COMMUNICATION THEORY APPLIED TO THE SCORING OF THE HUMAN TRACKER

by

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CHAPTER I

INTRODUCTION

The limitations of the human when operating as part of a control system are becoming more apparent every day. Today many control systems are so complex and require such fast response times that the human does not possess the ability to operate them. In many cases the human operator can be eliminated completely from the system, but for the most part the intelligence of the human is required within the system. Therefore, engineers today have the problem of determining what the human operator can control. This problem has prompted considerable research in the area of human behavior in control systems.

Research in this area was started in 1962 by the Psychology Department at Kansas State University with the conception of the VETA (Versatile Electronic Tracking Apparatus) system. The VETA system was documented (Trumbo, 1963), and the original purpose of the system has been retained in the system presently used; however, many improvements have been made. The system is now called the Motor Skills system. A brief discussion of this system will be presented at this time to familiarize the reader with its main objectives. A complete description of the Motor Skills system will be given later in the thesis.

The Motor Skills system creates a tracking task to which a subject or operator can respond. The tracking task is in the form of a 1/2 inch vertical line which moves horizontally on an oscilloscope. This line is displayed to the subject, and the horizontal movement of the line is controlled by the system. This line is called the target. Another line, the cursor, is displayed below the target. The cursor is also a 1/2 inch vertical line which moves horizontally, but the cursor is controlled by an arm control. In this way the Motor Skills system can present the tracking task by moving the target, and the operator can respond by trying to keep the cursor lined up with the target.

The main deficiency of the Motor Skills system is in the scoring of the human operator. The system gives an integrated error score (IES) which provides the continuous error accrued by the operator during a tracking task. The IES alone does not give enough information to score the performance of the operator. In the past the position of the target and cursor was displayed on Visicorder records to obtain more information. The scoring of these records was accomplished by a clerk hand scoring them. This was a long and laborious task and in many cases called for the scorer to make a judgement on the relative scores obtained. For this reason research on the scoring of the human tracker was requested and supported by the Psychology Department at Kansas State University.

To obtain a general scoring procedure a decision was made to use the facilities of the IBM 360 computer which was available on campus. The first objective was to place the data in some form so it could be read into the computer. The data obtained from the Motor Skills system was in the form of two analog signals. One of these signals was from the target and the other from the cursor. The amplitudes of the signals were a function of the positions of the target and cursor. These signals were then quantized with an analog to digital converter, and the quantized points were then placed on magnetic tape in a format which could be read by the computer.

A computer program was written to measure the same indices which were obtained from hand scoring. This program obtained the indices, but it was restricted to the quality of tracking which could be accurately scored.

The tools of communication theory were checked to see if accurate results which were independent of the quality of the tracker could be obtained from them. The cross correlation of the target signal with the error signal gave information about the relative error which occurred before and after a change in the target signal. Another function, referred to as EAE, shows the average error accrued about a change in the target signal. From this several conclusions were obtained pertaining to some equipment which could be implemented into the Motor Skills system to obtain better scores on the human tracker.

CHAPTER II

DESCRIPTION OF APPARATUS

The apparatus used in this study consisted of the Motor Skills system and the analog to digital conversion equipment. The Motor Skills system provided a tracking task which was presented to several students who volunteered to participate as subjects. The data collected from the Motor Skills system was recorded in analog form on a magnetic tape recorder. Therefore, to score this data on a computer the analog to digital conversion equipment was used to convert this data into digital information. A discussion of these two systems follows.

A. MOTOR SKILLS SYSTEM

The Motor Skills system presents a tracking task by displaying two vertical lines on an oscilloscope. One of these lines is the target and the other line is the cursor. The horizontal movement of the target is read into the system on paper tape. Two types of target movements can be presented by the system and are referred to as the step and ramp tracking tasks. For the step tracking task the target can move instantaneously to one of fifteen different horizontal positions on the face of the oscilloscope. When the ramp tracking task is presented, the target moves horizontally across the face of the oscilloscope at one of seven different velocities in either direction. The horizontal movement of the cursor is controlled by a response lever. During one trial of an experiment a series of target movements are displayed to the subject. The subject then tries to follow the target by moving the response lever in such a way as to keep the distance between the target and cursor at a minimum. The absolute value of the distance between the target and cursor is integrated over one trial, and the final value of this integration is referred to as the integrated error score. The inputs to the oscilloscope which control the position of the target and cursor are called the target signal s(t) and cursor signal c(t). The voltage of these signals at any time, t, is a function of the position of the target and cursor. The target and cursor signals are recorded on an FM tape recorder to facilitate future scoring of the subjects. A simplified block diagram of the Motor Skills system is shown in Figure 1. The main parts of the Motor Skills system are: the system control, a digital to analog converter, the display, a response lever, the scoring units, and the analog data recorders.

The Motor Skills system is controlled by a Digitronics Model 2500 paper tape reader. The tape reader is an eight-channel, photoelectric reader. The reader has a photoelectric cell for each channel to sense whether or not the channel has a hole punched in the tape. A hole condition implies that a hole is punched in the tape, and a no-hole condition implies there is not a hole punched in the tape. Each time the tape reader reads the tape it reads one frame, and at the output of each channel it presents 0 volts for a no-hole condition and -12 volts for a hole condition. The tape reader is driven by a Tektronix Type 162 pulse generator. The tape reader steps to the next frame each time it receives a pulse from the pulse generator. The first four channels of the reader are used to control the position of the target which is the main tracking task. Channels 5-8 are used to control secondary tasks and initiate a rest interval. Since the main tracking task is the only part considered in this thesis, outputs for channels 1-4 of the tape reader are the only ones shown on Figure 1.

The target is displayed on an oscilloscope so the outputs of the paper tape reader must be converted to a voltage. To obtain this a simplified digital to analog (D/A) converter is used. The D-A converter consists of electronic switches ES_1, ES_2, ES_3, ES_4, and a summing amplifier (or integrator) AI-1. Channels 1-4 of the tape reader drive electronic switches ES_1 through ES_4 which switch +1 volt, +2 volts, +4 volts and +8 volts respectively. These switches were designed so each output would be the selected voltage for a hole condition and zero volts for a no-hole condition. These voltages along with -7 volts are placed at the inputs to the summing amplifier (or integrator) AI-1. Switch S_5 selects which function AI-1 is to perform. The operational amplifier used for AI-1 is a Philbrick Model P2 differential operational amplifier.

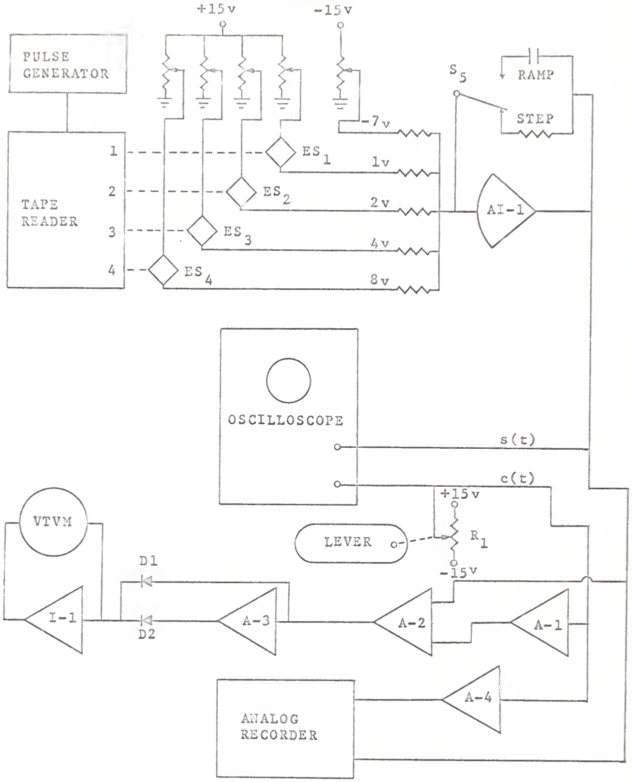

Figure 1   Block diagram of the Motor Skills system

If switch S_5 is in the summing amplifier position (STEP), the output voltage s(t) is

$$s(t) = -\left[-7 + ES_1(1) + ES_2(2) + ES_3(4) + ES_4(8)\right] \text{ volts}$$

where $ES_i(V_i)$ implies that the value is either V_i or zero depending on the state of switch ES_i. The minus sign describes the inversion obtained from the summing amplifier. Then

$$s(t) = 7 - \sum_{i=1}^{4} ES_i(V_i) \text{ volts} \qquad (1)$$

where $V_i = 2^{i-1}$ volts. This output voltage is a series of step voltages where the voltages are selected by the tape reader.

