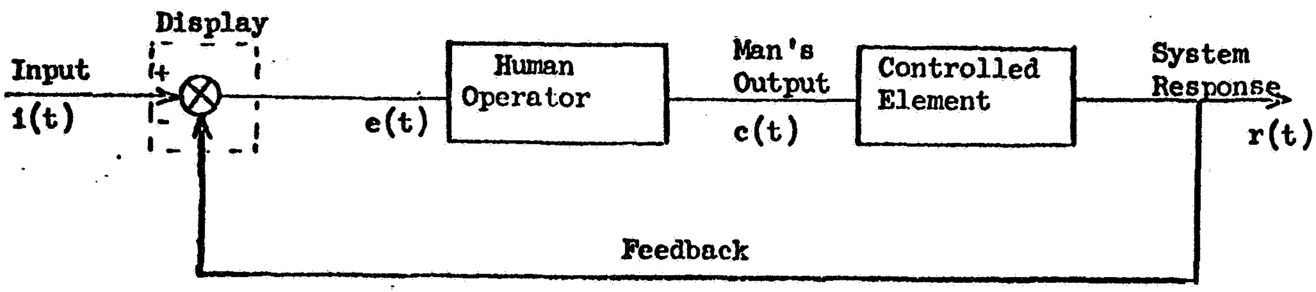


Figure 3

Block Diagram of Manual Control System

aircraft fire control during the World War II. More recently it has been applied to problems of aircraft control, spacecraft control, submarine control, and automobile control [2,4,10,11]. It is evident that there are two classes of questions which may be asked in connection with the block diagram of Figure 3. The first category, which we shall refer to loosely as the "psychological approach" is concerned with such questions as: task difficulty, task loading, human operator vigilance, display-control compatibility, human operator training, learning effects, motivation, stress, etc. The second group of questions which characterize the "engineering approach" include such items as: the effect of display gain on the stability of the feedback system, choice of forcing function frequency, the nature of the probability distribution of error, the relation between human operator performance and the performance of an appropriately defined "optimum controller" stability margins of the system with the human operator present, etc.

4.2 Psychological and Engineering Approaches

It is evident that there is a great deal of crosscoupling between the two classes of questions indicated above. Both are concerned with system performance and experience has shown that, for example, the degree of training of the human operator has a significant effect on loop stability margins, i. e. the "psychological" and "engineering" approaches in the study of manual control systems are difficult to separate.

Nevertheless, there are differences of emphasis and motivation. Some psychologists (e. g. J. Adams [12]) have found the engineering approach inadequate and overly confining for describing the details of human information processing. In many cases, psychologists have been concerned with procedural variables (such as training, motivation, stress) while engineers have been concerned with task variables such as spring loading and forcing function frequency. However, a more fundamental difference has arisen as a result of the variety of performance measures which are used for evaluating the quality or state of the complete tracking system. Engineers, as a result of their greater mathematical training, have a tendency to specify the process in such a way as to enable the deduction of an appropriate measure. As an example, much control system design is concerned with the use of mean-square performance criteria, since it is known that such criteria, when used as a basis of optimum design, lead to linear controllers. Tracking research in the psychological literature, however, has often been based on a convenient performance measure without a careful analysis of the limitations which may arise from its use. For example, "time-on-target" has been used as a performance measure for some time even though difficulties of interpretation of results have been demonstrated a number of times. An additional problem has arisen in connection with measures of task difficulty, which has been shown to be related in a complex and anomalous way to so many other system variables that it indicates little about the physical requirements of the task.

4.3 Types of Tracking Systems

Two basic types of tracking systems can be distinguished on the basis of the kind of display information presented to the operator:

(a) Pursuit Tracking, as the name implies, refers to a situation where the target motion and response motion are separately displayed. The operator attempts to make his response output correspond to to the target position, whether it be positioning an instrument needle to follow another one, or making a spot on a cathode ray screen follow another.

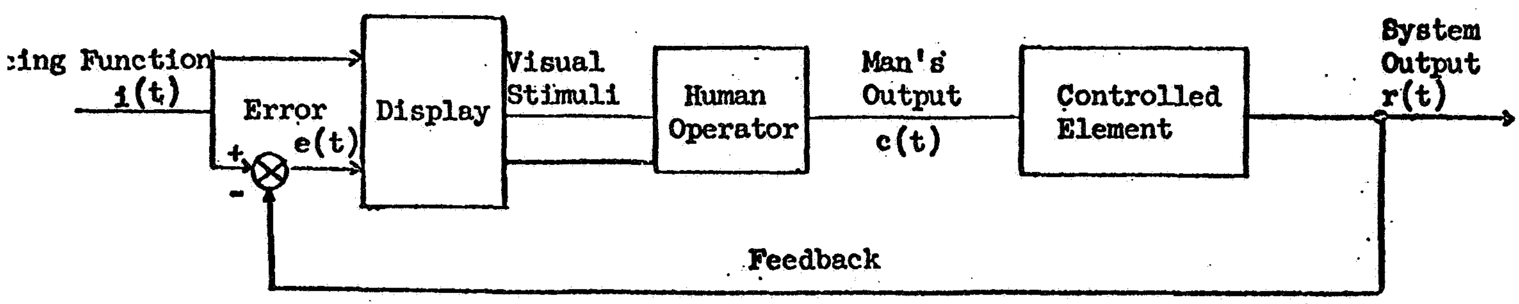
(b) Compensatory Tracking refers to a situation where the display presents the error or difference between the target position and the controlled system response. Thus, in terms of Figure 3, the compensatory display presents only the difference between the forcing function i(t) and the system output r(t). The two configurations are presented in more detail in Figure 4 [13, 14, 15].

4.4 Displays

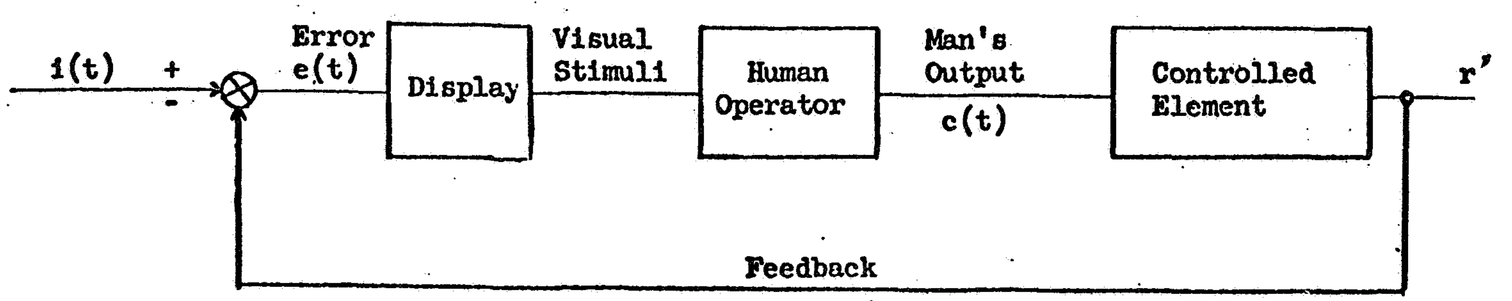
Display design is an important part of manual control. As we have indicated above, visual inputs are the most commonly used input channels. Most of the information used by automobile driver or astronaut for control purposes comes by way of the visual channel, either by direct observation of the "outside world" or by reference to displays. Improved display design can substantially improve operator performance, ease the work load, and reduce skill requirements. A detailed discussion of the problems of display system design are beyond the scope of this chapter, and the interested reader is urged to consult the references [16, 17]. However, some aspects of display design will be quickly enumerated.

a. Separated vs. Integrated Displays

Most common display concepts are based on the use of a separate indicator for each variable to be displayed, along with auditory alarms and warning lights for special purposes. The clear advantage of this approach is that failure of a given instrument will in general not be catastrophic. On the other hand, in recent years, multipointer and integrated instruments such as "three-axis eight-ball" attitude indicators have been used. With these



(a) Pursuit Tracking



(b) Compensatory Tracking

Figure 4

Pursuit and Compensatory Tracking

instruments it is possible to display three, six or even more variables with a single instrument. This approach minimizes display panel clutter. On the other hand failure of such an instrument may indeed be catastrophic to the system.

b. Literal vs. Symbolic Displays

A literal display, such as a photograph has a one-to one corresoondence with the features of the actual situation. A symbolic display such as a map contains symbols which represent the actual objects but may have no necessary correspondence with them.

c. Analog vs. Digital Displays

Analog displays represent magnitudes by distances along a scale (whether it be circular or linear) while digital displays use numerical read-outs.

d. Display-Control Compatibility

This phrase refers to the relationship between movement of the display needle or indicator and movement of the control. Thus, it is desirable to have a clock wise display needle movement correspond to a clockwise controller placement, in order to minimize both training time and errors. This area continues to be an important research problem, particularly in connection with spacecraft displays.

e. Inside-Out vs. Outside-In Displays

This term is a special case of control-display compatibility, of particular importance in aircraft, spacecraft, and submarines. The artificial horizon display shows the motion of the horizon in the cockpit as it would be seen looking out of the window. If the display horizon bar moves relative to a fixed aircraft symbol, it is an "inside-out" display. If an aircraft symbol moves relative to a fixed horizon, it is an "outside-in" display.

f. Types of Displays

In addition to the commonly used dials and tapes recently electro-luminescent displays have been used, cathode ray tubes are common in many modern display systems, three-dimensional displays are coming into use to provide the proper stimulus to spatial variables, contact analogs have been in use since 1956, and predictor displays represent another important class.

