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RESEARCH ON NEW TECHNIQUES FOR THE ANALYSIS OF MANUAL CONTROL SYSTEMS

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1. INTRODUCTION

This report presents a summary of progress during the period December 15, 1965, to June 15, 1966, under a research program concerned with new techniques for the analysis of manual control systems.

During this period the major effort was concentrated in three areas:

1) Modeling of human operator behavior by means of asynchronous modulated pulse sequences and decision networks.

2) Study of random parameter models of human controllers.

3) Application of automata theory to manual control, including development of finite-state models of tracking behavior.

In addition, the development of the USC experimental facility continued. During the report period a pilot's seat has been installed, a new hand controller has been designed, eye movement instrumentation has been developed and a number of digital programs have been written.

The following pages present a brief review of the accomplishments in the above areas. In all areas, more extensive reports have been (or will be) prepared.

2. MANUAL CONTROL DATA ACQUISITION FACILITY

Personnel: M. J. Merritt, S. H. Shaar

The construction of an experimental station for studies of multiple input manual tracking control tasks is almost completed. The pilot's seat obtained from NASA/Ames Research Center has been refurbished and installed. A three degree of freedom manual control stick, also obtained from NASA/Ames Research Center was mounted on the pilot's seat. This stick was subsequently replaced with a two degree of freedom control stick designed and constructed at U.S.C.

A report will be written describing the unusual aspects of the two degree of freedom control stick and its constructional details. Its simplicity, ease of construction, low price, and performance make it highly desirable for human operator experiments.

Cables were fabricated to connect the analog computer patchboard to the:

1) display devices
2) control sticks
3) eye position transducer
4) FM tape recorder
5) communication system

Calibration procedures for the FM tape recorder were developed. The following digital computer programs were written to support the

Manual Tracking Data Acquisition Facility:

1) 7X SAMPLE: samples the FM tape recorder outputs at 100 millisecond intervals. If signals are recorded at 15 ips and played back at 3-3/4 ips, this corresponds to 25 millisecond sample intervals in the original record. The digital information is stored on the IBM 1311 Disk File.

2) 7X DUMP: allows the digitalized information to be listed in a convenient format for visual inspection.

3) SCALE FACTOR: Locates zero, +100, -100, calibration signals in digitalized record. Subtracts zero offset from digital data and multiplies by a scale factor to normalize all data.

4) DISTRIBUTION: Computes the distribution function of each signal.

5) D LOAD and D DUMP: System routines which allow the digitalized information on the disks to be efficiently punched on IBM cards for future use. These routines are used when disk storage capability is exceeded.

3. PULSE MODELS OF HUMAN OPERATORS PERFORMING COMPENSATORY TRACKING WITH COORDINATED MULTIPLE INPUTS

Personnel: M. J. Merritt, C. Jacobs, G. A. Bekey

It is well known that manual control of second and higher order systems often results in pulsing (on-off) behavior on the part of the human controller. Our first progress report [1] outlined an approach to modeling human performance in single-loop compensatory systems of this type. An asynchronous, pulse-amplitude, pulse-width model of the human operator has been successfully synthesized and a report is in preparation [4]. The project is now continuing by attempting to extend the same general approach to compensatory systems with more than one input.

The control task selected resembles that of a terrain avoidance problem or an ILS/navigational system. The operator is instructed to maintain constant altitude while flying over rather bumpy terrain. The operator inputs are obtained from two display devices separated by 30° of eye rotation which present pitch angle and altitude error, respectively. The operator is told to manipulate the control stick so as to minimize the altitude error without exceeding $\pm 40^{\circ}$ of pitch angle. The general structure of the compensatory tracking task is shown in Figure 1.