The photoelectric cells in the tape reader read the tape at all times. This includes the time between frames. Between the frames the tape is blank (no holes) so the output voltage of the D-A converter goes to +7 volts. The time it takes the tape reader to jump from one frame to the next is approximately 3 milliseconds. This causes the target signal s(t) to contain a 3 millisecond 7 volt pulse each time the tape reader reads a new frame. The human eye cannot detect this pulse when the target signal is displayed to the subjects, but it is still present in the target signal. Later in this thesis a reference will be made to high-level noise in the target signal. This high-level noise will refer to these 3 millisecond pulses.

If switch S_5 is in the integrator position (RAMP), the output voltage is

$$s(t) = \int_0^T \left[7 - \sum_{i=1}^{4} ES_i(V_i) \right] dt \text{ volts.}$$

If one frame read by the tape reader is considered,

$$s(t) = V_o + \left[7 - \sum_{i=1}^{4} ES_i(V_i) \right] t \text{ volts} \qquad (2)$$

where V_o is the output voltage present at the time the frame is read. This output voltage is a series of ramp voltages where the slope of the ramp voltages is controlled by the tape reader.

The display for the system is obtained from a Tektronix Type 561A oscilloscope with two Type 3A72 dual-trace amplifier units. In this way the oscilloscope is essentially an X-Y oscilloscope. A high frequency sine wave is placed at the vertical inputs of both channels. This creates a vertical line for each trace. The vertical amplifier unit is then adjusted to make the lines 1/2 inch long with the two lines overlapping 1/8 inch. The target signal s(t) and the cursor signal c(t) are connected to the horizontal amplifier. The target is connected to channel one, and the cursor is connected to channel two. In this way the target is displayed on the top trace, and the cursor is displayed on the bottom trace.

The response lever is a lateral armrest which pivots at the elbow. Connected to this lever is a Helipot potentiometer. The potentiometer is shown schematically as R_1 in Figure 1. The output of the center tap of the potentiometer is the cursor signal c(t).

To obtain the integrated error score, c(t) is inverted by A-1 and fed into A-2 along with s(t). The output of A-2 is c(t) - s(t). Inverter A-3 along with diodes D1 and D2 take the absolute value and have an output $|c(t) - s(t)|$. The absolute value is then fed into integrator I-1 which integrates the error over one trial. The integrated error is then read out by a voltmeter. The integrated error score (IES) is

$$IES = \int |c(t) - s(t)|\, dt. \qquad (3)$$

The time of integration is controlled by the tape reader channel used to initiate a rest interval and by two timers which are not shown in Figure 1. When a rest interval is initiated after a trial, the first timer starts timing; the tape reader stops; and the input to integrator I-1 is set to zero volts. During this time interval the IES is recorded. When the first timer stops, the second timer starts; and during this interval the integrator I-1 is cleared. When the second timer stops, a new trial begins; the tape reader starts; and the integrator I-1 starts integrating again. The operational amplifiers used for A-1, A-2, A-3 and I-1 are Philbrick Model K2W operational amplifiers stabilized by Model K2P stabilizing amplifiers.

The analog recording of the data is performed by first sending the cursor signal c(t) through A-4, a Philbrick Model PP55Au amplifier, which is a non-inverting amplifier used as a buffer to prevent any loading on the output of R_1. The target and cursor signals are then recorded on a Honeywell Model 8100 FM recorder and/or a Honeywell Model 906c Visicorder depending on which type of recording is desired. Generally the FM recorder is used because Visicorder records can be obtained from the FM recorder at a later time.

B. ANALOG TO DIGITAL CONVERSION EQUIPMENT

The analog to digital (A/D) conversion equipment takes an analog input and samples it at a fixed rate. Each sample is then quantized and converted into a digital code which corresponds to the voltage of the analog signal at the time of the sample. This digital code is recorded on a digital tape recorder so the samples can be read into the IBM 360 computer for further data processing. A complete description of the A-D conversion equipment was presented in a thesis by C. H. Hightower (1968) so the following discussion on the equipment will be brief.

The A/D conversion equipment consisted of a Remington Rand Univac (Phase II) Athena computer, a Texas Instruments Model 848 A/D converter and multiplexer, and a Digi-Data Model DSR 1420 digital tape recorder. The Athena computer was used to control the A/D converter and tape recorder, store data and transfer data. The Athena computer was not used to process the data because the storage capacity of the Athena is limited to 256 24-bit words which was too small for the data processing performed. The A/D converter and multiplexer can sample up to 25,000 times per second and multiplex sixteen different channels. Only two of the channels were used for this study, one for the target signal and one for the cursor signal. The Athena computer was programed to select which channel would be sampled and the time at which the sample would occur. When the A/D converter samples a selected channel, it quantizes the input voltage and at the output presents this quantized sample in a digital code. This digital code can then be transferred by the Athena to the digital recorder.

To convert the analog data to digital form, the target signal s(t) and cursor signal c(t) were fed from the FM analog recorder into the A/D converter on channels one and two respectively. The Athena computer was programed to command the A/D converter to sample channels one and two with a time of 120 microseconds between samples. The Athena then sent these digitized samples to the digital recorder to be recorded. This process was repeated every 50 milliseconds which gave a sampling rate of 20 times per second. Since the time between the target sample and the cursor sample was only 120 microseconds, any future reference to these samples will assume that they occurred simultaneously, and one sample point will refer to both the target and the cursor samples.

After the data was placed on digital tape, the data was read into the IBM 360 computer. The computerized scoring procedures to be discussed in this thesis were performed by the IBM 360 computer.

CHAPTER III

HAND SCORING

Before a computerized scoring method can be discussed, a description of the scoring method previously used is needed. As stated before the Motor Skills system gives an IES which is the total error accrued by the subject for one trial, but to score the subject, information on what caused a certain IES is needed. To obtain this information the Psychology Department recorded the target signal s(t) and cursor signal c(t) for the step tracking task on Visicorder records. Then a clerk took the record for each trial and hand scored it. To help describe this hand scoring method a small section of a Visicorder record is reproduced in Figure 2, and each index described will be applied to Figure 2.