The contact analog display (see Figure 5) is a computed pictorial display which is an analog of the real world and real time situation, presented in perspective to the observer. The pattern usually includes an artificial horizon, perspective information and a textured ground plane. A flight path generator produces a commanded path for the pilot.

Predictor displays indicate not only the present condition of the vehicle, but also the expected condition of the vehicle at some time in the future if present velocities and accelerations were maintained without change. Such a prediction is based on the use of a mathematical model and a faster than real time computation. Predictor displays are discussed further in Section 5.6.

4.5 Controls

The proper design of control devices is equally important to the design of displays. Controllers may be hand or foot operated. For example, in many aircraft pedals are used for rudder control while levers are manually operated for elevator control. Typical control devices include:

- joysticks: used for attitude control in aircraft
- fingertip controllers: used for attitude control under conditions of high acceleration, such as on spacecraft
- wheels: used for steering on ships, automobiles, etc.
- thumbwheels: used for a number of purposes on aircraft as well as spacecraft, and many others.

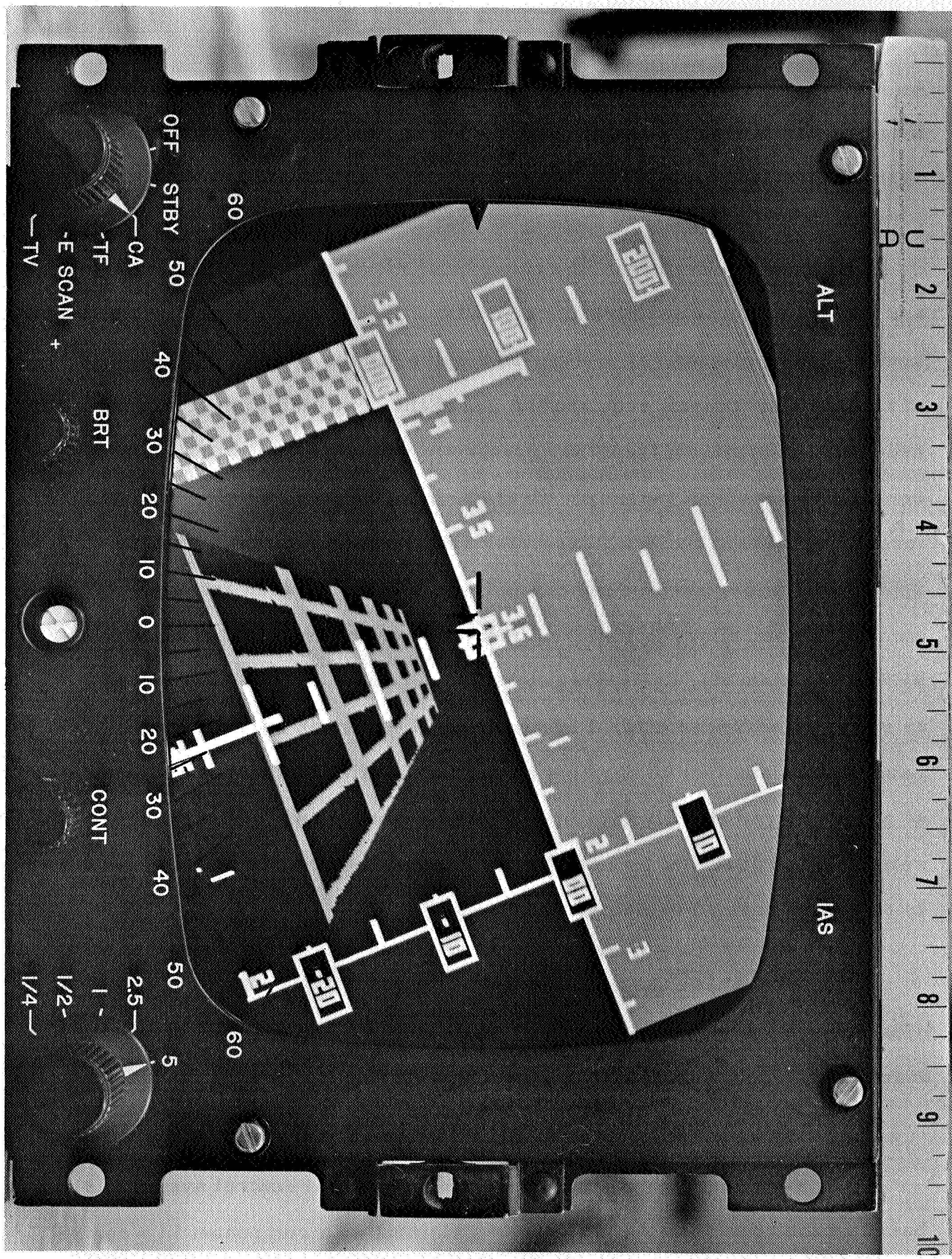


Figure 5
Typical Contact Analog Display (courtesy of Norden Division, United Aircraft Corporation)

An interesting design for a spacecraft controller [18] has made use of a three-dimensional model of the spacecraft which could be rotated to the desired orientation. Appropriate sensors then pick up the model orientation and generate the necessary signals to reorient the vehicle.

It is evident even from the above brief discussion that modern display and control systems are strongly computer dependent. The generation of a contact analog display, or a situation display for the spatial orientation of an Apollo spacecraft requires the use of the computer to generate the necessary information from the appropriate data sensors. Similarly, controls of a modern passenger aircraft, or of a space vehicle, where the forces available to the human operator require augmentation by means of appropriate power assist devices, and where the integrated action of a number of controllers is required in order to maintain appropriate flight profile and stability, again computers are necessary. It is probably fair to state that advanced control systems involving human operators will nevertheless continue to augment human capabilities by the use of computers to generate synthetic displays upon which he can act and to process the relatively low levels of force under his limited degrees of freedom in order to obtain the desired vehicle performance.

4.6 Example

Figure 6 shows the main flight display panel of the Apollo spacecraft, illustrating a variety of display devices. Figure 7 shows an experimental 3-degree of freedom fingertip controller designed by the TRW Systems Group.

5 Engineering Approaches to Manual Control Systems

The engineering approach to the study of manual control systems is based on the consideration of the human element as a component in a control

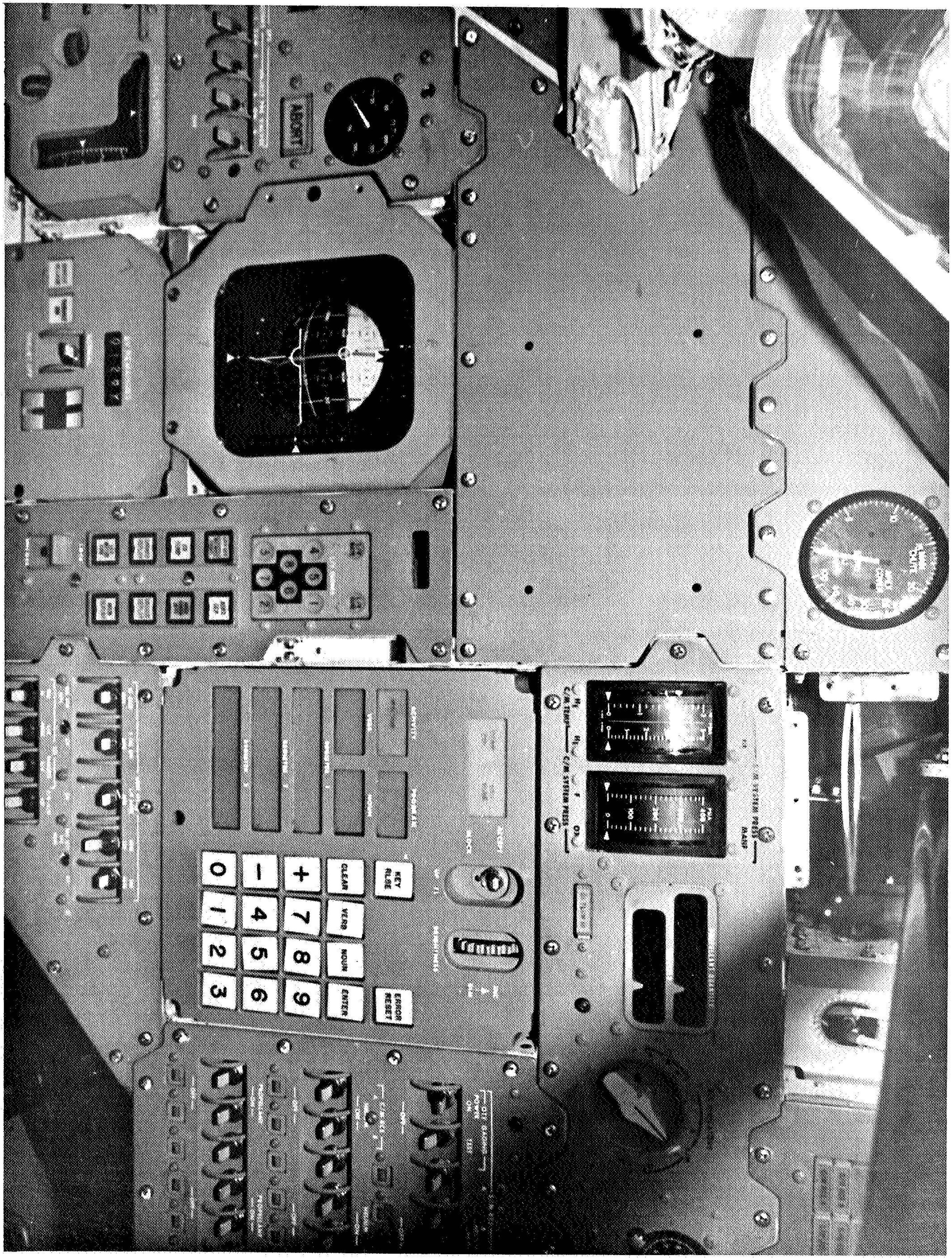


Figure 6
Display Panel of Apollo Spacecraft (courtesy of NASA Manned Spacecraft Center)