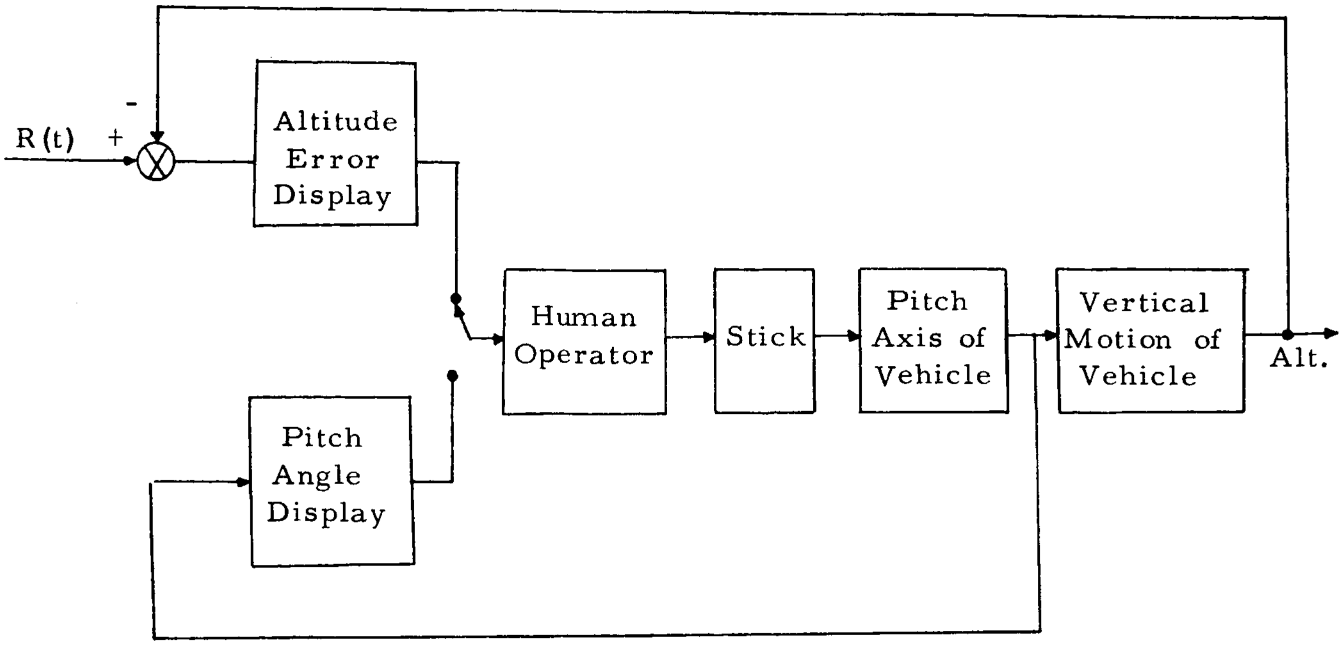

Figure 1

Block Diagram of Tracking Task

The transfer functions selected are:

$$\frac{\text{Pitch angle}}{\text{Stick output}} = \frac{2}{s\,(s+2)}$$

$$\frac{\text{Altitude}}{\text{Pitch angle}} = \frac{50}{s\,(s^2+10s+100)}$$

The tracking station is shown in Figure 2 and the two displays are illustrated in Figure 3.

The training of one subject is well underway. Modeling of the pulsing behavior of the subject has begun, but, as yet no results are available.

