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DISCUSSION OF MANUAL CONTROL PROBLEMS

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DISCUSSION OF MANUAL CONTROL PROBLEMS

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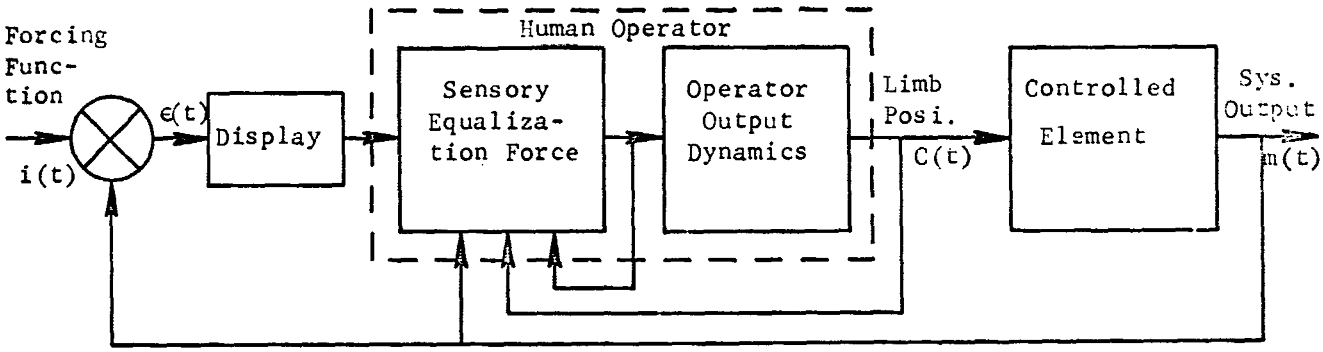
In compensatory tracking, the operator observes and corrects the error, which is the difference between a commanded state and an existing state. In a pursuit system, the operator is presented with the error

Compensatory Tracking



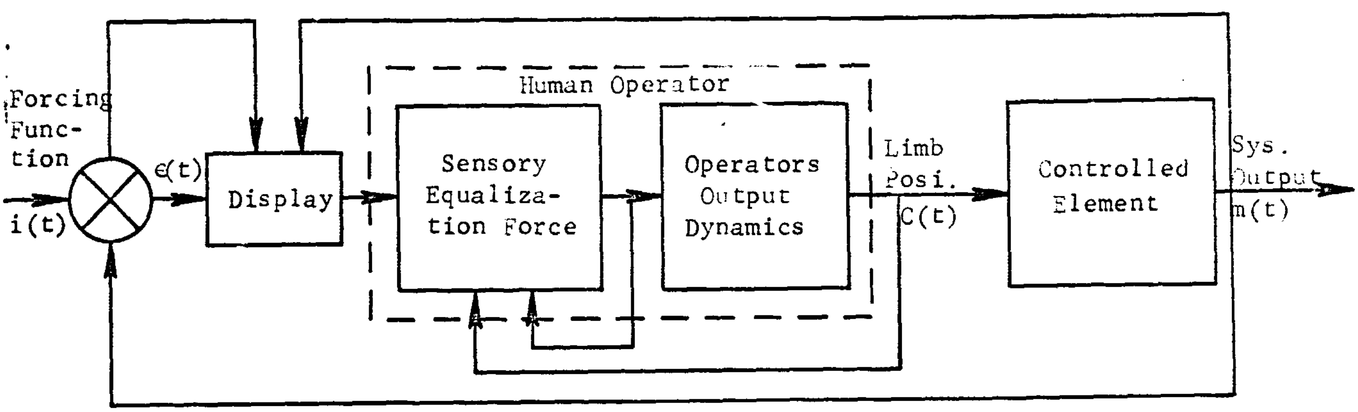
$\epsilon(t) = i(t) - m(t)$ where $i(t)$ is the system input

$m(t)$ is the system output

$\epsilon(t)$ is the error term.

term plus the system input and output. The operator selects the things he will respond to. He may or may not choose to anticipate a control motion's requirement and apply a correction before the error exists. This can result in a negative delay time. Switching back and forth of course makes the pursuit system much more difficult to analyze than the compensatory system.

Pursuit Tracking



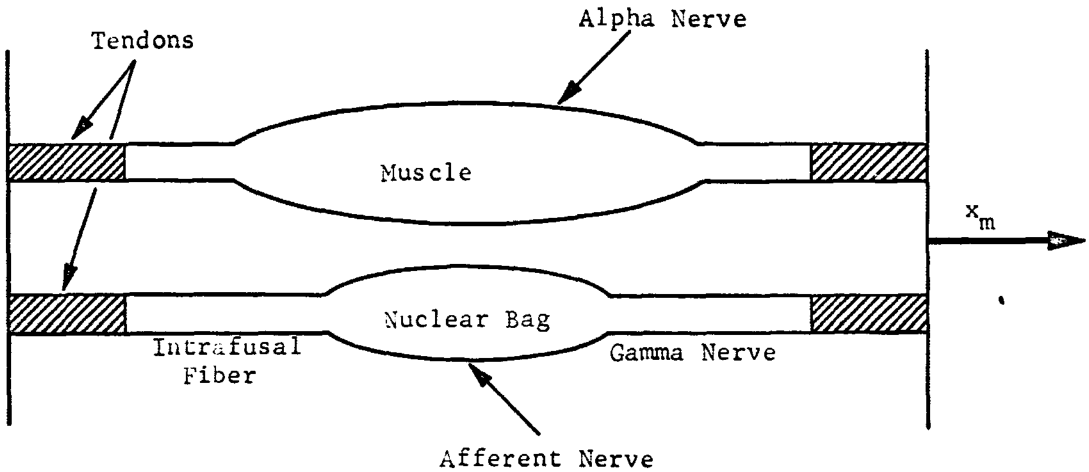
$\epsilon(t) = i(t) - m(t)$ where $i(t)$ is the system input