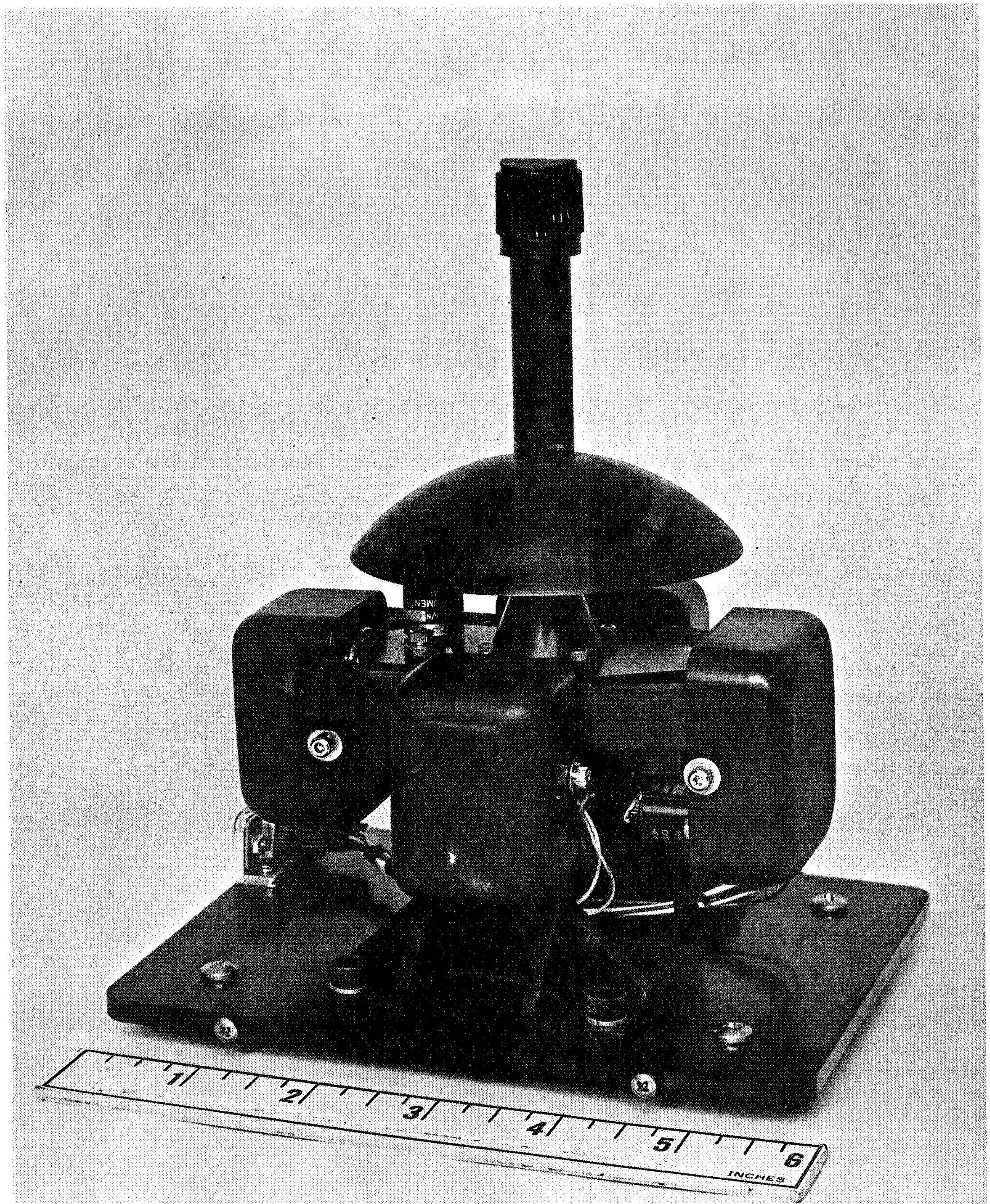


Figure 7
Experimental 3-degree of Freedom Fingertip Controller
(Courtesy TRW Systems Group).

system which could be represented mathematically (at least approximately) in order to predict the system performance. In this section, we shall review briefly the characteristics of a human controller as a system element, examine once again the question of control and display design, and sketch briefly some mathematical models of the human controller's performance.

5.1 Characteristics of a Human Operator in a Control System

The behavior of a human operator in a control system, when viewed as a system element, has been characterized by several major features [13, 14 15, 19]. These characteristics, some of which form the basis for the engineering models of human performance, were identified through the efforts of both psychological and engineering investigators. The major characteristics are the following:

a. Reaction Time

The operator's behavior is characterized by the presence of a pure time delay or transport lag, since muscular response to a sensory input connot take place instantaneously. A portion of this delay is due to transmission time along peripheral nerve fibers, a portion is due to data processing in the retina, and a portion is due to the information processing activity of the cerebral cortex. Reaction time can be clearly observed in the response to step function inputs, but cannot be measured directly in closed-loop tracking situations, where it is impossible to distinguish individual stimuli and response.

b. Low-Pass Behavior

Visual examination (and Fourier analysis) of tracking records reveals that the tracker tends to attenuate high frequencies, the amount of attenuation increasing as the frequency increases.

c. Task Dependence

The operator is able to adjust his input-output characteristics in order to perform his control function with a wide range of controlled element dynamics.

d. Time Dependence

The dependence of the operator's characteristics on time can be seen in two forms: First, his performance changes with time as he learns, and secondly, he is capable of sensing changes in environmental parameters and controlled system parameters and adjusting his characteristics accordingly.

e. Prediction

The ability of the human operator to predict the course of a target based on past performance is well known [20]. This ability to extrapolate is important in tracking since it means that tracking behavior is different with "predictable inputs" (such as sine waves or constant frequency square waves) than it is with random or random-appearing inputs. Tracking with a predictable input has been called "pre-cognitive" tracking [15].

f. Nonlinearity

For certain tasks the operator's behavior appears to be approximately linear while for other tasks his behavior is nonlinear.

g. Determinacy

A human operator is a non-deterministic system, since his performance is different in successive trials of the same experiment. However, his variability is small in situations where training time is adequate and the task is not considered difficult. Consequently, a deterministic model may be used to describe his performance in a statistical sense.

h. Intermittency

There is a considerable body of evidence which indicates that the human operator behaves as a discrete or sampling system in certain tracking operations [21].

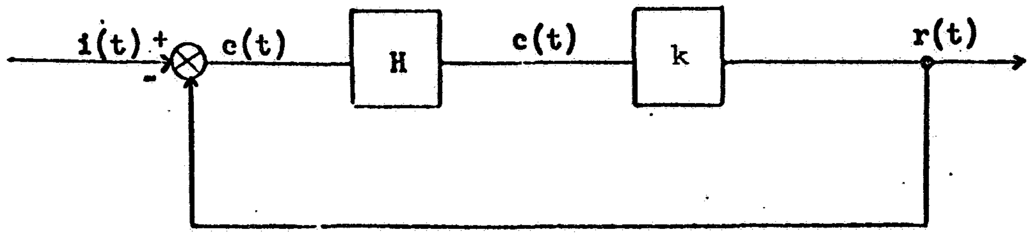
5.2 Types of Manual Controllers

In order to perform the mathematical representation of a manual control system, it is necessary to describe quantitatively the plant or controlled element, control device, the display system, and the human operator himself. The dynamics of the controlled element in Figure 3 represent a combination of the dynamics of control and mechanism. If we separate them, as indicated below in Figure 8, we can distinguish the following basic types of manual control systems.