The position scale on Figure 2 is from -3 to +3 units. The units are not defined on Figure 2 so an explanation is necessary. The inputs to the oscilloscope in the Motor Skills system for the target and cursor signals have maximum values of ±7 volts. The oscilloscope is adjusted to display the target and cursor in the center of the CRT for an input of zero volts, four centimeters to the right of center for an input of +7 volts, and four centimeters to the left of center for an input of -7 volts. On Visicorder records +3 units on the position axis corresponds to +7 volts input to the oscilloscope or means the target or cursor is displayed four

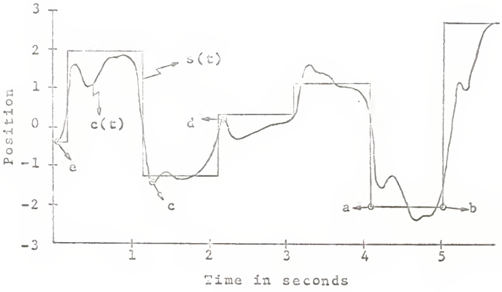

Figure 2. Part of a Visicorder record showing the hand scoring indices.

centimeters to the right of center on the CRT, and -3 units corresponds to -7 volts input to the oscilloscope or means the target or cursor is displayed four centimeters to the left of center on the CRT. An actual Visicorder record has five subdivisions for each division on the position axis shown in Figure 2 and ten subdivisions for each division on the time axis. All measurements made by the Psychology Department were in terms of these subdivisions. Therefore, one unit of distance measured on the position axis by the Psychology Department is equal to .467 volts input to the oscilloscope or .267 centimeters displacement on the CRT. One unit of measured time is equal to .1 second. The accuracy of the measurements was to the nearest 1/2 subdivision on the Visicorder record.

In discussing the Visicorder records for the step tracking task the following four terms are used: step number, step position, step time, and dwell time. A step number with value N implies that this is the N^{th} step on the record. The step a-b on the record in Figure 2 is step number 5 because it is the 5^{th} step on the record. Step position refers to the position of a step. The step position of step a-b is -2.15 units on the position axis. In many cases the step position is given in terms of the input voltage to the oscilloscope and is called the step voltage. The step voltage for step a-b is -5 volts. Step time is defined as the time at which the target signal changes from one step position to the next step position. The step time for step number 5 is the time measured at point a which is 4.2 seconds. The dwell time of a step is the time the step voltage remains constant. The dwell time for step a-b is 1 second. The dwell time for the different steps is not necessarily constant as shown in Figure 2 and can vary within a trial depending on how the Motor Skills system is programed.

When a record is scored one of the indices obtained is overshoot-undershoot. This index is obtained for each step. Overshoot-undershoot is measured at the time, t_o, of the first point of inflection in the cursor signal after a change in step position occurs. The absolute value of this index is $|s(t_o) - c(t_o)|$. The sign of this index is negative for an undershoot and positive for an overshoot. The overshoot-undershoot for step number 2 in Figure 2 is measured at point c and has a value of +.5, and for step number 3 overshoot-undershoot is measured at point d and has a value of -1.

Another index which is measured for each step is lead-lag. Lead-lag is measured at the point where the cursor signal breaks away from the previous step position and heads for the next step position. The absolute value of this index is the time between the break away point and the step time. The sign of this index is negative for a lag and positive for a lead. The lead-lag for step number 1 in Figure 2 is measured at point a and has a value of +.1 seconds.

No criteria for scoring the ramp tracking task are given in this thesis because no criteria are available at this time. A preliminary study using the ramp tracking task is presently being conducted by the Psychology Department, but no information on a scoring procedure is available at this time. Therefore, only the step tracking task will be discussed in this thesis.

CHAPTER IV

COMPUTERIZED SCORING

The hand scoring procedure discussed in the previous section takes considerable time and effort to perform. For this reason a computer program was written to score the data obtained from the Motor Skills system. The indices defined for the hand scoring procedure could not be used in a computer program because they were too general. Therefore, to obtain a computerized scoring procedure the indices had to be redefined. Some indices that were not obtained before were also defined and obtained by the computer program. This section describes the indices obtained by the computer, the data preparation programs, and the scoring program.

A. DESCRIPTION OF INDICES

To help describe the indices obtained by the computer the Visicorder record shown in Figure 2 is again reproduced in Figure 3. Also the following definitions are needed to describe the indices. Step number (SN), step position (SP), step time (ST), and dwell time (DT) were defined in the previous section. Error (E) will always refer to $|s(t)-c(t)|$. Dwell level (DLEVEL) and the error levels (ELEVEL) are imaginary levels placed around the target. Examples of ELEVEL 1 are shown on Figure 3 with dotted lines. These levels are placed around the target signal so the relative position of the cursor signal can be located. If the cursor signal is in

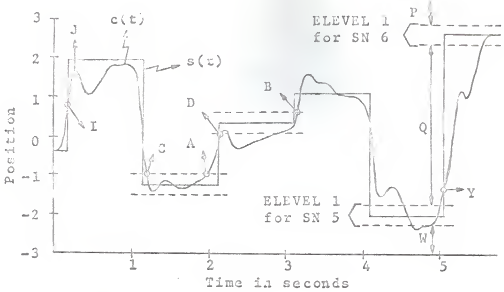

Figure 3. Part of a Visicorder record showing the computerized scoring indices

ELEVEL 1, this means that $|s(t)-c(t)| \leq$ ELEVEL 1. An inspection of step number 2 on Figure 3 shows that the cursor signal is in ELEVEL 1 between points C and A for this step. In the computerized scoring program five ELEVEL's and one DLEVEL are used. These levels are all defined the same as ELEVEL 1, but they may have different values depending on how close to the target the relative position of the cursor is required.

The next term used in the computerized scoring program is time leave (TL) which is used to describe the time at which the cursor signal leaves ELEVEL 1 of the previous step in the direction of the step being considered. If the subject does not follow the target well enough to either reach or pass through ELEVEL 1 of a step, the time leave of this step cannot be obtained. An example of the points at which time leave is measured is shown on Figure 3. Points A and B are the points at which time leave is measured for step numbers 3 and 4 respectively.

Another term used is time arrive (TA) which is the time at which the cursor signal reaches a new step position. This time is defined as the time at which the cursor signal enters ELEVEL 1 of the step being considered from the previous step position. Again, if the cursor signal does not enter ELEVEL 1 for a given step, this time cannot be obtained. Time arrive for step numbers 2 and 3 on Figure 3 are measured at points C and D. With these terms defined the indices obtained by the hand scoring program can be defined.

The average error (AERR) and the RMS error (RMSE) are two indices which are obtained for a whole trial. The scoring program calculates this average error by summing the absolute values of the error at each sample point in a trial and dividing this summation by the total number of points sampled in the trial. The RMS error is the square root of the total squared error divided by the time of the trial. The RMS error is obtained by squaring the error at each sample point and summing these values over the trial. This summation is divided by the number of sample points in the trial, and the square root is taken of the result.

Another set of performance indices is obtained by taking the absolute values of the error for each sample point and classifying them into different groups according to their value. These indices are referred to as the percent of time the error is in interval (PTEI) one, two...six. The intervals and the values of the error in these intervals are

PTEI 1 $E \leq \mathrm{ELEVEL}\ 1$
PTEI 2 $\mathrm{ELEVEL}\ 1 < E \leq \mathrm{ELEVEL}\ 2$
PTEI 3 $\mathrm{ELEVEL}\ 2 < E \leq \mathrm{ELEVEL}\ 3$
$\vdots$
PTEI 6 $\mathrm{ELEVEL}\ 5 < E$.

The lead-lag (LL) index is obtained by the scoring program, but the definition used by the scoring program is different from the hand scoring method. The computerized scoring program defines lead-lag as the step time minus the leave time. With this definition LL is positive for a lead and negative for a lag.

To indicate the time required for a tracker to move from one step position to the next the computerized scoring program measures the time of response (TR). Time of response is defined as time arrive minus time leave divided by the absolute value of the target change. The value of the target change is the step position of the step being considered minus the step position of the previous step. On Figure 3 the time of response for step number three is the slope of a straight line connecting points A and D.