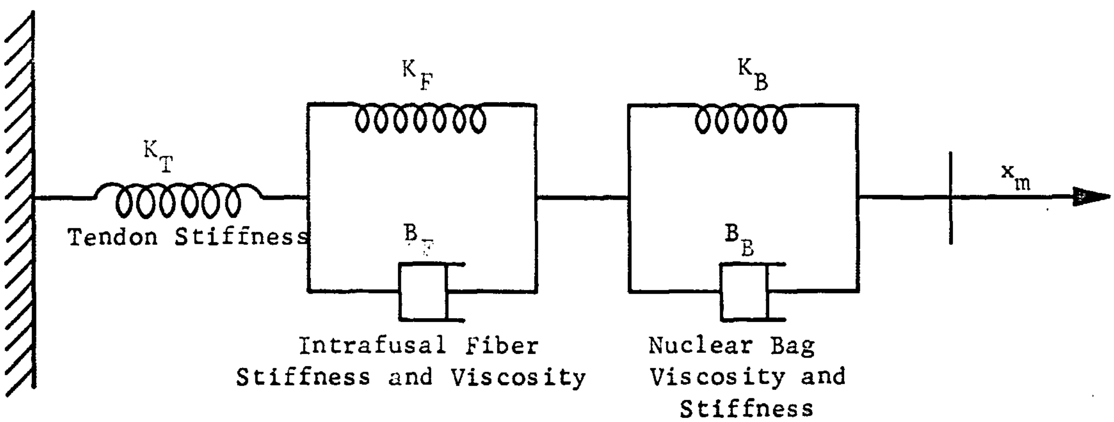
$m(t)$ is the system output

$\epsilon(t)$ is the error term.

II. MOTOR COORDINATION

Fulton and Pi-Suner demonstrated that there is a muscle spindle receptor in parallel with contractile fibers of muscles [1]. A differential length receptor, its importance in human motor coordination is great. Its positional feedback characteristics are basic to the stretch reflex, and it may send kinesthetic information to higher centers to help control complex motor coordination tasks. A model of this mechanism is shown below.





The direct mechanical effect of the spindle on the muscle is negligible. Also the inertial forces resulting from accelerating the mass of the muscle may be neglected in comparison with elastic forces. The length of the muscle, X_m, can be considered to be an input produced either through the alpha nerve or through stretch by external forces. The afferent nerve informs the control nervous system about the length of the nuclear bag. The gamma nerve excites the contractile element, or intrafusal fiber of the spindle. It is another input that may bias the output of the nuclear bag, or it may act indirectly as an input to control movement of the muscle. This follow-up servo configuration has been suggested by Merton and Roberts [2].

Lippold, Nocholls and Redfern [3] found the response of the spindle receptor to a step input of stretch to show approximately 400 percent overshoot. After approximately 200 m sec the output settles down to its steady state values. According to Young and Stork [4] the steady state gain increases with increased gamma bias; also the gamma bias has a role in maintaining sensitivity of the spindle to stretch. The spindle system, having a differentiating action over the frequency range of 1/2 to 3 cps, acts as a damping element in movement. The spindle is an ideal damping element, and the gamma bias which sets its activity level and gain is well suited to modify the system damping on command in an adaptive fashion. This adaptive nature of man makes him well suited to participate in the control of any system which will tolerate his slow response time. In situations where slow response time is critical, man's adaptive ability can be valuable when things start going wrong.

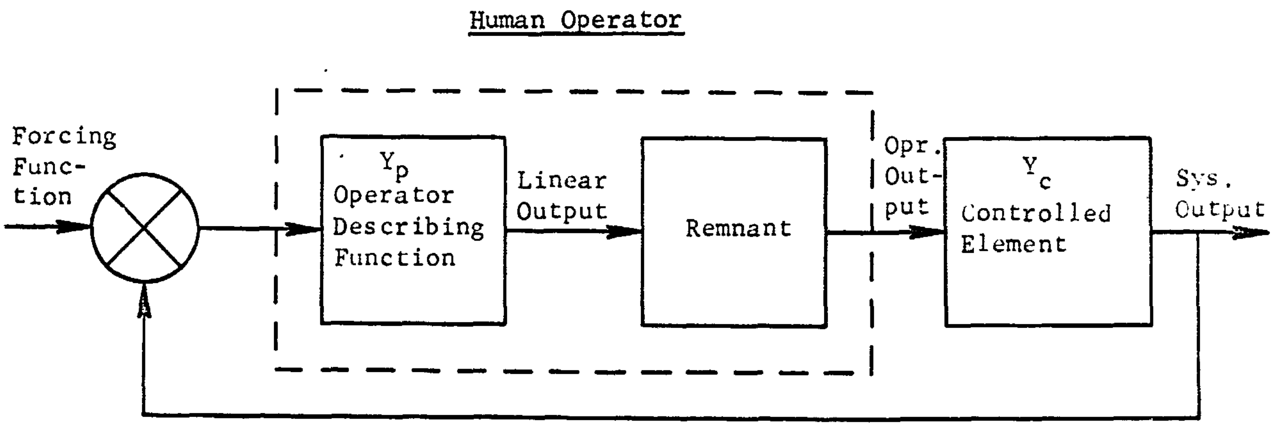
Stork and Young have performed some interesting experiments [4]. One such experiment was performed by asking the subject to rotate a handle as fast as possible, picking a comfortable amplitude of swing. (This is similar to the system operating as an open loop bang-bang control system.) The subject was then requested to oscillate the stick as rapidly as he could, while always being prepared to receive a blow to the stick without it being deflected very much from its course. The subject's oscillating frequency was about two-thirds of what it was when he was not expecting the blow. The subject was then told to imagine a pointer oscillating as fast as he could track it and then instructed to track this imaginary pointer. The oscillating frequency is slowed to about one-third of the free-wheeling frequency. This slow-down seems to be because of the necessity to transmit and process all control signals through the imaginary portion of the mental tracking process. This implies that the interactions between the eye and hand control mechanism are intricate. Mechanical disturbance impulse responses are simpler and can be fitted by quasi-linear second-order system models, while responses to visual inputs are much more complex.