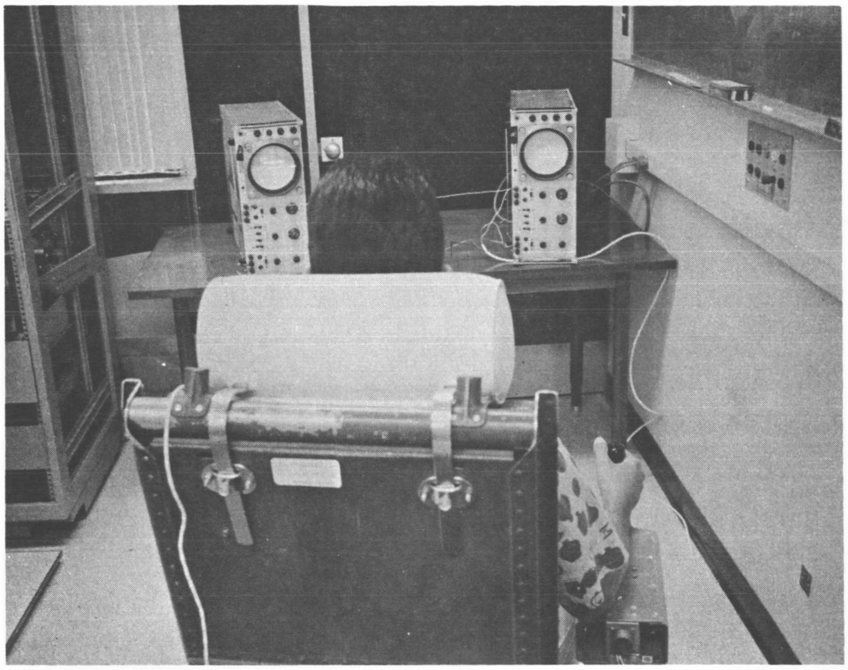

Figure 2

Manual Control Station Showing Display Separation

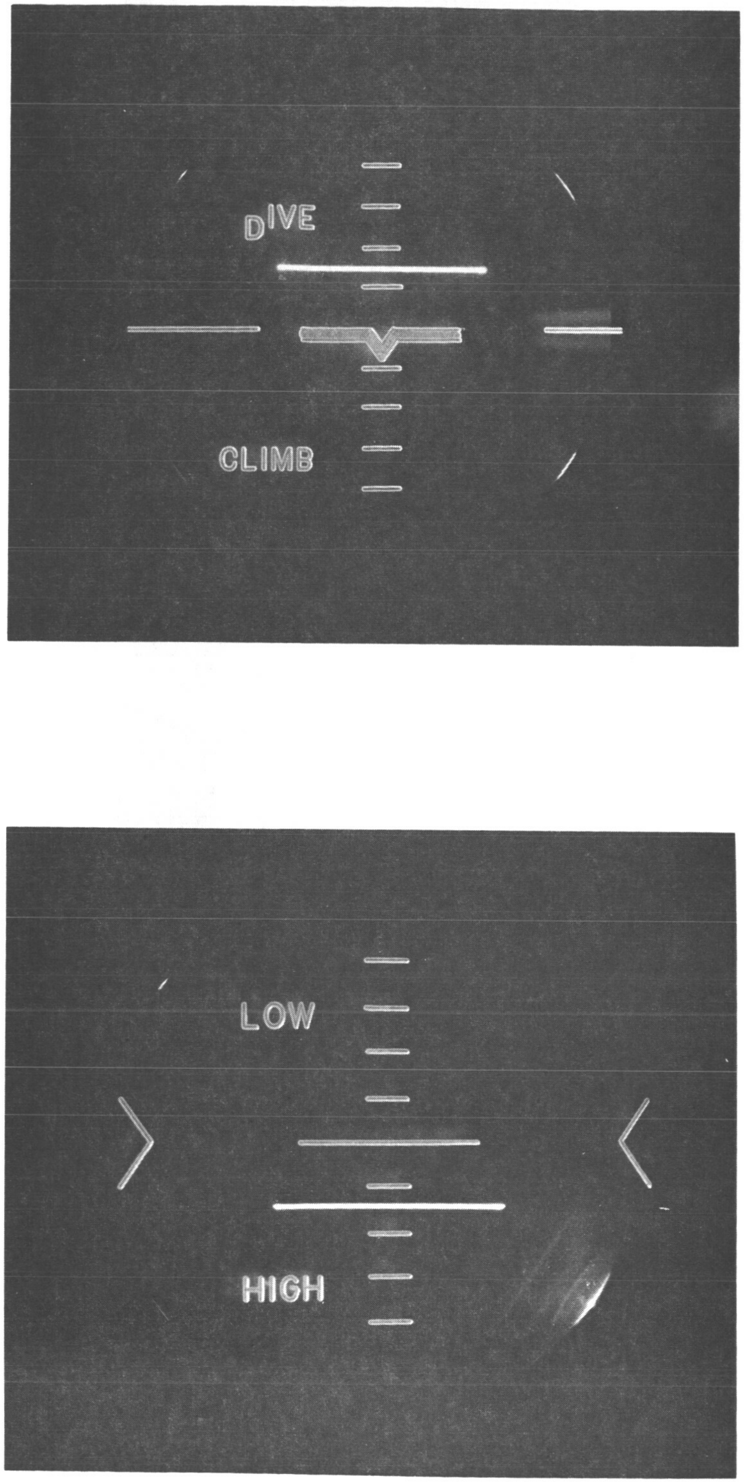

Figure 3

Illuminated Displays

Eye Motion Measurement. In order to model the performance of human pilots in the manual control task described above, it is necessary to record their switching or commutation between the two displays. Our first Progress Report [1] indicated that the pilot's head movement would be monitored using photocell instrumentation. Due to a number of experimental difficulties, this method has been abandoned in favor of measuring eye movements with the head itself restrained from moving. Eye motion is determined by measuring the subject's electro-ocular potential. This is a D.C. voltage proportional to eye position. The instrumentation includes three