To give an indication of how well the tracker follows the target for each step an index of performance referred to as time on target (TT) is obtained. Time on target is defined as the time during a step that the error is less than the DLEVEL divided by the dwell time of the step. The computerized scoring program counts the number of sample points which satisfy the condition that $E < DLEVEL$ during a step and then divides this number by the dwell time of the step.

The last index obtained by the computer is overshoot-undershoot (OU). This index is defined as the first point of inflection in the cursor signal after the cursor signal obtains a value equal to one-half the distance between the step position for which the OU is measured and the previous step position. For step number 1 on Figure 3 the OU is measured at the first point of inflection after point I. The point of inflection occurs at point J. The absolute value of OU is equal to the error at the point of inflection. The sign of the OU index is negative for an undershoot and positive for an overshoot. The time that OU occurs (TOU) is also obtained.

B. DATA PREPARATION PROGRAMS

The sample points obtained from the A-D converter were read into the IBM 360 computer from the digital tape recorder. The sample points for each trial were placed into two arrays. These arrays were the target array (TG) which contained the sample points of the target signal and the cursor array (CR) which contained the sample points of the cursor signal. There were 1000 sample points obtained for each trial so there are 1000 points in TG and CR. The value of every sample point was multiplied by a constant so the different values corresponded to the step positions displayed on Visicorder records and not the step voltages recorded by the tape recorder. This was performed so the values measured by the computerized scoring program would correspond to the values measured by the hand scoring method.

An inspection of the target and cursor arrays for different trials showed that there were noise points in the data that did not correspond to the target and cursor signals at the time the sample occurred. The noise observed consisted of low level noise and high level noise. The cause of the high level noise was discussed in Chapter 2 of this thesis. The source of the low level noise was not traced, but a good source for this noise would be the analog and digital recording equipment. To remove these noise points two programs were written. One program removed the noise points from the target array, and the other program removed the noise points from the cursor array.

The program to remove the noise points from the target array is SUBROUTINE TANOST(TG,NPTS,ZERO,ONE,TWO,THREE,FOUR, FIVE,SIX,SEVEN). The name TANOST was derived from TArget-NOise-STep. The target-noise designated that this subroutine removes the noise from the target, and the step implies that this subroutine is for the step tracking task only. The arguments of this subroutine are, TG which is the target array; NPTS which is the number of points in the array; ZERO, ONE, . . . SEVEN which are the absolute values of the different step voltages that can be programed into the Motor Skills system. The last seven arguments have a value of 1 or 0. The value is 1 if the step voltage was used and 0 if the step voltage was not used. This tells the subroutine which values the target array can have.

When subroutine TANOST is called it takes every point N in array TG and sets TG(N) equal to the nearest step position. This removes all of the low level noise points. Then the subroutine goes back through the array and changes the remaining noise points such that each point in the array satisfies one of the following conditions:

1. TG(N)=TG(N-1)
2. TG(N-1)≠TG(N)=TG(N+1)=TG(N+2).

The first condition assumes that N is a point on a constant step position, and the second condition assumes that N is the first point on the next step position.

The noise in the cursor array is removed by SUBROUTINE CUNO(CR,NPTS,MR). The name CUNO is derived from CUrsor-NOise. This program is not limited to the step tracking task. The arguments of this subroutine are CR which is the cursor array, NPTS which is the number of points in the array, and MR which is the assumed maximum response of the human being. MR is the maximum change the cursor signal can make in 50 milliseconds. After comparing several cursor signals displayed on a Visicorder record with a plot of the cursor arrays MR was set at .2. This program checks every point N in the cursor array until a sign change occurs in the equation (CR(N)+10)-(CR(N+1)+10). This equation checks for the points at which the cursor signal changes direction. If a noise point exists in the cursor array, a plot of the cursor signal described by the cursor array must either change directions to reach the noise point or it must change directions to return from a noise point. If a noise point exists without causing the cursor signal to change directions, the noise point was assumed negligible. Ten is added to CR(N) and CR(N+1) to remove the bipolar property of the cursor signal so that a sign change in the equation is created by the relative position of CR(N) and CR(N+1) and not the original sign of CR(N) or CR(N+1). When a sign change occurs, the equation AV=(CR(N-1)+CR(N+1))*.5 is compared with CR(N). If AV-CR(N)>MR, then CR(N) is set equal to AV. If AV-CR(N)<MR, CR(N) is not changed.

A listing of SUBROUTINE TANOST and SUBROUTINE CUNO is presented in Appendices A and B respectively (All programs listed in the Appendices were written in Fortran IV language.).

C. SCORING PROGRAM

The program which was used to score the data from the Motor Skills system is SUBROUTINE SCORE. A flow diagram of subroutine SCORE (SCORE) is given in Appendix C and a listing is presented in Appendix D. In discussing this program references will be made to the flow diagram and listing by (23-27). When this occurs, it will mean that the operation(s) just described is performed by statement number(s) 23 to 27. The designation of the different variables used in this program are the same as the abbreviations of the terms defined in part A of this section. The arguments for subroutine SCORE are:

Input

TG........Target array

CR........Cursor array

ELEVEL....Array containing the values of the five error levels

DLEVEL....Value of the time on target level

NPTS......Number of points in the target and cursor arrays

LIST......Printing instruction

Value of one = Print indices

Value of Zero = Do not print indices

Output

NSTEP.....Number of steps scored and the number of values in the following arrays

ST........Step time array

TL........Time leave array

TA........Time arrive array

TT........Time on target array

LL........Lead-lag array

TR........Time of response array

SP........Step position array

OU........Overshoot-undershoot array

TOU.......Time of OU array.

The arrays contained in the arguments as output are all of the indices scored for each step so they have a value for each step. The following is a description of how SCORE obtains these indices.

When the target and cursor signals were sampled, the sampling rate was 20 times per second or 50 milliseconds between samples. To obtain more accurate results SCORE generates a mid-point between every two points of the TG and CR arrays (16-19). The new arrays are called the S array for target array and C array for the cursor array. The time between points for the S and C arrays is 25 milliseconds. The number of points in these arrays is NP=2(NPTS). After generating the mid-points SCORE sets all the values in the TL and TA arrays to zero (20-25). This is done so the presence of new values can be detected later in the program.

All the operations (30-850) in the next part of SCORE are performed on every point in the S and C arrays. SCORE uses N to define which one of the points in S and C to operate on, and M is used to keep track of which step is being scored.

The first thing SCORE checks for is a change in step position (101). At this point SCORE goes to one of two different parts of the program depending on whether or not a step change occurred. If a step change does occur, SCORE tries to find the indices that have not been scored for that step and records these indices if they are obtained. Therefore, before the operations performed by SCORE at a step change (102 or 104-620) can be discussed, an examination of the operation performed when a step change does not occur (700-850) is needed.