There is some correlation between eye and hand response times at low frequencies. However, at high frequencies, the eye may spontaneously stop moving without noticeably interfering with hand tracking. The eye has shorter response times than the hand when tracking irregular steps because the eye muscles have considerable power with respect to their constant load, the eyeball. At moderate frequencies (0.7 to 1.0 cps) the hand develops prediction faster and to a greater extent than the eye. At higher frequencies (1.2 cps) the hand shows considerable prediction, while the median eye response time begins to lag. The hand has a natural frequency of 40 rad/sec while the eyeball has a natural frequency of 240 rad/sec.

III. QUASI-LINEAR MODELS

Experiments relating human response to visual input are necessary to integrate man into a system as complicated as a guided missile. Many of these experiments have already been performed. Human operator characteristics are affected directly by the forcing function, manipulator dynamics, and controlled element dynamics. Other factors affecting the operator indirectly are environmental variables such as illumination and temperature, training, fatigue and motivation.

Most of the experiments have taken the general form of the following diagram. The linear portion of the human operator model is represented



by the following generalized describing function, with several adjustments to be made:

$$N = \frac{K_p e^{-\tau S}(T_L S + 1)}{(T_n S + 1)(T_\ell S + 1)}$$

where

τ = reaction time delay

K_p = operator's gain

T_L = lead time constant

T_ℓ = lag time constant

T_n = neuromuscular lags

$\left(\frac{T_L S + 1}{T_\ell S + 1}\right)$ = operator's equalization characteristics.

According to McRuer, the adjustments are not easy. In general, they are divided into two categories: adaptation and optimization. Adaptation is the selection (by the operator) of the specific form of equalization characteristics (such as lag-lead, lead-lag, pure lag, pure lead, or pure gain), or the selection of the form compatible with low-frequency closed-loop response and general system stability. Optimization is the adjustment of parameters of the form selected.

Optimizing criteria are not well known. For insight, we can examine measurements and adjust parameters so that the system phase margin is between 60 and 110 degrees.

In applying these rules, we consider the following:

When the controlled element transfer function is:	The operator's equalization from is:	
K	lag-lead,	$T_\ell > T_L$
K/S	pure gain,	K_p
K/S^2	lead-lag,	$T_L > T_\ell$
$\frac{K}{S^2 + 2\delta\,\omega_n + \omega_n^2}$	lag-lead if lead-lag if	$\omega_n > 2/\tau$ $\omega_n < 2/\tau$

This formula works well when the operator can make the controlled element follow the fastest fluctuations of the input. When the operator cannot follow the fastest fluctuations of the input, the system exhibits degraded closed-loop dynamics. The operator becomes more nonlinear than usual and may attempt to overcome his difficulties by generating higher order lead terms and possibly an on-off type of control. The operator is sometimes nonlinear, but he is more often linear [5-10].

This generalized describing function works well for a wide range of forcing functions, manipulators, and controlled elements when the operator is tracking signals of low frequencies. It gives evidence of near-linear behavior of the human operator in this case. However, this quasi-linear model must be applied with caution because it suffers from a number of drawbacks in addition to the frequency limitations. Among these limitations are the following: (1) The model does not account for the predictive ability of the human operator; (2) being linear and continuous, the model cannot generate frequencies beyond the bandwidth of the input signals (which are known to exist in human operator output); (3) the model cannot account for a substantial body of experimental evidence which suggests intermittent behavior of the tracker; and (4) the coefficients will vary as necessary to reflect the pilot's effort to stabilize the system and to minimize the RMS error.

The time delay term, $e^{-\tau S}$, results from nerve conduction, human sensor, excitation, computational lags and other data-processing activity in the central nervous system. Experimental results show τ to be essentially constant when considered as a function of controlled element dynamics and forcing function. The largest variation is between the subjects being tested. The value of τ will normally be between 0.1 and 0.2 second.

The neuromuscular lag, T_n, varies with the task. The observed variation of T_n with the forcing function is between 0.1 and 0.6 second. Work in the area of muscular control mechanism has not progressed far enough to make the required adjustments.

The equalization characteristic

$$\left(\frac{T_L S + 1}{T_\ell S + 1}\right)$$

and the gain K_p are the major elements in the human transfer function which allow the operator to stabilize differing dynamic devices. The coefficients of the equalization term require alteration for each of the differing types of input in order to properly represent the human operator. The value of T_L will normally vary between 0 and 2.5 seconds.

The value of T_ℓ will normally vary between 0 and 20 seconds; K_p will normally be between 1 and 100. These figures are according to McRuer, Graham, Krendel and Reisener [5].