Beckman Type biopotential skin electrodes (PN350069) and a Dana, Model 3850 high gain, high common-mode rejection preamplifier. The voltage obtained from the electrodes is approximately 20 microvolts per degree of eye motion. The technique has been found highly successful. The location of the electrodes on the subject's head is shown in Figure 4.

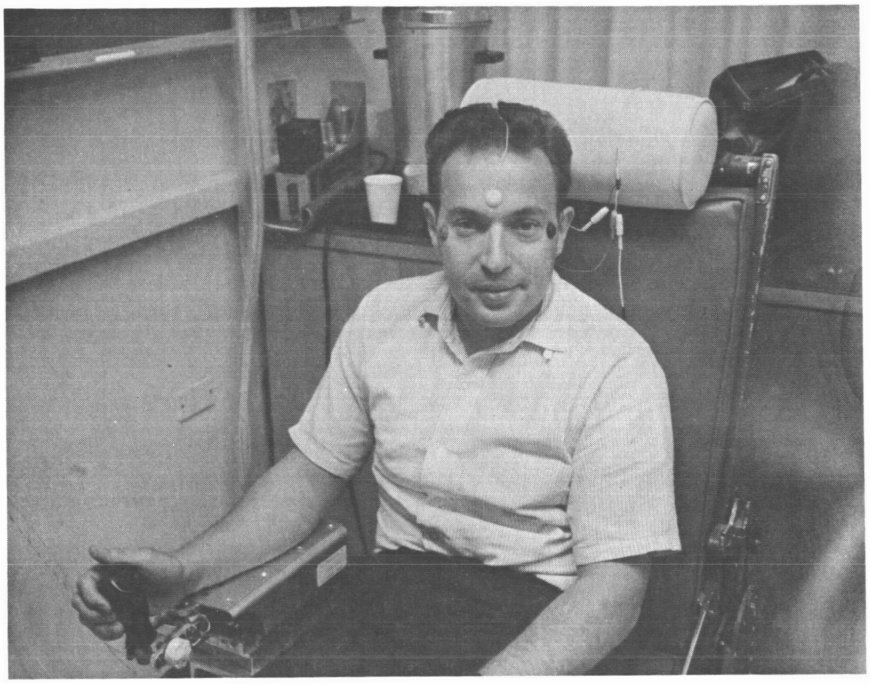

Figure 4

Subject showing location of biopotential skin electrodes for eye motion measurement

Some subjects' electro-ocular potentials contain a small D.C. level. If the amplifier is not to be overloaded, by the D.C. level, the gain must be reduced. The resultant loss of signal to noise ratio makes it difficult to detect eye motion. When this becomes troublesome, the device shown in Figure 5 is inserted in series with an electrode.