SCORE runs each point through this part of the program even if a change in step position is detected. The absolute value of the error (E) is calculated first (700). Then SCORE checks to see if E is less than or greater than ELEVEL 1 (706). (In the program ELEVEL 1 is changed to EL1 and ELEVEL (K) is changed to EL(K)(14-16).) If E is less than ELEVEL 1, the cursor signal is in ELEVEL 1; and if E is greater than ELEVEL 1, the cursor signal is out of ELEVEL 1. At this point SCORE needs to know whether or not the error signal was in or out of ELEVEL 1 for the previous sample point so the location of time leave or time arrive can be located. SCORE uses the variable IO to keep track of this. IO is set for each point in the S and C arrays and has a value of + 1 (715) if the cursor is in ELEVEL 1 and - 1 (721) if the cursor signal is out of ELEVEL 1. Therefore, the next operation performed by SCORE is to check IO (708 or 71[illegible]) to see if the cursor was in or out of ELEVEL 1 for the previous sample point. If the cursor signal is out of ELEVEL 1 for this sample point and if it was in ELEVEL 1 for the previous sample point, SCORE records the time of this sample as time leave for the next step (720). SCORE checks this for every sample point so if the cursor leaves ELEVEL 1 for a given step more than once, the value for time leave which is finally recorded is the last time that this occurs in a step. If the cursor signal is in ELEVEL 1 for this sample point and if it was out of ELEVEL 1 for the previous sample point, SCORE checks to see if a value for time arrive had been recorded previously (712). If a value had not been recorded, SCORE records the time of this sample as time arrive. If there is no change in the relative position of the cursor and ELEVEL 1 for the two sample points, nothing is recorded.

After checking for a time leave or a time arrive SCORE locates which error interval E is in (740-750) and adds one to the proper interval (800). E is added to the total error (802), and E^2 is added to the total squared error (804). E is checked to see if it is less than the DLEVEL (815); if it is, the number of points for which E is less than the DLEVEL for this step is increased by one (815). SCORE then returns to check another point.

The operations performed by SCORE at a step change are as follows. The direction of the step change is recorded (102 or 104). The variable M which keeps track of the step number being scored is advanced by one (106), and the time that this sample occurred is recorded as the step time (107). The time on target for the previous step is calculated by dividing the number of points during the step for which

$E \le DLEVEL$ by the total number of points which occurred during the step (108). The variable which counts the number of points during a step for which $E < DLEVEL$ is then set back to zero (109).

The next thing SCORE must check is whether or not the proper value of time leave has been recorded and whether or not the proper value of time arrive will be recorded. To check this SCORE must find the location of the cursor signal at this sample point (C(N)) and compare this location with the target position (S(N-1)) of the previous step and the target position of the next step (S(N)). To illustrate this, assume that SCORE has found the step change between step number 5 and step number 6 on Figure 3. The step change would have been detected at the N^{th} sample point so S(N) is equal to step position 6 and S(N-1) is equal to step position 5. C(N) must be between the bottom end of range W and the top end of range P. The first place SCORE checks for C(N) is in ELEVEL 1 of step number 5. If C(N) is in ELEVEL 1, SCORE advances N until the point at which the cursor signal leaves ELEVEL 1 is found; and this value of N is recorded as time leave (202-206). If C(N) is not in ELEVEL 1 of the previous step, SCORE checks whether C(N) is above or below ELEVEL 1 of the previous step (300). SCORE compares this with the direction of the target change to see if the cursor signal is in the proper direction (302 or 304). On Figure 3 the improper direction is range W and the proper direction is in ranges Q, ELEVEL 1 for SN 6, and P. If the cursor signal is in the improper direction, SCORE advances N until the cursor signal reaches a value greater than or equal to the step position of the previous step and records this value of N as time leave (400-420). If the cursor signal was in the proper direction, an assumption is made that time leave had been obtained when it left ELEVEL 1 during the previous step. On Figure 3 C(N) would designate point Y which is in the proper direction. If a value of time leave was recorded, SCORE continues to that section of the program described first; but if the cursor signal is in the proper direction, SCORE checks to see if the cursor is in Q, P or ELEVEL 1 of the step being scored. SCORE checks ELEVEL 1 (500) first, and if the cursor signal is in ELEVEL 1, SCORE decreases N until the point at which the cursor signal enters ELEVEL 1 is found. This value of N is recorded as time arrive (502-506). If C(N) is not in ELEVEL 1, SCORE checks to see if it is above or below ELEVEL 1 (600). Then SCORE compares this with the direction of the target change to see if C(N) is in the proper direction (601-608). For this case the proper direction on Figure 3 is range Q, and the improper direction is range P. If C(N) is in the improper direction, SCORE decreases N until the cursor signal is less than or equal to the step position and records this value of N as time arrive (601-620). If C(N) is in the proper direction (range Q on Figure 3), an assumption is made that time leave will be recorded when the cursor signal reaches ELLVEL 1 of the step. Then SCORE continues to that part of the program which was described first.

After SCORE performs the above described operations, the number of steps scored is recorded (851). The average error (852) and the RMS error (854) are obtained, and the six PTEI scores are converted to percent (855). All of the values of time which were recorded are converted back so they correspond to the original sampling rate (857-859). Lead-lag (lead-lag is called ZL in the program) (867) and time of response (868) are obtained, for the steps where the time leave and time arrive were scored. If TL or TA were not scored for a step, lead-lag (863) and time of response (864) are set equal to 77.7 to designate that the value could not be obtained. Then SCORE finds the mid-point for each step change (869-872) and locates the sample point C(N) where the cursor signal is equal to this mid-point (874-894). On Figure 3 this point for step number one is point I. After this point is located, SCORE increases N until the point at which the cursor signal changes directions is located (896-908). On Figure 3 this point is point J. The difference between the cursor signal and target signal at this point is recorded as OU (910), and the value N for this point is recorded as TOU (912,. Then SCORE checks to see if a listing was requested and either prints all of the information obtained or terminates (950-1000).

CHAPTER V

MATHEMATICAL ANALYSIS

The computerized scoring program, (SCORE), described in the previous section obtains many useful indices on each step change. To obtain information about a whole trial, averages of the indices must be taken. Also, before SCORE can obtain lead-lag and time of response for a step, the subject must pass through ELEVEL 1 which places a restriction on the level of performance which can be scored. Therefore, to obtain general information on a whole trial which is independent of the performance of the tracker, the tools of communication theory were studied to see if they could be used to score the human tracker. To accomplish this a mathematical model was assumed for the human tracker; the tools of communication theory were applied to this model; and the results were compared with actual data. The mathematical model and the application of the tools of communication theory to this model are discussed in this section. The comparison of the results with actual data will be discussed in the next section.

A. MATHEMATICAL MODEL*

The mathematical model used to describe the human tracker is shown in Figure 4.

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*This thesis was not designed to obtain a mathematical model for the human being. The model was used only as a tool to obtain a scoring method. The description of the human being is left to the psychologist.

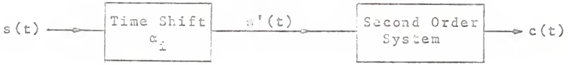


Figure 4. Mathematical Model

This model was assumed after inspecting several Visicorder records of the target and cursor signals. The records showed that the response of the trackers to the step tracking task could be approximated by an underdamped or overdamped second order system. In some cases the trackers anticipated the time at which the step change would occur and lead the step change, and in other instances the subjects would lag the step change. The time shift α_i was included in the mathematical model to obtain a lead or a lag in the response. The subscript i is used to describe the i^{th} step in the step tracking task so α_i can have a different positive or negative value for each step. No records were available for the ramp tracking task so only the step tracking task will be used in this analysis.

The input signal or target signal s(t) can be described by

$$s(t) = \sum_{i=0}^{n} V_i U(t-T_i) \tag{4}$$

where V_i = value of the step change for the i^{th} step

T_i = time the step change occurs for the i^{th} step

n = number of step changes in a trial

t = time.

The unit step function $U(t-T_i)$ has a value of 0 for $-\infty<t<T_i$ and a value of 1 for $T_i \leq t<\infty$. The Motor Skills system is programed such that the target signal starts at zero and ends at zero. Therefore, $V_o = 0$ and $\sum_{i=0}^{n} V_i = 0$.