The quasi-linear descriptions may be defined as the best fit linear model of the human operator for a given control task, in which the input signal and the nature of the controlled process are specified. The model takes on a different, though still linear, representation for a different forcing function, a different controlled process, or different task specifications. Thus, the name quasi-linear model is used. Since these models do not account for all the manual output motion of the human operator, usually a remnant term is added to account for the output which is not correlated to the input signal.

A partial summary of some of the work done in human controller models, which are applicable to manual or partially manual control of space vehicles, is given below.

Adams [11] used a model to determine the human transfer function computations required to go from input-output time histories to the transfer function. He used three variable gains, which he adjusted to match the human pilot, and compensatory tracking. The output had twelve frequencies (the highest about 1 cps), the amplitudes of which were equal. His objective was to develop a method for automatically determining the human transfer function during an experiment, thus avoiding lengthy and complicated computations required to go from input-output time histories to the transfer function.

His model is

$$\frac{\delta}{D} = \frac{K_1\tau\left(1 + \frac{K_2}{\tau}S\right)}{(\tau + S)^2}$$

when the plant dynamics are

$$\frac{2.5}{S + 2.5}, \quad \frac{1}{S + 1}, \quad \frac{10}{S^2 + 3S + 10},$$

and

$$\frac{\delta}{\epsilon} = \frac{K_1\tau\left(1 + \frac{K_2}{\tau}S\right)}{(\tau + S)^2}$$

when the plant dynamics are 2/S, where

K_1 and K_2 = the gains

τ = lag frequency break point

δ = pilot output

D = disturbance signal

ϵ = error signal

S = Laplace operator.

Adams and Bergeron [12] measured the variation in the human transfer function. They varied the display sensitivity and control sensitivity systematically, using a one-axis fixed-base simulator. The disturbance signals were obtained by filtering the output of a Gaussian noise generator. The filters were two first-order lags with break frequencies located at 1 rad/sec for the attitude dynamics and 0.5 rad/sec for the rate and acceleration dynamics. The main body of data was on compensatory tracking, with limited data on pursuit tracking. Their model is,

$$\frac{\delta}{D} = \frac{\frac{K_1}{\tau}\left(1 + \frac{K_2}{\tau} S\right)}{(1 + \frac{S}{\tau})^2}$$

when plant dynamics are

$$1, \quad \frac{1}{S + 1}, \quad \frac{10}{S^2 + 3S + 10}$$

and

$$\frac{\delta}{\epsilon} = \frac{\frac{K_1}{\tau}\left(1 + \frac{K_2}{\tau} S\right)}{(1 + \frac{S}{\tau})^2}$$

when plant dynamics are

$$2/S, \quad \frac{K}{S(S + 1)}, \quad \frac{10}{S^2}$$

where

$\frac{K_1}{\tau}$ = static gain

$\frac{K_2}{\tau}$ = lead time constant

$\frac{1}{\tau}$ = lag time constant.

They found that human pilots change their transfer function when any element of the control loop is changed. However, fairly consistent results in terms of closed-loop characteristics are obtained. The pilot will adjust his transfer function to obtain closed-loop oscillatory characteristics with a frequency of 3 rad/sec and damping ratio of 0.4 to 0.7 with the following qualifications. With acceleration dynamics, the damping ratio is usually reduced below 0.4. The characteristic frequency is reduced when the display sensitivity or the control power is reduced. The real roots of the closed-loop characteristic are kept as high as possible, usually higher than 1 rad/sec. More experienced pilots operated to keep the highest real roots, frequency and damping ratio.

Adams and Bergeron also measured the human transfer function with various model forms [13]. To determine whether a more elaborate model would give a better match or more significant results in their earlier work, they used a model-matching technique in which the form of the model was preselected and the three gains included in the model were automatically adjusted to provide the best possible match to the pilot's output. The form used in these tests was kept as simple as possible. In their efforts to find better matches, Adams and Bergeron included model forms having a time delay term in them. Also, the linear model was altered to include four variables instead of three. This modification involved changing the denominator, or lag terms, of the model. Closed-loop characteristics for the complete system, pilot plus controlled element dynamics, were calculated and compared with results of their earlier study where the model was simpler. The human pilot was replaced by the model pilot in the control loop, and the resulting time history of the system error was compared with that obtained with the human pilot. Since tests were conducted by using data stored on magnetic tape, it was possible to make direct comparisons in all cases.

The control loop consisted of an oscilloscope display, a lightweight spring-restrained center-located control stick, and the analog simulation of dynamics. A disturbance signal was entered between the output of the dynamics and the display. This disturbance was obtained from a Gaussian noise generator with two first-order filters with break frequencies of one rad/second. The task was presented as a compensating tracking task in which the pilot was required to keep the moving indicator aligned with a fixed reference mark. The simulated dynamics included four systems which varied from an easy-to-handle rate mechanism 2/S to a more difficult acceleration system $10/S^2$ as well as a third-order system with an oscillatory factor

$$\frac{10}{S(S^2 + 3S + 10)},$$

which is typical of good airplane pitch characteristics. The numerators of these dynamics were adjusted so that reasonable control-stick deflections were required in each test.