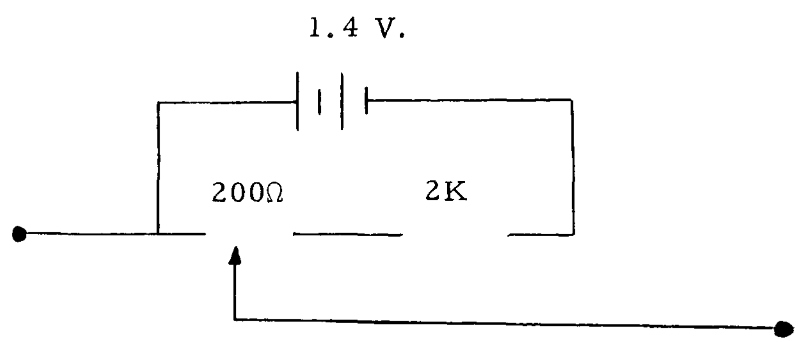

Figure 5

DC Potential Correction Circuit

The polarity of the correction is reversed by reversing the battery in its holder. The potentiometer is adjusted periodically to insure that the output of the amplifier is within its specified ± 10 V range.

4. RANDOM PARAMETER MODELS OF HUMAN CONTROLLERS

Personnel: S. M. Brainin, G. A. Bekey

This research project is concerned with the identification of random parameters, with the objective of modeling manual control performance. In the past human controller models have been deterministic, and any portion of the operator's output not predicted by the model has been included in a residual term called the "remnant". It is now widely recognized that the major portion of the remnant which arises in conjunction with linear constant coefficient models is probably due to time variation of the operator's performance, rather than to nonlinearities [5]. However, no satisfactory theoretical basis existed for an identification algorithm which could estimate the statistical properties of human operator models with random parameters. The first portion of this research, as reported in the previous Progress Report [1] was concerned with development of the theory. Using the Fokker-Planck equation and the theory of Brownian motion, and the techniques of regression analysis, successful digital computer methods for solving the problem have been obtained. The results are published in a report [2] and, in greater detail, in S. M. Brainin's Ph.D. dissertation [3].

As a preliminary test of the usefulness of the technique for modeling human performance, a human tracking record obtained at TRW Systems was modeled. An attempt was made to fit the data with a first-order model by assuming that the system could be represented by the equation

$$\dot{y} + By = Kx \qquad (1)$$

where x is the operator's input

y is the operator's output

$K = K + n_1$ is a random gain

$B = b + n_2$ is a random time constant

n_1 and n_2 are wide-band, zero mean, gaussian random variables assumed to be correlated with a correlation coefficient $\rho = 0.6$.

Accordingly, a model was assumed to be of the form

$$\dot{m}_1 + C_2 m_1 = C_1 \bar{x} \qquad (2)$$

where m_1 is the estimator for $\bar{y}$ (a short-term sliding average of the operator's output y)

C_1 is the estimator for k (the mean of K)

C_2 is the estimator for b (the mean of B)

$\bar{x}$ is a short-term (finite sample) mean of the operator's input

The techniques of References [2] and [3] were used to obtain similar relationships for the unknown variances σ_1^2 and σ_2^2, which refer to the variance of the gain K and the time constant B respectively.

If the identification is successful, the statistical properties of the model output must approximate those of the operator's output. In this test, the output means over 8-second samples of data were compared using the quality factor

$$Q.F. = \frac{\sum_{i=1}^{n} (m_{1i} - \bar{y}_i)^2}{\sum_{i=1}^{n} \bar{y}_i^{\,2}} \tag{3}$$

A low pass filter was used to obtain the operator's output mean $\bar{y}$. The smaller Q.F. is, the better the identification. Results from digital processing of the first 19 eight-second samples of the tracking data are presented in Table 4-1. (Each sample consisted of 100 samples of the operator's input and output, obtained with a sampling interval Δt = 0.08 seconds.)