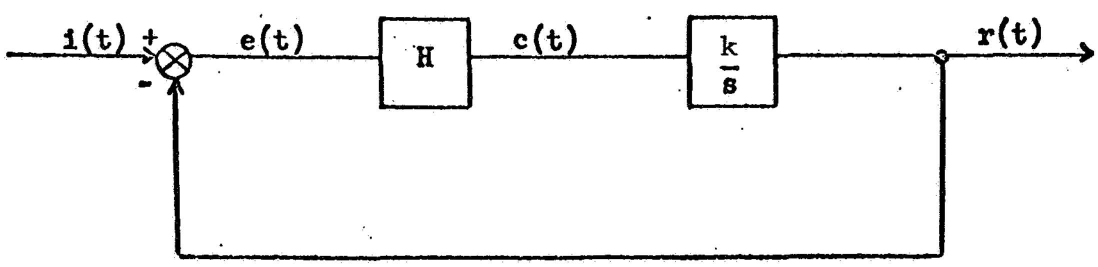
(a) Position - Position Control, in which a displacement of the control handle produces a corresponding displacement of the output. If the linkage between handle and output member is rigid (such as gear train, for example) the positional control may be instantaneous. If a power servo is introduced into the system, there may be an appreciable lag between handle displacement and output displacement.

(b) Position - Velocity Control: The displacement of the handle produces a corresponding output velocity of the controlled element; as for example, with a rheostat controlling the speed of an electric motor. This can be expressed mathematically as

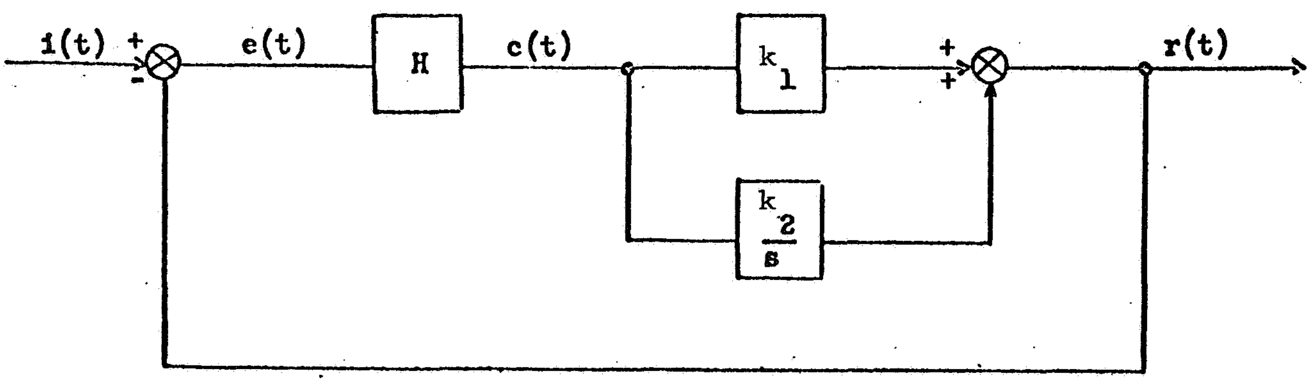
$$\frac{dr}{dt} = kc \qquad (1)$$



(a) Position Control



(b) Velocity Control



(c) Rate-aided Control

Figure 8

Simple Manual Control System

where c and r are the control and output motions respectively, as indicated in Figure 8 and k is a constant. It should be noted that the motion of the output is now given by integration of input displacement, i.e.,

$$r(t) = k \int c(t)\, dt \qquad (2)$$

(c) Position - Acceleration Control: The displacement of the control handle produces a corresponding output acceleration, or

$$\frac{d^2 r}{dt^2} = k\, c(t) \qquad (3)$$

(d) Rate - Aided Control: The control handle displacement can give the output not only a proportional displacement but an increment of velocity as well. In this case we can write,

$$r(t) = k_1\, c(t) + k_2 \int c(t)\, dt \qquad (4)$$

The basic control configurations are illustrated in the block diagrams of Figure 8, where H represents the human operator, and s is the complex frequency.

Thus, for example, if a displacement of a knob results in the proportional increase in the speed of a motor, this is evidently a rate control device. On the other hand, if an angular displacement of a joystick produces a proportional angular change in an elevator surface of an aircraft, this would be refered to as a position-position control.

5.3 Controller Dynamics

The control devices themselves may include nonnegligible inertia, damping, and may or may not be spring restrained. For example, many hand controllers are so constructed that in a "hands-off" situation, springs return it to a center null position. If one considers man's primary output as force, applied to a controller with non-negligible dynamics, then the displacement resulting from a force input will be described by the equation

$$I \frac{d^2x}{dt^2} + B\frac{dx}{dt} + kx = f(t) \tag{5}$$

where I is the controller inertia, B is the controller damping coefficient, K is the controller spring constant, x is the resulting displacement, f(t) is the force input. The selection of a control device can be viewed as a selection of the magnitude of the terms I, B, and K in the above equation. As we shall see below, the selection of control devices has an important bearing on system stability and thus on the kind of compensation which must be introduced for stable operation, either by the designer or by the control strategy of the operator himself.

The controller dynamics indicated by equation(5) above are based on the assumption that the controller is linear. In many control system applications this is not true. For example, on-off switches, bang-bang controllers and similar devices produce no output until the controller displacement exceeds some specified amount. In other controllers the output may be proportional to an input force over a given range, after which limits are encountered. These are nonlinear effects which further complicate the analysis of both stability and human performance in manual control systems.

5.4 Performance Criteria

If one examines the compensatory tracking scheme, of the type illustrated in Figure 7, it is evident that a measure of the operator's tracking ability must be based in some way on the loop error, indicated by e(t) in the figure. Common measures which have been used in the past include the following: [26]

a. Time-on-Target

This is simply a measure of the fraction of time during which the tracking error remains within a specified distance of the desired zero error or center of the screen. It can be accomplished by scoring the tracker's performance on the basis of the percentage of time during which a dot on the oscilloscope screen remains within a small circle of specified radius.

b. Mean value of error

The mean value of error is defined as

$$\overline{e} = \frac{1}{T} \int_0^T e\,dt \tag{6}$$

where T is the time interval over which the averaging is performed. It is evident that the mean value of the error can be zero, while the tracker's performance may in fact involve instantaneously large excursions away from zero. However, this criterion is useful in revealing the possible presence of a bias, positive or negative, in the error signal.

Mean square error is defined by

$$\overline{e^2} = \frac{1}{T} \int_0^T e^2\,dt \tag{7}$$

It can be seen that this error criterion penalizes large errors much more severly than small errors, because of the squaring operation.

A question of some interest in the study of manual control systems has been to determine whether the above or any similar criterion can be used to judge the quality of a man-machine system. There is some evidence to indicate that manual control systems which are judged by the operator as vastly different in quality nevertheless yield similar values of mean square error. Scales such as the Cooper Rating Scale [10] which are used as a subjective measure of a pilot's evaluation of an aircraft control system, show very little correspondence with the mean squared error. It may be hypothesized that pilots control their craft in such a way as to minimize the mean square tracking errors, but that depending on the aircraft design this minimization may require considerably different degrees of effort and concentration on the part of the pilot. A quantitative approach to this difference of tasks is provided by the use of mathematical models of pilot performance, which are discussed in Section 8.6 below.

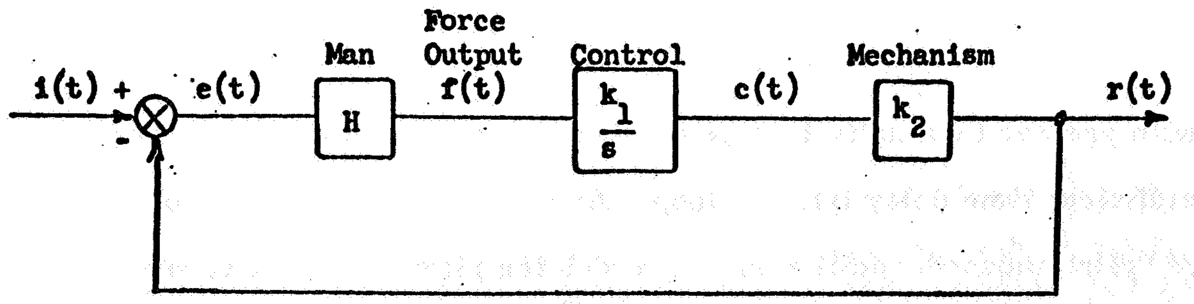
5.5 Stability Criteria

From a control system point of view, a system is defined as stable if an error due to temporary disturbance does not continue to grow indefinitely. A system is defined as asymptotically stable if the errors resulting from a disturbance progressively decrease to zero. If a system is unstable, any input disturbance will either cause the output to grow without limit or will cause it to oscillate it with progressively larger amplitudes. In a completely linear system the stability criteria can be formulated mathematically quite simply. The presence of the human operator, however, renders the problem considerably more complex. Man has a sensory threshold. This dead zone may result in a small amplitude oscillation, with the error oscillating within the threshold region, which is known as a limit cycle. If a threshold is a small proportion of the total excursion allowed, the system can still be stable insofar as large input signals are concerned. In addition, man's reaction time introduces a finite time delay into a system. It is easy to shav that any stable system with greater than unity loop gain can be made unstable by the insertion of sufficient time delay into the loop. An example of this situation is a problem of "pilot-induced-oscillations" in which the pilot's corrective maneuvers are always too late to check the increasing amplitude of oscillation of his aircraft, and his attempt to control it results only in larger and larger oscillation. In some cases, the solution to pilot induced oscillation is simply for the pilot to abandon all attempt to control, relying upon the damping effect of the atmosphere and the structural design of the vehicle to reduce the oscillations. In other words, a human controller by his very presence introduces de-stabilizing effects into a control system which require compensation to insure stability. Hence, the human operator is required to adjust his performance strategy (or, in mathematical terms, his gain and other parameters), in order to produce optimum response consistent with stability.