The models checked were

$$\frac{\delta}{\epsilon} = \frac{K_1A + K_1K_2S}{(A + S)^2}\, e^{-K_3S} \; ; \quad \frac{\delta}{\epsilon} = \frac{K_1B + K_1K_2S}{(A + S)\;(B + S)}\, e^{-K_3S} \; ; \quad \frac{\delta}{\epsilon} = \frac{K_1 + K_1K_2S}{S^2 + AS + B}\, e^{-K_3S}$$

and

$$\frac{\delta}{\epsilon} = \frac{K_1A + K_1K_2S}{(A + S)^2} \; ; \quad \frac{\delta}{\epsilon} = \frac{K_1B + K_1K_2S}{(A+S)(A+B)} \; ; \quad \frac{\delta}{\epsilon} = \frac{K_1 + K_1K_2S}{S^2 + AS + B},$$

with plant dynamics of

$$\frac{2}{S}, \quad \frac{10}{S(S + 1)}, \quad \frac{10}{S^2}, \quad \frac{10}{S(S^2 + 3S + 10)},$$

where

δ = model output

K_1, K_2 = model gains

K_3 = time delay, sec.

A = model feedback gain representative of lag breakpoint frequency, or damping factor, radians/sec

B = model feedback gain representative of lag breakpoint frequency, radians/sec, or w_n^2, radians^2/sec^2

ϵ = displayed error

w_n = undamped natural frequency, radians/sec

S = Laplace operator, 1/sec.

The effect of time delays K_3 (0, 0.1, 0.15, 0.2) showed some improvement between the match of time histories of the model to the pilot. Measurements of the root-mean-square values of the difference between the pilot and the model show, in general, a slight decrease with increase in delay up to 0.15 seconds, but show a noticeable increase with further increase in delay up to 0.20 seconds. Therefore, the value of 0.15 is recommended. However, the form

$$\frac{K_1 A + K_1 K_2 S}{(A + S)^2}$$

gives a reasonable match and is simpler to mechanize.

Beckey, Messinger and Rose [14], in a study to determine the parameters in human pilot models, used

$$G(S) = \frac{K(1 + jwT_1)}{(1 + jwT_2)(1 + jwT_3)},$$

or in differential equation form:

$$\ddot{z} + a_1\dot{z} + a_2 z = a_3\dot{x} + a_4 x,$$

where

$$K = \frac{a_4}{a_2}; \quad T_1 = \frac{a_3}{a_4},$$

and T_1 and T_2 are roots of

$$S^2 + a_1 a_2 S + a_2 = 0.$$

The apparatus consisted of

(1) An oscilloscope display as follows:

The side stick had three degrees of freedom.

Inputs to the stick were from filtered Gaussian noise generators.

The pilots output was tape recorded and used as input for various model matching techniques.

The above models are the result of matching postulated models to taped pilot performance.

Compensatory tracking was used.

(2) Plant dynamics as follows:

(a) Time-invariant single axis control

$$\frac{12.5}{S + 1}, \quad \frac{12.5}{S^2}, \quad \frac{12.5}{S(S + 1)} .$$

(For two-axis control, $\frac{10}{S(S + 1)}$ in both axes.)

(b) Time-varying plant single axis control

$$\frac{20}{S(S + 1)}, \quad \frac{45}{S(S + 1)}, \quad \frac{45}{S^2} .$$

Typical results for the parameters are

$$\frac{z}{x} = \frac{.29(.525S + 1)}{.036S^2 + .21S + 1}$$

for single-axis control and

$$\frac{z}{x} = \frac{.269(.286S + 1)}{.0385S^2 + .154S + 1}$$

for the two-axis control.

It is worthwhile to note that Bekey's model differed from Adams in that Bekey considered unequal denominator roots which could be complex. Both investigations used plant dynamics of

$$\frac{K}{S(S + 1)}$$

Bekey noted that most of the complex roots come with continuous model adjustment techniques, and real roots come with iterative adjustment technique. Bekey concluded that the nature of the roots is a function of adjustment technique rather than plant dynamics.

Adams and Bergeron [15] tested the effects of motion cues on their transfer function. They used the transfer function of the pilot in the form

$$\frac{\delta}{\epsilon} = \frac{\frac{K_1}{\tau}\left(1 + \frac{K_2}{\tau} S\right)}{(1 + \frac{S}{\tau})^2} ,$$

where

$K_1 + K_2$ = gains

τ = lag frequency break point, radian/sec

δ = pilot output

ϵ = displayed error.

The plant dynamics was

$$\frac{2}{S(S + 1)} .$$

Again the type of tracking was compensatory. This study attempts to investigate the effect of multi-axis tasks, with and without motion cues, on the characteristics of a human transfer function. The transfer functions were obtained by using an automatic model-matching technique. Although visual cues are considered to be the principal basis for pilot control, motion cues may have an effect on the control of vehicles in which motion cues can readily be detected. Multi-axis operation is important because it represents a more realistic job; that is, under normal conditions, a pilot will usually have to perform two or more operations simultaneously. In this investigation Adams and Bergeron mechanized first a one-axis and then two-axis tasks, using a gimbal-mounted moving cockpit simulator. They used three pilots and took their average values. The test results are given below:

No Motion

	1-axis	2-axis	roll
Avg. pilot	$\frac{1.77(1 + 1.28S)}{(1 + .23S)^2}$	$\frac{1.53(1 + 1.07S)}{(1 + .24S)^2}$	$\frac{1.41(1 + 1.01S)}{(1 + .181S)^2}$

With Motion

	1-axis	2-axis	roll
Avg. pilot	$\frac{2.05(1 + 1.1S)}{(1 + .248S)^2}$	$\frac{1.53(1 + 1.19S)}{(1 + .21S)^2}$	$\frac{1.74(1 + .698S)}{(1 + .26S)^2}$

The results show that, although a pilot operates in a manner similar to a linear mechanism with constant gains when in a fixed-based, single-axis control loop, the addition of a second axis to his task causes him to operate with time-varying gains. The further addition of motion to the simulation greatly reduces the amount of time variation in the measured gains of the pilot. The average pilot, when going from one-axis to a two-axis task, will reduce his gain and add lead time. When motion cues are added (one axis), the average pilot will increase his gain and add lead time. When motion cues are added (two axes), the average pilot will increase his gain in roll and add lead time. However, there is not much change in pitch. In general, the addition of motion cues greatly reduced the time variation of measured gains of the pilots. These linear models are summarized in the appendix.