The results are clearly tentative. The following observations can be made:

a) On the average, Q.F. was equal to about 0.5. This can be crudely taken to indicate that the first order, 2-parameter model accounts for some 50% of the operator's output. A better model may do much better.

b) During each 8-second interval, the operator adjusts to a different set of requirements and his performance is somewhat different.

c) The variances of both parameters were extremely large, probably due in part to the low order of the model (i.e.,

TABLE 4-1

TABLE OF ESTIMATED PARAMETERS
AND THEIR VARIANCES. ρ = .6

	c_1 (k)	c_2 (b)	σ_1^2 (k)	σ_2^2 (b)	Q.F.
1.	-1.048	1.395	40.63	27.97	.378
2.	-.2830	1.209	22.85	18.34	.587
3.	-.5422	2.00	.4386	64.30	.389
4.	-.3013	1.198	17.62	36.12	.687
5.	.0714	1.768	3.258	42.21	.625
6.	-.2654	.4357	10.20	9.008	.654
7.	-.6563	2.378	52.48	36.85	.524
8.	.5144	2.00	56.20	18.92	.355
9.	-.3633	1.867	.5574	36.82	.488
10.	-1.105	1.852	22.76	30.89	.544
11.	-45.13	0	8.345	.09925	.457
12.	-.6071	.3243	20.45	.2883	.624
13.	.2087	2.411	1.039	54.58	.571
14.	-.4350	1.407	49.90	17.73	.416
15.	.1156	.3196	.0750	5.93	.425
16.	.1925	.2373	0	4.699	.755
17.	-.6722	2.00	.477	59.56	.806
18.	-.6837	1.047	4.837	13.41	.344
19.	-1.949	2.00	20.55	14.12	.555

K and B had to account for the variability of all other parameters in the human operator which were not included in the model).

d) The negative value of gain is due to the polarity of the analog tracking data, and is to be expected. Note however that occasional mean values of K are positive (i. e., indicate control reversals). Furthermore, the wide variance on B (σ_2^2) compared to its mean shows that part of the time the pole of this model moves from the left to the right half of the complex plane.

The above results can only be taken as indicative of a direction of research. The work is continuing and identification using more realistic models will be attempted in the future.

5. FINITE-STATE MODELS OF MANUAL CONTROL SYSTEMS

Personnel: E. S. Angel, G. A. Bekey

Our work on finite-state models of manual tracking is continuing. A paper describing the first phase of the research was presented at the NASA-MIT Conference on Manual Control in February, 1966, [4].

The original asynchronous model of the human operator used quantised samples of error and error rate to initiate pre-stored asynchronously generated force programs. The first model, composed of only threshold gates, flipflops and hybrid actuators, while very promising, did not have the ability to converge to within any desired maximum error. The model has now been made adaptive through a fairly simple procedure.

The adaptation procedure involves setting more sensitive threshold levels on the error and error rate gates in response to decreasing errors. The heights of the force programs are adjusted to correspond to the increased sensitivity of the input gates.

This adaptation procedure has the following interesting features:

1) Changes of input for simple deterministic waveforms such as steps and ramps are immediately detected and the model rapidly adapts to the new input.

2) For step inputs, the convergence rate with n error threshold levels is at least $\frac{1}{2n+1}$ per step.

3) If two or more levels are used on the input thresholds, the model will distinguish between simple inputs (ramps and stops) and more complex waveforms, allowing the model to track the more complex waveforms.

4) Compensation is made for quantization errors in the estimated error rate. This compensation is dependent on force program duration and affects the convergence rate. This feature may aid in explaining some time varying aspects of human operators. At the present time this new model is being simulated by computer.

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