The dwell time for the i^{th} step is defined as $d = T_{i+1} - T_i$. In this analysis the dwell time for each step (d) is assumed constant because all of the data available at this time has constant dwell times. If the dwell time is not constant, then d must be the minimum dwell time in the trial for this analysis to be valid. The records of the target and cursor signals showed that the time shift α_i could be restricted to $-d/4<\alpha_i<d/4$ except for the very poor trackers. With this assumption the signal after the time shift can be described by

$$s'(t) = \sum_{i=0}^{n} V_i U(t-T_i-\alpha_i) \tag{5}$$

where $-d/4<\alpha_i<d/4$

The second order system has a transfer function in the complex frequency domain of

$$H(s) = \frac{\omega_n^2}{s^2+2\delta\omega_n s+\omega_n^2} \tag{6}$$

where s = Laplace transform operator

δ = damping ratio

ω_n = undamped natural frequency.

Equation 6 is used in most control system books to describe a general second order system. For a specific example see Kuo (1962, pp. 126-129). A better approximation to the actual data would be equation 6 multiplied by a constant K, but this adds to the complexity of the analysis without a sufficient increase in information obtained from the analysis.

The impulse response h(t) for the second order system can be obtained by taking the inverse Laplace transform of equation 6. This can be found in tables of Laplace transforms as

$$h(t) = \frac{\omega_n}{\sqrt{1-\delta^2}} e^{-\delta\omega_n t} \sin\omega_n\sqrt{1-\delta^2}\, t \quad . \tag{7}$$

The output signal c(t) can be obtained by the convolution integral (Hancock, 1961). Then

$$c(t) = \int_0^\infty h(\tau)s'(t-\tau)dt \tag{8}$$

where $s'(t-\tau)$ can be obtained from equation 5. The summation in equation 5 can be interchanged with the integral which gives

$$c(t) = \sum_{i=0}^{n} V_i \int_0^\infty h(\tau)U(t-T_i-\alpha_i-\tau)dt \quad . \tag{9}$$

Assume that h(t) has a different set of parameters for each step and let $\delta_i = \delta$ and $\omega_i = \omega_n$ in equation 7. Then equation 7 can be rewritten as

$$h_i(\tau) = \frac{\omega_i}{\sqrt{1-\delta_i^2}} e^{-\delta_i\omega_i t} \sin\omega_i\sqrt{1-\delta_i^2}\; t \quad . \tag{10}$$

If $h(\tau)$ is obtained from equation 10, the evaluation of equation 9 becomes

$$c(t) = \sum_{i=0}^{n} V_i\left[1 - \frac{1}{\sqrt{1-\delta_i^2}} e^{-\delta_i\omega_i(t-T_i-\alpha_i)} \times \sin[\omega_i\sqrt{1-\delta_i^2}\,(t-T_i-\alpha_i)+\beta_i]\right]U(t-T_i-\alpha_i)$$

$$\text{where } \beta_i = \tan^{-1}\frac{\sqrt{1-\delta_i^2}}{\delta_i} \quad . \tag{11}$$

Let

$$R_i(t-T_i-\alpha_i) = \frac{1}{\sqrt{1-\delta_i^2}} e^{-\delta_i\omega_i(t-T_i-\alpha_i)} \times \sin[\omega_i\sqrt{1-\delta_i^2}\,(t-T_i-\alpha_i)+\beta_i]$$

then

$$c(t) = \sum_{i=0}^{n} V_i[1-R_i(t-T_i-\alpha_i)]U(t-T_i-\alpha_i) \quad . \tag{12}$$

Figure 5 shows some normalized plots of $c(t)$ versus $\omega_i t$ ($\alpha_i = 0$) for different values of δ. In referring to the damping ratio of a second order system three terms are used. These

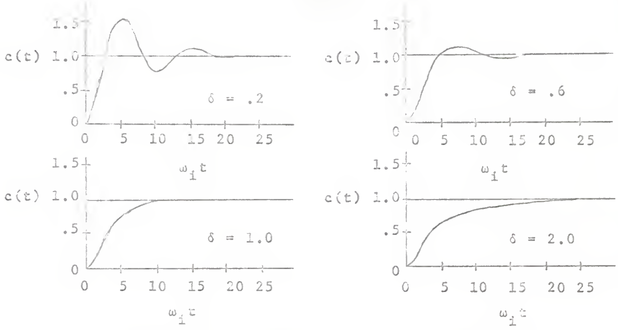


Figure 5. Plots of c(t) for different δ's.

terms along with the range of δ are:

underdamped system $0<\delta<1$

critical damped system $\delta = 1$

overdamped system $\delta > 1$.

Figure 5 shows the type of response obtained for each of these cases.

With s(t) described by equation 4 and c(t) described by equation 12 the error signal e(t) is

$$e(t) = s(t) - c(t)$$

$$= \sum_{i=0}^{n} V_i [U(t-T_i) - U(t-T_i-\alpha_i)] \qquad (13)$$

$$+ \sum_{i=0}^{n} V_i K_i (t-T_i-\alpha_i) U(t-T_i-\alpha_i) .$$

Therefore, s(t) describes the target signal, c(t) describes the cursor signal and e(t) describes the error signal.

B. APPLICATION OF THE TOOLS OF COMMUNICATION THEORY

The correlation functions (auto correlation and cross correlation) were applied to s(t), c(t) and e(t). In describing the correlation functions $\phi(\tau)$ will be used to designate the correlation function, and the subscripts on $\phi(\tau)$ will designate which signals were correlated. Then $\phi_{ss}(\tau)$ is the auto correlation of the target signal s(t), and $\phi_{sc}(\tau)$ is the cross correlation of the target signal s(t) with the cursor signal c(t). After checking the results obtained from applying the correlation functions to s(t), c(t) and e(t) the cross correlation of the target signal and the error signal, $\phi_{se}(\tau)$ was found to be the most sensitive to a time shift τ; therefore, more information can be obtained from $\phi_{se}(\tau)$ than the other correlation functions.

The cross correlation of two aperiodic functions $f_1(t)$ and $f_2(t)$ is, according to Lee (1960, p 44)

$$\phi_{12}(\tau) = \int_{-\infty}^{\infty} f_1(t) f_2(t-\tau)\, dt. \tag{14}$$

Substituting $f_1(t) = s(t)$, $f_2(t) = e(t)$ into equation 14, $\phi_{se}(\tau)$ becomes

$$\phi_{se}(\tau) = \int_{-\infty}^{\infty} s(t) e(t-\tau)\, dt \;. \tag{15}$$

If $e(t) = s(t) - c(t)$ is substituted into equation 15, $\phi_{se}(\tau)$ can also be expressed as $\phi_{se}(\tau) = \phi_{ss}(\tau) - \phi_{sc}(\tau)$.

If equation 4 is substituted for $s(t)$ and equation 13 is substituted for $c(t)$, equation 15 becomes,

$$\phi_{sc}(\tau) = \sum_{i=0}^{n} \sum_{j=0}^{n} V_i V_j \int_{-\infty}^{\infty} U(t-T_i)[U(t-T_j-\tau)-U(t-T_j-\alpha_j-\tau)]dt$$

$$+ \sum_{i=0}^{r} \sum_{j=0}^{n} V_i V_j \int_{-\infty}^{\infty} R_j(t-T_j-\alpha_j-\tau)U(t-T_i)U(t-T_j-\alpha_j-\tau)dt. \qquad (16)$$

The limits of integration on the two terms in equation 16 are controlled by the unit step functions. The limits on α_i were stated previously as $-d/4<\alpha_i<d/4$. If the time shift τ of the cross correlation function is restricted to $-d/2\leq\tau\leq d/2$, then $-3/4d<\tau+\alpha_i<3/4d$. With these bounds placed on α_i, τ and α_i+T the time, t, at which the integrands of equation 16 are zero can be located. Table 1 lists different ranges of j and τ along with the location of the boundaries of the unit step functions of equation 16. From this the lower and upper limits of integration are listed if the integrand is not zero.