The quasi-linear models take into account the adaptive ability of the operator, but only after the adaptation process is complete. If a trained operator is subjected to a sudden change in the dynamics of the controlled element, he will gradually change the parameters of his transfer characteristics until he has achieved optimum equalization for the new situation. Following the adaptation, the quasi-linear model will again apply, with a new set of parameter values. During the adaptation process, however, the model does not apply.

The linear or quasi-linear models are preferable to nonlinear models since it is possible to use well-known analytic techniques with linear systems. Furthermore, the open-loop parameters of the quasi-linear models can be deduced from closed-loop measurements for the compensatory tracking situation. However, the quasi-linear model fails to take into account several known characteristics of human tracking perfomance such as adaptability, ability to predict, and tendency to respond intermittently if his stimulus exceeds about 1 cps. These effects cannot be overlooked, if man is to be considered as being in the control loop of something as complicated as a guided missile. The unpredictability of his time delay becomes important. For instance, he will respond to pulses of varying widths presented at irregular times in about 150-250 m sec. If the width is decreased to a short interval, he will delay as much as 400 m sec on the trailing edge. Navas proposed the following breakdown of the 250 m sec delay [16]:

(1) Visual latencies 40 m sec.

(2) Implicit control nervous system and alpha motor neuron delay times 165 m sec.

(3) Conduction time 15 m sec.

(4) Contraction time 30 m sec.

(5) Total delay for basic movement and response 250 m sec.

This adaptation takes 400 to 800 m sec provided the operator expects a change (not knowing exactly what or when). The resulting error is usually reduced to its asymptotic level in the next one to three seconds. During this possible 3.8 seconds the quasi-linear models do not apply.

Other weaknesses of the continuous linear model are as follows:

(1) When a human operator tracks a series of steps which are spaced less than 1/3 to 1/2 seconds apart, the effective reaction time in response to the second stimulus is often much greater than expected had the stimulus occurred in isolation. For any quasi-linear model, the response to successive stimuli would be the superposition of responses to each individual stimulus, and could never hope to match this time delay.

(2) Examination of tracking records reveals that the error curves have a pronounced periodicity in the vicinity of 2 to 3 cps even when this frequency is not in the input.

(3) Prediction of target motion by human operators suggests that they are capable of extrapolating on the basis of recent samples of target velocity.

(4) The operator has the ability to introduce various kinds of compensation into his transfer characteristics if required to do so by stability considerations or performance requirements. There are instances where trackers have generated up to second-order lead or lag terms. For low frequency inputs, a tight tracking loop can be achieved by using high gain and almost pure integration as the control law. For higher input frequencies, however, such a control law introduces excessive phase-lag, especially since the high frequency response was necessarily reduced to avoid instability. Therefore, when the input frequency is high (0.4 to 2.4 radians per second) the operator adjusts his transfer function by accentuating the high frequency response through change in lag break frequency, and reduces his relative gain at low frequencies.

(5) The human operator's output is clearly continuous, but there is a considerable body of evidence which indicates that he behaves as a discrete or sampling system in certain tracking operations. For instance, when he is tracking a continuous signal, he will make intermittent corrections. Most of these corrections are separated by intervals of 0.2 to 0.6 seconds, indicating that at least a portion of the operator's output results from a discrete process leading to sudden ballistic movements. All of this coupling energy is lost as a misfit when an attempt is made to match the operator output with linear models, since the linear models can contain at their output only those frequency components present at their input.

(6) When the pilot is confronted with higher order dynamics, he behaves in a discontinuous fashion. This leads to the hypothesis that, when a great deal of phase lead is necessary, the human pilot operates in a bang-bang control fashion rather than as a continuous controller.

Another problem is the use of compensatory tracking rather than pursuit tracking. It is difficult in a real system to limit information presented to the human to nothing but the error (as compensatory tracking does). The operator is continuously receiving information from his senses of touch, balance, hearing, and vision, and he will respond to one, all, or any combination of the inputs he selects.

The researcher is confronted with the problem of, on the one hand, trying to simulate the real situation and, on the other hand, trying to get a system which he can analyze. When the operator is tracking in the compensatory mode, this operation is most like a conventional feedback servo system and lends itself to analysis. Pursuit tracking and multiple input control involve much more difficult mathematical description. Perhaps as new methods in control theory for multi-input control are developed, pursuit tracking can be used more. For relatively simple tasks with easily controlled element dynamics and random inputs, there is no difference in performance between the compensatory and pursuit displays according to Chernikeff, Bermingham and Keller [17]. For tasks involving difficult input signals or controlled element dynamics requiring operator lead, the superiority of the pursuit display has been established by Sanders and Crugen [18]. The input information in a pursuit display permits the operator to make predictions about the input and therefore establish the necessary lead required for stable closed-loop performance. If his display is limited to the error term in a complicated situation, his time delay of 0.1 to 0.3 seconds will soon cause him to be overwhelmed.