5.6 Compensation

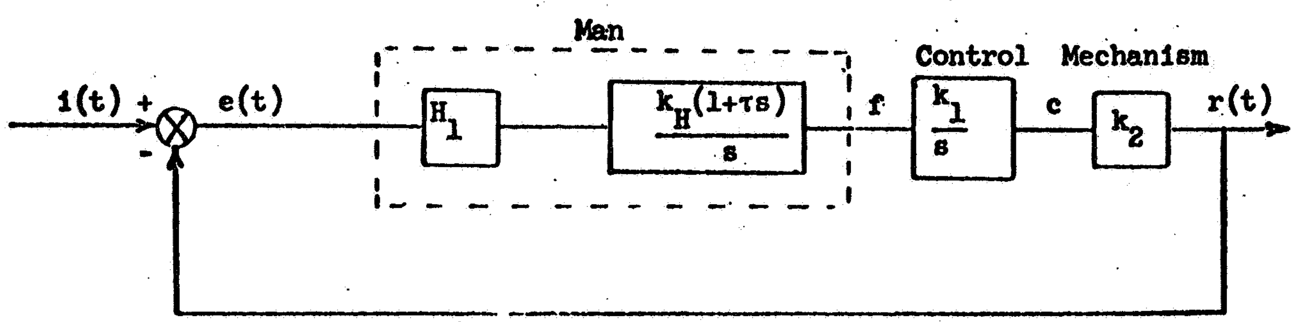
Consider a tracking task in which the operator is required to follow a constant velocity input (a ramp signal) with zero error. It can be shown [22] that the design of such a system requires at least two integrations in the forward loop. Let us now assume that the controlled system or mechanism has negligible dynamics and can be represented simply by proportional factor, and that the man is provided with a damped joystick which introduces a single integration into the system. This situation is depicted in figure 9a. The requirements on the man's tracking strategy can now be stated from a servo point of view as follows:

(a) the man must introduce at least one integration in order to be



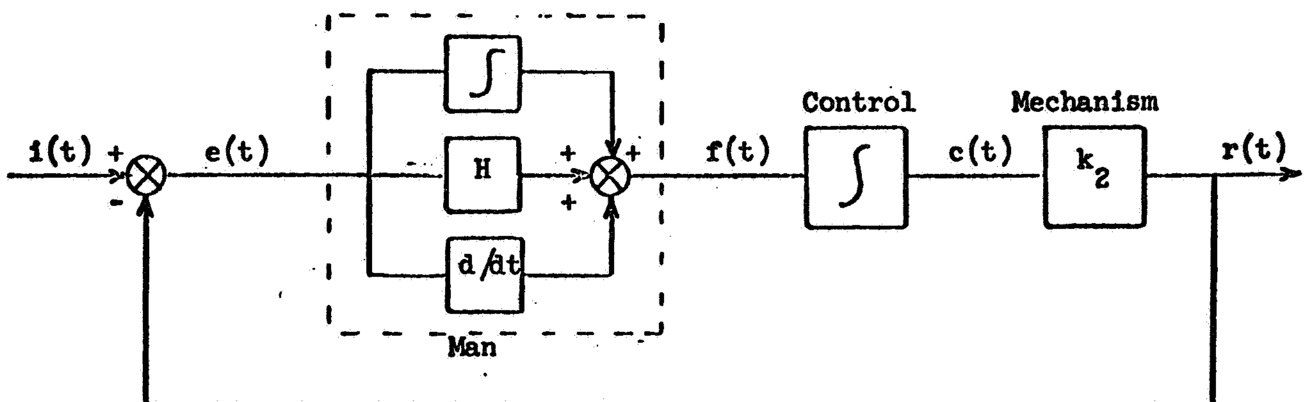
(a)

Tracking loop with damped control



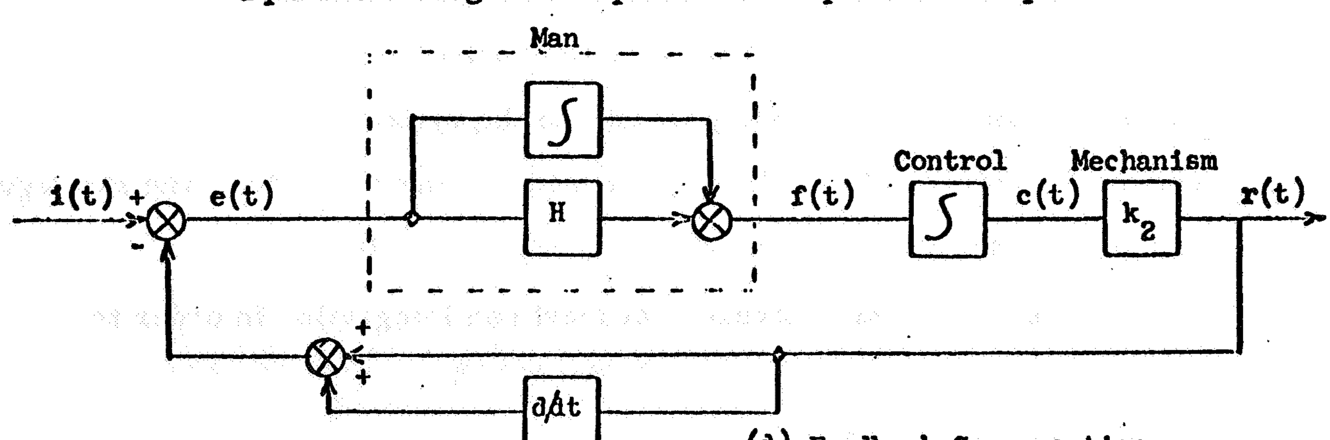
(b)

Compensation required of human operator



(c)

Equivalent diagram of operator's compensation requirement



(d) Feedback Compensation

Figure 9
Human Operator Compensation

able to maintain zero error as desired.

(b) a system with two integrations and time delay (reaction time) can be shown to be unstable.

(c) hence the man must also introduce some anticipation, in the form of a derivative term which introduces "lead" into the control system. Hence the human controller is required to introduce an integral and a derivative term to maintain the desired system performance (as shown in Figure 9b), in addition to whatever subjective additional criteria he may use.

Evidently, a human controller does not literally perform the operations of differentiation and integration in a mathematical sense. Nevertheless, his tracking strategy, learned by experience and practice, results in control signals which can be closely approximately by those devices which have the required compensation characteristics. It is intuitively clear that the more complex the mathematical operations required of the operator are, the more "difficult" the task will be, and the longer it will take to acquire the necessary skills. In a classical paper, Birmingham and Taylor [23] have suggested that an ideal criterion for the design of man-machine systems is to insure that the human operator's task reduces to that of a simple amplifier, i. e. that he is required to perform no integrations and no differentiations. (It may of course be argued that in this case, from a system point of view, it may be more economical to replace the human operator by a simple amplifier, as has in fact been the case in many systems.)

Relieving the operator of the necessity of differentiating or integrating is generally known as aiding. The removal of differentiations from the task is called "quickening". Figure 9c shows a derivative term inserted into the feedback loop of a system. When this is done the operator no longer sees the actual system error, but rather an error signal which includes some element proportional to the rate of change of the control variable. In some cases such derivative terms can be added directly to the display devices, as indicated in Figure 9d. This type of display is termed a rate-aided display.

An aided display is anticipatory in the sense that it provides the operator with the knowledge of the results of his own actions. This anticipation is not true prediction, however, since it does not take the dynamics of the controlled element (airplane, or submarine for example) into account. The inclusion of error derivatives in the display simply indicates to the operator the trends resulting from his actions and thus prevents excessive overshoots. Actual prediction can be obtained if the display is produced by a computer which uses a mathematical model of the system to compute its behavior. The display may then show, for example, the predicted error at some time in the future, as calculated by the computer. Clearly, the accuracy of prediction depends on the adequacy of the equations representing system behavior. Predictive displays are considerably more complex than aided displays but they further simplify man's task and tend to null the reaction time. A predictive control system is shown in Figure 10. Predictive displays have been extensively studied by Kelley [4, 24] who has used them with considerable