If the limits described on Table 1 are placed on equation 16 and the integrals are evaluated, equation 16 becomes

Table 1. Limits of Integration for Equation 16

Ranges for j	Ranges for τ	Statements on unit step boundaries	Lower limits	Upper limits
FIRST TERM				
$j \leq i - 1$	$-d/2 \leq \tau \leq d/2$	$T_j + \alpha_j + \tau < T_i$	Integrand is zero	
$j \geq i + 1$	$-d/2 \leq \tau \leq d/2$	$T_j + \alpha_j + \tau > T_i$	$T_j + \tau$	$T_j + \alpha_j + \tau$
$j = i$	$-d/2 \leq \tau \leq \min(0, -\alpha_i)^*$	$T_i \geq T_i + \alpha_i + \tau$	Integrand is zero	
$j = i$	$-\alpha_i \leq \tau \leq 0$	$T_i \leq T_i + \alpha_i + \tau$	T_i	$T_i + \alpha_i + \tau$
$j = i$	$0 \leq \tau \leq -\alpha_i$	$T_i \geq T_i + \alpha_i + \tau$	$T_i + \tau$	T_i
$j = i$	$\max(0, -\alpha_i)^* \leq \tau \leq d/2$	$T_i \leq T_i + \alpha_i + \tau$	$T_i + \tau$	$T_i + \alpha_i + \tau$
SECOND TERM				
$j \leq i - 1$	$-d/2 \leq \tau \leq d/2$	$T_j + \alpha_j + \tau < T_i$	T_i	∞
$j \geq i + 1$	$-d/2 \leq \tau \leq d/2$	$T_j + \alpha_j + \tau > T_i$	$T_j + \alpha_j + \tau$	∞
$j = i$	$-d/2 \leq \tau \leq \min(0, -\alpha_i)$	$T_i \geq T_i + \alpha_i + \tau$	T_i	∞
$j = i$	$-\alpha_i \leq \tau \leq 0$	$T_i < T_i + \alpha_i + \tau$	$T_i + \alpha_i + \tau$	∞
$j = i$	$0 \leq \tau \leq -\alpha_i$	$T_i \geq T_i + \alpha_i + \tau$	T_i	∞
$j = i$	$\max(0, -\alpha_i) \leq \tau \leq d/2$	$T_i \leq T_i + \alpha_i + \tau$	$T_i + \alpha_i + \tau$	∞

*The term $\min(0, -\alpha_i)$ is equal to $-\alpha_i$ if $-\alpha_i < 0$ and 0 if $-\alpha_i \geq 0$, and $\max(0, -\alpha_i)$ is equal to $-\alpha_i$ if $-\alpha_i > 0$ and 0 if $-\alpha_i \leq 0$.

$$\phi_{se}(\tau) = \sum_{k=0}^{n} V_i^2 \begin{cases} c_i e^{b_i(\tau+\alpha_i)} \sin[a_i(\tau+\alpha_i)+2\beta_i] \; ; & \\ \qquad -d/2 \leq \tau \leq \min(0,-\alpha_i) & (1a) \\ [\alpha_i+\tau+\dfrac{2\delta_i}{\omega_i}] \quad ; \quad -\alpha_i \leq \tau \leq 0 & (1b) \\ [-\tau+c_i e^{b_i(\tau+\alpha_i)} \sin[a_i(\tau+\alpha_i)+2\beta_i] \; ; & \\ \qquad 0 \leq \tau \leq -\alpha_i & (1c) \\ [\alpha_i+\dfrac{2\delta_i}{\omega_i}] \quad ; \quad \max(0,-\alpha_i) \leq \tau \leq d/2 & (1d) \end{cases}$$

$$+ \sum_{i=0}^{n} \sum_{j=0}^{i-1} V_i V_j c_j e^{-b_j(T_i-T_j-\alpha_j-\tau)} \sin[a_j(T_i-T_j-\alpha_j-\tau)+2\beta_j] \tag{17}$$

$$+ \sum_{i=0}^{n} \sum_{j=i+1}^{n} V_i V_j [\alpha_j + \frac{2\delta_j}{2\omega_j}]$$

where

$$a_i = \omega_i \sqrt{1-\delta_i^2}$$

$$b_i = \omega_i \delta_i$$

$$c_i = \frac{1}{\omega_i \sqrt{1-\delta_i^2}} \quad .$$

The first term of equation 17 can be one of four terms depending on the relation of τ and α_i. One thing that should be noted is for all $\alpha_i \leq 0$ and $-d/2 \leq \tau \leq 0$ term 1a describes the result, and for all $\alpha_i \leq 0$ and $0 \leq \tau \leq d/2$ term 1d describes the result.

Term two of equation 17 can be reduced by assuming that the exponential part of the term is zero for $j \leq i-2$. Substituting in for b_i and considering the limits on α_{i-2} and τ the smallest value for $b_i(T_i - T_{i-2} - \alpha_{i-2} - \tau) = b_i(2d - \alpha_{i-2} - \tau)$ is $\omega_i \delta_i (2d - d/4 - d/2)$ $= \omega_i \delta_i (5d/4)$. An assumption that the exponential part of term two is zero for $j \leq i-2$ implies that $\omega_i \delta_i (5d/4) >> 1$ which is valid except for very poor trackers.

The third term of equation 17 is not a function of τ so the shape of the $\phi_{se}(\tau)$ versus τ curve is independent of the third term.

The evaluation of equation 17 at $\tau = 0$ is

$$\phi_{se}(0) = \sum_{i=0}^{n} V_i^{2} \begin{cases} c_i e^{b_i \alpha_i} \sin[-a_i \alpha_i + 2\beta_i] & \alpha_i \leq 0 \quad \text{(1a)} \\ [\alpha_i + \dfrac{2\delta_i}{\omega_i}] & \alpha_i \geq 0 \quad \text{(1b)} \end{cases}$$

$$+ \sum_{i=0}^{n} V_i V_{i-1} c_{i-1} e^{-b_{i-1}(d-\alpha_{i-1})} \sin[a_{i-1}(d-\alpha_{i-1}) + 2\beta_{i-1}] \tag{18}$$

$$+ \sum_{i=0}^{n} \sum_{j=i+1}^{n} V_i V_j [\alpha_j + \frac{2\delta_j}{\omega_j}] \quad .$$

By assumption $-d/4<\alpha_i<d/4$ then if $d/4\leq\tau\leq d/2$, τ is in the range $\max(0,-\alpha_i)\leq\tau\leq d/2$. Therefore, equation 17 evaluated for $d/4\leq\tau\leq d/2$ is

$$\phi_{se}(\tau) = \sum_{i=0}^{n} V_i^2 [\alpha_i + \frac{2\delta_i}{\omega_i}]$$

$$+ \sum_{i=0}^{n} V_i V_{i-1} c_{i-1} e^{-b_{i-1}(d-\alpha_{i-1}-\tau)} \times$$

$$\sin[a_{i-1}(d-\alpha_{i-1}-\tau)+2\beta_{i-1}] \tag{19}$$

$$+ \sum_{i=0}^{n} \sum_{j=i+1}^{n} V_i V_j [\alpha_j + \frac{2\delta_j}{\omega_j}] \quad .$$