IV. SIMULATIONS

Hardy, Keerokowski and Ritter [19] performed a study on the NASA Ames Research Center five-degrees-of-freedom simulator. The purpose of the study was to determine the feasibility of using the astronauts in the attitude control loop during the propelled phase of the Saturn V vehicle. Two manual backup control systems were considered: a "load-relief" and a "no-load-relief" system. Both allowed the pilot to close an adaptive control loop, which is parallel to the primary automatic system.

Primary system failures (10), as well as those associated with the additional hardware for the piloted backup system (9), were considered.

An analog piloted simulation which included rigid-body, engine-actuator, vehicle bending, propellant-sloshing, and control-system dynamics was used. Almost a thousand flights with randomly selected failures were simulated, with three test pilot subjects.

Wind is the primary external disturbance during first-stage flight. Two Marshall Space Flight Center synthetic wind profiles were used in this study: the 95 percent profile with 99 percent vertical shears, and the 50 percent profile with 99 percent shears. Two wind directions were chosen, 135 and 225 degrees, relative to vehicle launch heading. Previous experience had shown that quartering winds were the most difficult for piloted control.

For the load-relief system, attitude error (from the launch vehicle guidance system), as well as outputs from body-mounted accelerometers in the launch vehicle, were added to the pilot's display. These accelerometers were located near the vehicle's instantaneous center of rotation such that their outputs were nearly proportional to $q\alpha$, the product of dynamic pressure and angle of attack. Aerodynamic loads on the vehicle are directly related to this product. The output of the pilot's controller was passively filtered and summed with the output of the launch-vehicle automatic system at the control computer. The filter was a passive second-order network with natural frequency of 2.7 rps and a damping ratio of 0.5. The no-load-relief system was identical to the load-relief system except that it had no body-mounted accelerometers or associated display. The load-relief system had 19 failures, the no-load relief system had 17 and the automatic system had 10. There were two wind magnitudes, two wind directions and three major time intervals for the failure to occur (before high q, at high q, and after high q). From these variables, it was determined that there were 176 basic failure situations for the load-relief system, 166 basic failures for the no-load-relief system, and 116 for the automatic system; 79 additional runs were added to these basic situations. Each of three pilots flew 255 simulated flights using the load-relief system. A single unknown (to the pilot) failure at an unknown time occurred during each flight. Display and controller failures were deleted for the automatic system, resulting in 195 simulated flights.

The following failures were studied:

(1) One actuator hardover.

(2) Loss of thrust.

(3) Two actuators inoperative.

(4) Loss of platform.

(5) One actuator oscillatory.

(6) Loss of $\dot{\varphi}$.

(7) One actuator inoperative.

(8) Loss of φ.

(9) φ saturated.

(10) $\dot{\varphi}$ saturated.

(11) φ display (locked, jumped, drift).

(12) φ display null.

(13) φ display saturate.

(14) $\dot{\varphi}$ display null.

(15) $\dot{\varphi}$ display saturated.

(16) Accelerometer display null.

(17) Accelerometer display saturate.

(18) Hand controller null.

(19) Hand controller saturate.

These failures are for the load-relief system. For the no-load relief system, the failures were the same except that there were no accelerometer display failures. For the automatic system, there were no display-orientated failures, and no hand-controller failures.

In analyzing the results of these simulated runs, an effectivity number E was used. This number is defined by

$$E = \frac{N_1 T_c}{N_f T_s},$$

where N_1 is the number of vehicles lost from a particular failure mode, for instance, actuator hardover; N_f is the total number of particular failures, for instance, actuator hardover; T_c is the time interval in which this particular failure is potentially dangerous; and T_s is the total stage flight time. Therefore, the larger the number E, the worse the situation from a vehicle loss standpoint.

Listed below are the failures with these effectivity numbers E for each of the three control modes:

Actuator hardover	.042	Load Relief
	.322	No Load Relief
	.488	Automatic
Two actuators inoperative	.011	Load Relief
	.064	No Load Relief
	.392	Automatic

Loss of platform	.044	Load Relief
	.666	No Load Relief
	.666	Automatic
One actuator oscillatory	.577	Load Relief
	.400	No Load Relief
	.400	Automatic
Loss of signal	.090	Load Relief
	0	No Load Relief
	.201	Automatic
One actuator inoperative	0	Load Relief
	0	No Load Relief
	.101	Automatic
Loss of thrust	.439	Load Relief
	.450	No Load Relief
	.450	Automatic
Loss of attitude signal	0	Load Relief
	0	No Load Relief
	.576	Automatic
Attitude signal saturate	.444	Load Relief
	.444	No Load Relief
	.667	Automatic
Attitude rate saturate	.765	Load Relief
	.667	No Load Relief
	1.000	Automatic
Attitude display (lock, jump, drift)	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Attitude error display null	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Attitude error display saturate	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Attitude rate display null	0	Load Relief
	0	No Load Relief
	N.A.	Automatic

Attitude rate display saturate	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Accelerometer display null	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Accelerometer display saturate	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Hand controller null	0	Load Relief
	0	No Load Relief
	N.A.	Automatic
Hand controller saturate	.440	Load Relief
	0	No Load Relief
	N.A.	Automatic

During first-stage flight time, the most critical factor is structural loads, although trajectory dispersions are also important. This series of tests showed that the pilot can reduce trajectory dispersions. For example, when large attitude errors occur, he could reduce displacement errors of 5000 meters to 2500 meters, and velocity errors of 90 m/s to 50 m/s.