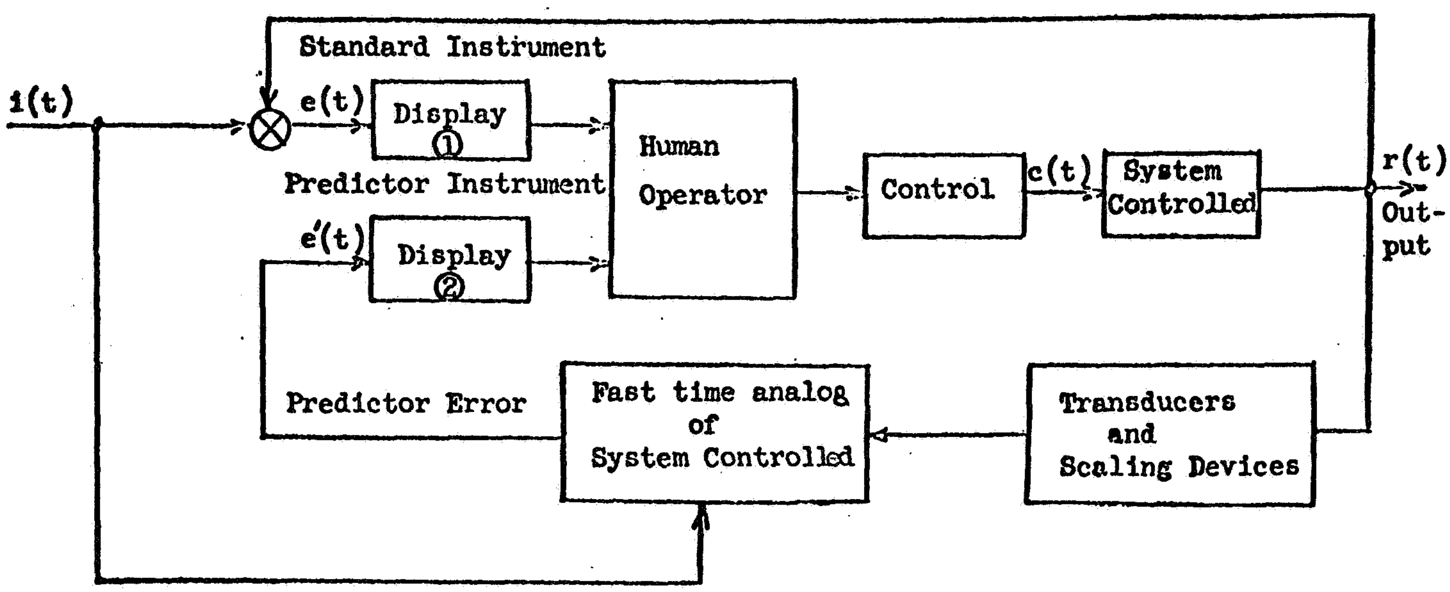


FIGURE 10

Predictive Control System Block Diagram

success in a variety of applications. Typical three-trace predictive displays during a submarine dive are shown in Figure 8.11.

5.7 Summary: The Operator's Function

In the above paragraphs some of the characteristics of manual tracking systems have been reviewed. The relations of the human operator to the dynamics of control and mechanism were discussed. It was shown that performance and stability were system functions, depending on the man as well as the machine, and on the communication links between them, namely, the display and control. If the operator is required to provide a complex computing function, he can do so only at the expense of increased reaction time, i.e., reduced system bandwidth. Methods of alleviating the man's computational task were discussed.

It may now be relevant to ask why the operator should be included in the loop at all when all the complex functions are taken away from him. There are several answers to this question. In the first place, even with all differentiating and integrating operations removed, the human still does not act as a "simple amplifier" [23, 25, 27]. He is still required to translate sensory inputs to motor outputs, i.e., meter deflections or spot displacements to crank motion. Clearly, this function is at least that of a transducer, rather than an amplifier. If the task calls for simple amplification, an electronic amplifier may be able to provide this function more efficiently than a man.

Secondly, even if the simple block diagrams do not show this, man's function in the loop is more complex and demanding than that of an information translator. Man is capable of detecting quite efficiently a signal

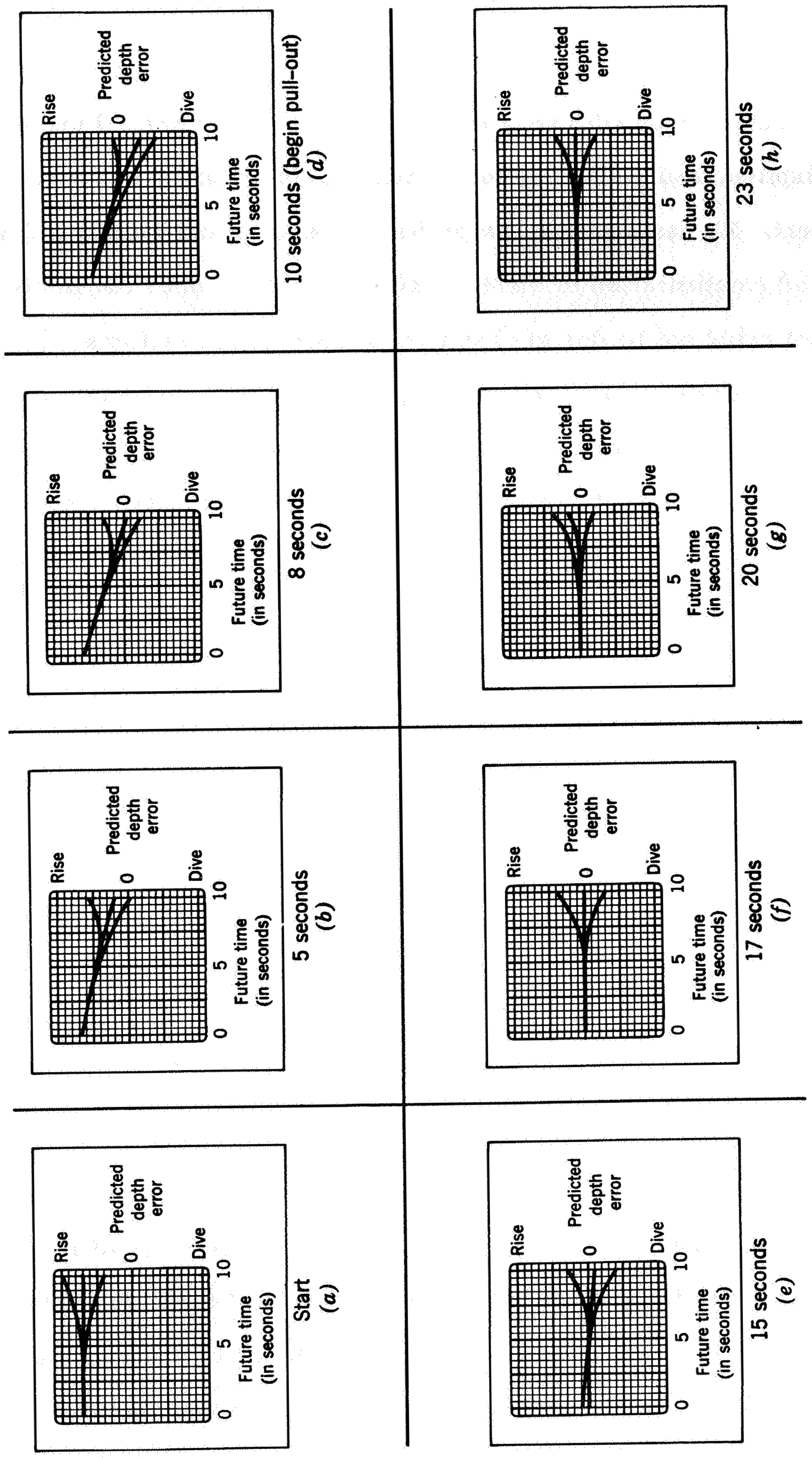


Figure 11
Typical Traces from a Predictive Display (Reproduced from Manual Control, by C. R. Kelley; Wiley, 1968, with permission from the publishers).

masked by noise, even with very low signal-to-noise ratios. Furthermore, man is adaptive, and his ability to function can be adjusted to the task requirement. He can monitor low probability events and quickly adjust his gain and compensation to meet the situation. This does not imply that an autopilot could not be designed to perform all these functions. It merely says that the versatility and adaptability of man make him a desirable component of many control situations, not merely to amplify, but to translate, interpret, compute, modify, plan, predict, guess, or perhaps to react, with his usual cussedness, in an unpredictable manner.

6 Mathematical Models of the Human Operator

6.1 Statement of the Problem

Thus far in the development of this chapter we have reviewed some of psychophysiological characteristics of the human operator in a tracking situation, and briefly analyzed several tracking situations from the point of view of performance and stability. It is clear that the human component is the limiting factor in the tracking loop. Adequate compensation cannot be designed unless the operator's behavior can be expressed in mathematical terms, thus making the whole loop amenable to analysis.

Several types of models have been proposed. The easiest model to formulate and use is a linear model with constant parameters. Unfortunately, such models cannot account for the nonlinear and adaptive behavior of man. Quasi-linear describing functions with various types of remnants are rather complex to evaluate but give good agreement with experimental data. Nonlinear and adaptive models can be formulated, but require computer simulation, since general techniques for the analysis and synthesis of nonlinear systems are not available. A stochastic model [29] has been proposed, which promises to give excellent results in terms of probabilities of certain events, but cannot give transient response information directly in the time domain. Sampled-data models have been suggested, which give some promise of representing correctly the intermittency and "refractory period" of the human operator [21].

In recent years the quasi-linear describing function models have been further developed to include some representation of the neuromuscular portion of the operator characteristics [31]. In addition thre has been considerable emphasis on obtaining mathematical models of human operators in multi-loop and multi-instrument tasks [28], as well as on attempts to describe the adaptive and learning characteristics of human controllers. A few of the salient points of some of these models will be described in the following paragraphs.