This study showed that the pilot can adapt to partial vehicle failure from a monitor mode as quickly as from an active mode. He can also do a good job of filtering the flexible body effects. In general, this study showed that the pilot can reduce the probability of mission failure by a factor of two.

V. CONCLUSIONS

The quasi-linear continuous models are considered adequate representations of tracking behavior when the input function bandwidth does not exceed about 5 rad/sec. Much more work needs to be done to understand man's behavior when tracking frequencies in the 5 to rad/sec region or even higher. Perhaps the most logical approach is to study the intermittency in manual tracking movements with sample data models.

If it is assumed that man is to be placed in the control loop of a missile after the missile control loop has been defined and the stability of the overall system analyzed, the problem arises as to where to insert him into the loop. There are essentially two possibilities.

The first is to insert him into the forward loop giving him complete manual control. This system is not recommended as a routine procedure. It may suffice as an emergency procedure to attempt to prevent disaster, but does not represent an ideal solution to the control problem. Much more testing is needed before this can be attempted.

The second approach is to either design or adopt a system that is stable and can operate automatically, but can be interrupted, monitored, augmented, or commanded as desired by the pilot. His participation should be limited to periods when he is needed to increase the reliability of the mission. A very simple way of accomplishing this is to add a three-axis proportional stick which the pilot can use to furnish manual inputs to be summed with the output of the vehicle computer. Also a load relief indicator would have to be furnished to the pilot. This could be body-mounted accelerometers, angle of attack meter, or perhaps the spacecraft digital computer.

Since the Ames tests showed that the pilot can adapt to a failure from a monitor mode as well as from an active mode, it is recommended that he operate in a monitor mode only until such time as a failure occurs. At the time of a failure, he should have the alternative of either supplementing or replacing the φ, $\dot{\varphi}$, and $\ddot{y}$ signals going into the control computer. The decision should be the pilot's based on his evaluation of what has gone wrong.

Another role which the pilot can play is to perform specialized tasks which are difficult to perform with hardware. One such task would be to let him relieve the aerodynamic loading on the structure as it is needed and then return the signals to the automatic system as soon as the high load peaks have been passed. Other specialized tasks for the pilot to perform may include the issue of discrete commands for staging, delayed ignition of upper stages for guidance corrections, or altitude control of an upper stage vehicle.

APPENDIX

Summary of Models

MODEL	PLANT DYNAMICS	AUTHOR AND PURPOSE
$\frac{\delta}{D} = \frac{K_1\tau\left(1 + \frac{K_2}{\tau}S\right)}{(\tau + S)^2}$ $\frac{\delta}{\epsilon} = \frac{K_1\tau\left(1 + \frac{K_2}{\tau}S\right)}{(\tau + S)^2}$	$\frac{2.5}{S + 2.5}, \frac{1}{S + 1}, \frac{10}{S^2 + 3S + 10}$ $2/S$	Adams, J. J. An attempt to match the input-output time histories.
$\frac{\delta}{D}$ $\frac{\delta}{\epsilon} = \frac{\frac{K_1}{\tau}\left(1 + \frac{K_2}{\tau}S\right)}{(1 + \frac{S}{\tau})^2}$	$1, \frac{1}{S + 1}, \frac{10}{S^2 + 3S + 10}$ $\frac{2}{S}, \frac{K}{S(S + 1)}, \frac{10}{S^2}$	Adams, J. J. and Bergeron, H. P. To measure the variation in the human transfer function.
$\frac{\delta}{\epsilon} = \frac{K_1A + K_1K_2S\ e^{-K_3S}}{(A + S)^2}$ $\frac{\delta}{\epsilon} = \frac{K_1B + K_1K_2S\ e^{-K_3S}}{(A + S)\ (B + S)}$ $\frac{\delta}{\epsilon} = \frac{K_1 + K_1K_2S\ e^{-K_3S}}{S^2 + AS + B}$ $\frac{\delta}{\epsilon} = \frac{K_1A + K_1K_2S}{(A + S)^2}$ $\frac{\delta}{\epsilon} = \frac{K_1B + K_1K_2S}{(A+S)(B+S)}$ $\frac{\delta}{\epsilon} = \frac{K_1 + K_1K_2S}{S^2 + AS + B}$	$\frac{2}{S}, \frac{10}{S(S + 1)}, \frac{10}{S^2}$ $\frac{10}{S(S^2 + 3S + 10)}$	Adams, J. J. and Bergeron, H. P. To determine if a more elaborate model than those used above would give a better match or more significant results.

Summary of Models (Continued)

MODEL	PLANT DYNAMICS	AUTHOR AND PURPOSE
$G(S) = \dfrac{K(1 + j\omega T_1)}{(1 + j\omega T_2)(1 + j\omega T_3)}$	Time invariant - single axis $\dfrac{12.5}{S + 1}, \dfrac{12.5}{S^2}, \dfrac{12.5}{S(S + 1)}.$ Time invariant - two-axis $\dfrac{10}{S(S + 1)}.$ Time varying $\dfrac{20}{S + 1}, \dfrac{45}{S(S + 1)}, \dfrac{45}{S^2}.$	Bekey, G. A., R. E. Rose and H. F. Messinger To determine the parameters in human pilot models for single and double axis control.
$\dfrac{\delta}{\epsilon} = \dfrac{\frac{K_1}{\tau}\left(1 + \frac{K}{\tau} S\right)}{(1 + \frac{S}{\tau})^2}$	$\dfrac{2}{S(S + 1)}$	Adams, J. J. and H. P. Bergeron. To investigate the effect of multi-axis tasks, with and without motion cues, on the characteristics of a human transfer function.

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