6.2 A Quasi-Linear Describing Function Model

This technique of representing human operator dynamics was pioneered by McRuer and Krendel [30] and is widely accepted as a representation of human performance in many aerospace systems. Basically, this is an engineering-oriented approach to modeling in which the operator characteristics are represented by the sum of two terms, as illustrated in Figure 12. The first term is a linear differential equation, chosen in such a way that it is the best possible linear approximation to the operator's response, (in the sense of minimizing the mean-square error of approximation). However, in this describing function the coefficients are constant, while human operator characteristics change with changes

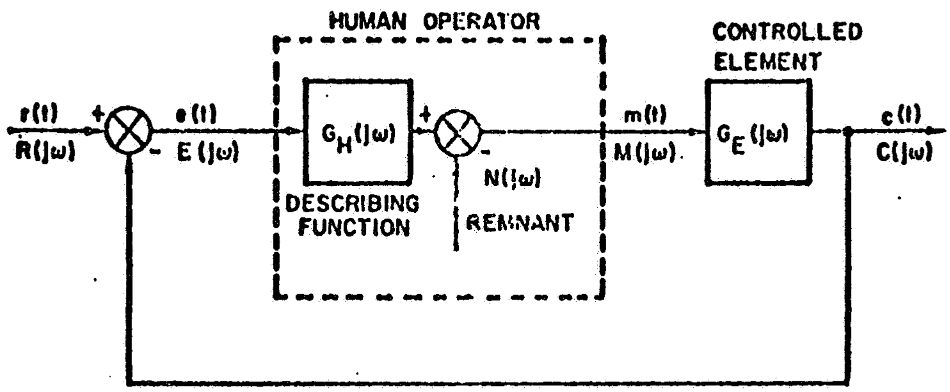


Fig. 12 Quasi-linear model of human operator

in the environment as well as with variable processes within the operator himself. Hence the describing function does not represent the totality of the human operator's output and the model includes an additional term known as the "remnant" which includes all those response components which are not linearly correlated with the input to the control system. These are assumed to be due primarily to time varying elements in the operator's characteristics and, to a lesser extent, to a human operator's nonlinearities. Commonly, the describing functions are measured by using spectral analysis techniques [30] under conditions where the operator tracks a random-appearing sum of non-harmonic sinusoids. An alternative method of determining the describing function by means of linear regression or "measurement by mimicking" was pioneered by Elkind [32]. In general, in the frequency domain, the describing function takes the form:

$$G_H(j\omega) = \frac{K(1 + T_L j\omega)e^{-\tau j\omega}}{(1 + T_I j\omega)(1 + T_N j\omega)} \tag{8}$$

where τ is the reaction time, T_M is an approximation to the neuromuscular system time constant, and T_I and T_L are representations of the compensation introduced by the operator to the system to maintain stability and satisfactory response. K is a gain factor, and ω is the frequency variable.

This model is known as "quasi-linear" because the values of the coefficients in equation (8) depend on the controlled element dynamics and on the nature of the forcing function. It has been shown that the human operator adjusts his open loop gain K to correspond to the gain of the controlled element so that the closed loop gain will be unity in the frequency range being tracked. The gain adjustment appears to be a function of individual training and motivation in each particular task. The equalization terms T_I and T_L have been shown to vary in an adaptive manner depending on the controlled elements. The adjustment rules used by the human operator have been summarized by McRuer and Graham [35] as follows:

a) the human adapts so that the gain and equilization characteristics are appropriate for stable control and

b) the human adapts so that the form of equalization characteristics is appropriate for good low frequency closed loop system response to the forcing function, in a sense of controlled system performance.

It has been shown that the parameter values of the human describing function vary with learning and become stabilized only after many hours of learning trials. For highly experienced aircraft pilots, the parameters have less variability and the lead time constants are larger. Detailed discussions of quasi-linear describing functions may be found in the literature [27].

6.3 Adaptive Behavior of Human Operator

The adaptive behavior of human controllers has been the subject of considerable research. In fact, it is this adaptability which makes the human controller a desirable element in space vehicles and other advanced systems. For example, it is known that a human pilot of a high performance jet aircraft is capable of modifying his control strategy within two to five seconds following the failure of the stability augmentation system. As an example of a recent study which attempts to model the adaptation strategy [33] consider the flow chart of Figure 13. This flow chart depicts a sequence of decisions made by the human controller on the basis of his observations

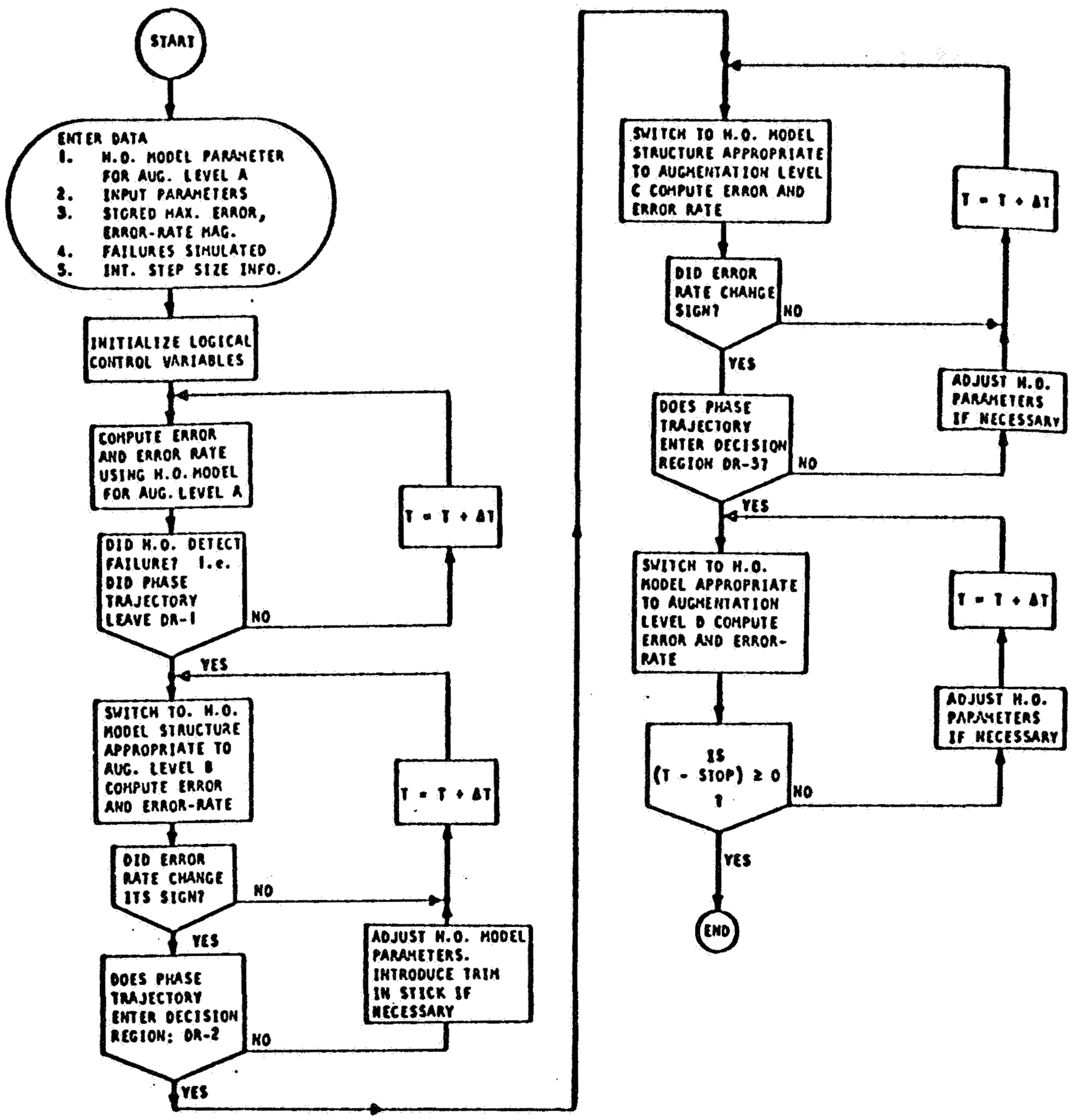


Figure 13 Flow Chart of Supervisory Control Algorithm for Set 1 Experimental Situation

of the tracking error, and the rate of change of the tracking error. On the basis of these observations he makes choices between various pre-stored control strategies, always testing the response against learned stability and performance criteria, until adequate performance is achieved. Studies by Elkind and Miller [34] have pursued the questions of adaptation and learning in considerable detail, using learning theory and Bayes rule statistics.

7 Simulation of Man-Machine Systems*

One of the most important areas of application of the simulation method is in the study of systems in which a human being participates, either as an element of the system such as the pilot of a vehicle or as a passenger whose tolerance to environmental characteristics is limited. In the design of piloted vehicles simulation techniques are so prevalent that in some quarters the word "simulator" is reserved for this type of activity.

7.1 Characteristics of Manned Simulation

Simulation involving man includes all the characteristics of unmanned simulation with the following additional ones which are introduced by the particular characteristics of human performance:

(a) Human performance is inherently time varying. There is variation of successive trials of the same task by the same operator and there is a variation in the responses of several operators trying the same task.

(b) Human response includes elements which are apparently not determined by the input and can only be accounted for by

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*A portion of this section is based on a chapter entitled "Simulation", by G. A. Bekey and D. L. Gerlough, in Handbook of System Engineering, edited by R. E. Machol, McGraw-Hill, 1964.

statistical descriptions. Consequently, the description of systems involving human operators must make use of statistical methods and the resulting descriptions will be in some sense statistical averages defined over particular populations.

(c) The inherent variability of human performance implies that many repetitions of each particular experiment must be tried.

(d) Simulation studies involving human operators must be run in real time whereas studies involving inorganic elements may be run in an accelerated time scale in many cases.

(e) The simulation method and the experimental situation must be selected in such a way as to avoid any possible injury to the operators involved.

Simulation of manned systems takes on two primary forms: envoronmental simulation and man-in-the-loop simulation. Environmental simulation involves creation of an environment which reproduces one or more unusual situations in which human beings may find themselves in a system undergoing design. Man-in-the-loop simulation involves an interaction between man and equipment. Both of these types of simulation will be examined briefly in the following paragraphs.

8.7.2 Environmental Simulation

Environmental simulators are needed because human beings are often subjected to environments drastically different from those of ordinary life. For example:

(a) Man may be exposed to situations where high temperatures and high levels of pressure are involved such as in certain types of mining or underground operations.

(b) Man may be asked to undergo long periods of weightlessness such as those occurring in interplanetary flight.

(c) Man may be asked to operate in atmospheres of different composition to that of his normal habitat.

In order to test the adequacy of the proposed design techniques and to insure human survival it is absolutely necessary to simulate the particular characteristics of this environment before a completed vehicle is constructed. Generally, a characteristic problem in the design of such simulators is the selection of the particular quantities or variables to be investigated. For example, it may be decided to construct a simulated space cabin for an interplanetary voyage in which human passengers may be subjected to temperatures, radiation levels, and illumination levels similar to those encountered in the actual flight. It may, however, be decided to avoid any attempt to simulate the gravitational environment of free space. On the other hand, other simulations may involve attempts to examine the ability of operators to perform certain tasks under conditions of reduced gravity and certain kinds of supporting harness structures have been used for this purpose. Note that the decision of what is simulated and what is omitted, what is important and what is negligible rests largely with the designer.

Environmental simulation has included the following major characteristics:

(a) Temperature simulation: Variable climate chambers and hangars have been constructed, some with temperatures which range from -300 to +1000°F. The dimensions of such a chamber may range from a cell barely adequate to accommodate one man to a chamber of sufficient size to accommodate an entire airplane or space vehicle.

(b) Acceleration: The effect of acceleration and deceleration on human operators and passengers is usually measured using centrifuges and rocket sleds which are capable of imparting wide ranges of acceleration and deceleration. For example, the human centrifuge at Johnsville, Pennsylvania has a cabin located at the end of a 50 foot arm. The centrifugal acceleration to which the operator is exposed may reach 40 and 50 g's. Rocket sleds, such as one located at Edwards Air Force Base, may provide acceleration as high as 50 or 60 g's.

(c) Unusual atmospheric conditions: Altitude chambers and environmental chambers have been constructed with a capability of generating ice and snow with atmospheric conditions ranging from sea level to 100,000 ft. altitude. Simulated desert sand and dust storms can be generated in certain simulators. Humidity ranges from 0 to 100%, salt spray, tropical rain storms and similar unusual conditions have been produced in the laboratory.

(d) Vibration: Simulators have been constructed which provide vibration and shock excitation ranging from 5 to 2000 cycles as well as random vibration sources with various spectral characteristics. Shock in the range of 0 to 100 g's and of various durations has also been simulated.

(e) Zero gravity: Conditions of null or zero gravity have been simulated in airplane cabins while the airplane flies a particular type of trajectory known as a parabolic flight, during which gravitational and centrifugal accelerations exactly cancel, resulting in periods of weightlessness. Zero g has also been simulated by spinning a man submerged in a fluid.

(f) Lack of atmosphere: The lack of atmospheric friction and resistance in space for the performance of particular taks has been simulated by means of minimum friction air bearing tables.

(g) Complete cabin simulations: A number of tests have been and are being performed in which simulated space cabins including complete closed-cycle ecological systems have been constructed. Human volunteers have stayed under simulated space cabin conditions for a number of days. In many cases such simulated cabins have included temperature, atmospheric composition and other aspects of the environment in simulated form.

Other environmental simulators have been constructed for the testing of equipment which does not involve human operators. Such simulators include methods for determining the effect of extreme levels of solar radiation, nuclear explosion effects and so forth.

Since no simulator takes into account each and every effect encountered by a human operator or a human passenger in a particular task, the addition or superposition of effects observed in various portions of the simulation must be handled with great care. In many cases a simple linear superposition of effects may not be valid.

8.7.3 Flight Trainers and Piloted Simulators

Where a human pilot performs control or guidance functions in the operation of a system some form of simulation is essential during the design phase. The simulation may be entirely an analog simulation, since in a control task the operator's input and output are generally continuous, or it may be a partially or entirely digital simulation, in which case some form of analog-to-digital and digital-to-analog conversion may be required. In the design of flight control systems the simulation generally becomes some form of physical simulation in which there is an interrelationship between a human pilot, an actual or simulated portion of a vehicle control system (including manual controls, displays, dials, knobs, and so forth) and a general purpose computer (analog or digital) which provides inputs to the cockpit and operator which represent the variation of environmental characteristics during a particular flight mission. Where the pilot responds to simple dial movements a general purpose or a special purpose computer may be adequate to provide the input signals. Where a more realistic simulation of the external environment is required, more elaborate equipment is also necessary.

Attempts to overcome various of the limitations of the fixed-base laboratory simulator of the type discussed above have resulted in a variety of more complex and generally considerably more costly simulators. These include the following:

(a) The moving base simulator: The simulated or actual cockpit is mounted on gimbals, suspended on chains, mounted in a sled, or supported in other similar fashion and subjected to movement similar to that which would be encountered during the actual mission. It should be noted in particular that all moving base simulations involve limitations of dynamic range and consequently may result in faithful movement over only certain particular ranges of angular or linear displacement. Furthermore, motion cues may be misleading since in the laboratory situation a pilot in a simulated space mission will be subjected to the motion in space without the gravitational environment of space and the effects upon his performance and physiological well-being may be different.

(b) The variable stability airplane: In an attempt to provide a more realistic simulation of flight control systems of vehicles under investigation, certain airplanes, helicopters, and other vehicles with adjustable handling characteristics have been developed. These vehicles include an airborne computer, analog, or digital, which alters their handling characteristics in order to simulate the performance of the system under design. Many such variable stability aircraft have been built and they have proven to be an invaluable research and design tool in the aircraft industry. In fact, the simulation of certain phases of re-entry from space has been and can be accomplished using the variable stability aircraft as a simulator.

(c) Increasing sophistication in physical simulation: It is possible to include in the simulation a whole range of equipment from a simple simulator cockpit to a complete mockup of the actual vehicle. In airplane simulators, for example, it is not uncommon to include not only the cockpit itself, but also the servos, actuators, tail assemblies, hydraulic mechanisms, and similar devices as portions of the simulation in order to insure that the performance of the pilot will not be distorted by a possibly inaccurate mathematical description included on a computer.

It is clear that simulation in one form or another is essential for the development of manned vehicles since it is important to subject man to simulated conditions before exposing him to actual and possibly hazardous operating conditions. Thus manned simulation has a dual purpose, as a research tool and as a design tool. As a research tool it enables us to determine conditions which will govern the design of future systems by providing envelopes of satisfactory performance. As a design tool they are invaluable by proving the absolutely necessary verification by human subjects of a proposed system configuration. It should be noted, however, that simulation cannot and should not be a substitute for design.

8.7.4 Computers Used With Manned Simulators

It has been noted above that some form of computer is required to generate the input signals to the cockpit and process the pilot's output signals in accordance with a predetermined mission such as a particular flight trajectory, a landing on a carrier deck, or a re-entry from space. Historically, analog computers have been used for flight control simulators for two reasons: (a) bandwidth requirements, since the mission characteristics as well as the input and output signals contained frequencies sufficiently high so that real time digital computation was impossible and (b) accuracy compatibility, since in many cases the physical characteristics of the air frame and the atmosphere were only known to levels of accuracy compatible with those of analog elements. Recently, the picture has changed for two reasons: first, the increasing speed of digital computers has made possible the real time digital simulation of certain portions of aerospace missions, and second, airborne digital computers are being used to an increasing degree to handle the complex levels of data processing and computation which are characteristic of modern high performance aerospace vehicles. Consequently, it is expected that an increasing use of digital computers in flight simulators will be seen in the future. In many cases, this simulation will take the form of the utilization of hybrid analog-digital equipment. A typical example of a man-machine simulator used for the study of space vehicle docking maneuvers is shown in Figure 14.

Figure 14
Block Diagrams of Apollo Mission Simulator (courtesy of NASA Manned Spacecraft Center)

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