If $-d/2\leq\tau\leq -d/4$, then $-d/2\leq\tau\leq\min(0,-\alpha_i)$. Equation 17 evaluated for $-d/2\leq\tau\leq -d/4$ is

$$\phi_{se}(\tau) = \sum_{i=0}^{n} V_i^2 c_i e^{-b_i(\tau+\alpha_i)} \sin[a_i(\tau+\alpha_i)+2\beta_i] \tag{20}$$

$$+ \sum_{i=0}^{n} V_i V_{i-1} c_{i-1} e^{-b_{i-1}(d-\alpha_{i-1}-\tau)} \times$$

$$\sin[a_{i-1}(d-\alpha_{i-1}-\tau)+2\beta_{i-1}]$$

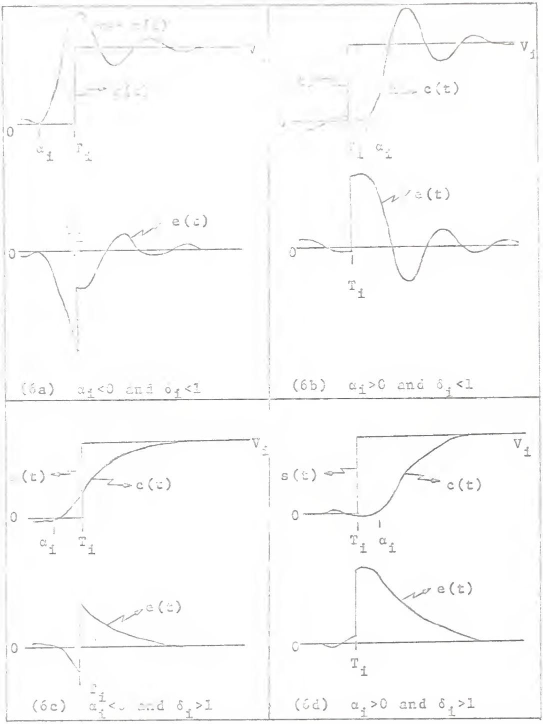
$$+ \sum_{i=0}^{n} \sum_{j=i+1}^{n} V_i V_j [\alpha_i - \frac{\text{[illegible]}}{m_j}] \quad .$$

Equations 18, 19 and 20 describe $\phi_{se}(\tau)$ for $\tau = 0$, $-d/2 \leq \tau \leq -d/4$ and $d/4 \leq \tau \leq d/2$. These equations will be used to describe the shape of the $\phi_{se}(\tau)$ versus τ curve.

Figure 6 shows several plots of c(t), s(t) and e(t) with $\alpha_i > 0$ and $\alpha_i < 0$ for the underdamped ($\delta < 1$) and overdamped ($\delta > 1$) response. This figure will also be used to describe $\phi_{se}(\tau)$.

An inspection of equation 11 shows that c(t) contains a unit step term and a decaying exponential sine or oscillatory term. The error signal e(t) (equation 13) contains the decaying exponential sine term, but e(t) contains a pulse term with a pulse width of α_i instead of a unit step term. This pulse is positive for $\alpha_i > 0$ and negative for $\alpha_i < 0$. The effects of the terms described above can be seen on Figure 6. These terms will be referred to in the following discussion.

The second term of equations 17, 18, 19 and 20 describes the area, which exists to the right of T_i, under the oscillatory term from the previous step multiplied by $V_i V_{i-1}$ and summed over i. On Figure 6 the oscillatory term from the previous steps is small compared to the response to the step shown. This case will generally be true except for the very poor trackers. Therefore, assume that the effect of term two of $\phi_{se}(\tau)$ is negligible compared to term one. The first term of $\phi_{se}(\tau)$ is multiplied by V_i^2 and summed over i. V_i^2 is always positive and does not affect



(6a) $\alpha_i<0$ and $\delta_i<1$

(6b) $\alpha_i>0$ and $\delta_i<1$

(6c) $\alpha_i<0$ and $\delta_i>1$

(6d) $\alpha_i>0$ and $\delta_i>1$

Figure 6. Plots of c(t), s(t) and e(t) for $\delta_i>1$, $\delta_i<1$, $\alpha_i>0$, and $\alpha_i<0$

the sign of the terms under the summation. If different responses to the same target signal are considered, the values for the V_i's will be [illegible]. Therefore, to use $\phi_{se}(\tau)$ to score different trackers the target signal must remain the same for the different trials.

If the target signal remains the same, the shape of the $\phi_{se}(\tau)$ versus τ curve is assumed to be dependent on terms 1a, 1b, 1c or 1d of equation 17 because the second term of equation 17 is assumed negligible and the third term is not a function of τ. Consequently, the following discussion will pertain only to the first term of $\phi_{se}(\tau)$. In discussing the first term of the equation for $\phi_{se}(\tau)$ the summation will be neglected for now, and only the terms under the summation will be considered. The i^{th} term in the summation describes the effects created by one of the steps in a trial.

Terms 1a or 1b of equation 18 describe the area under the error signal which exists to the right of T_i. If $\alpha_i<0$ (term 1a) and $\delta_i<1$, only the area due to the oscillatory term is included. In this case the area may either be positive or negative depending on α_i and δ_i (see Figure 6a). If $\delta_i>1$, the area is always positive as shown on Figure 6c. If $\alpha_i>0$, the area is always positive as shown by term 1b of equation 18. Term 1a has its maximum value at $\alpha_i=0$ and this value is $2\delta_i/\omega_i$.

Equation 19 describes $\phi_{se}(\tau)$ for [illegible] $\leq d/2$. Term one of equation 19 describes all of the area under the error signal. This means that the area to the left of [illegible] on Figure 6a and 6c is included in term one. This area is negative so equation 19 will always have a value less than equation 18. Equation 18 only includes the positive pulses of the error signal, and equation 19 includes both the positive and negative pulses of the error signal.

$\phi_{se}(\tau)$ for $-d/2 \leq \tau \leq -d/4$ is described by equation 20. Term one of equation 20 does not include any of the pulses of the error signal. The only area described by term one is the area under the oscillatory term which exists to the right of $T_i - \tau$. Therefore, equation 20 will always have a value less than equation 18.

Each i^{th} term in the summation describes the error which exists to the right or left of T_i. For $\tau=0$ the term describes the error to the right of T_i. As τ shifts to the right ($\tau>0$), the error to the left of T_i (negative area) is subtracted from the value obtained at $\tau=0$; and as τ shifts to the left ($\tau<0$), the error to the right of T_i is subtracted. Then the i^{th} term is multiplied by V_i^2 and summed over i which gives a weighted average of the effect of each i^{th} term.

To summarize the above discussion on $\phi_{se}(\tau)$ certain properties should be noted. $\phi_{se}(\tau)$ is only valid for scoring trackers if a comparison is made on the same target signal. $\phi_{se}(\tau)$ has a maximum value at $\tau=0$. The difference between $\phi_{se}(0)$ and $\phi_{se}(\tau)$ for $\tau>0$ is a weighted average of the error which exists to the left of T_i, and the difference for $\tau<0$ is a weighted average of the error which exists to the right of T_i.

Another function which can be used to score the human tracker is the ensemble average over all steps of the absolute value of the error, a distance τ from T_i normalized by V_i. This function will be referred to as EAE and designated by $\psi(\tau)$. The equation for EAE is

$$\psi(\tau) = \frac{1}{n} \sum_{i=0}^{n} \frac{|e(T_i - \tau)|}{V_i} \tag{21}$$

A plot of $\psi(\tau)$ versus τ shows the normalized average error that exists a distance τ from T_i. Since this function is normalized by V_i, it can be used to check results obtained from different target signals.

CHAPTER VI

EXPERIMENTAL RESULTS AND CONCLUSIONS

To verify the scoring programs 27 trials from nine different subjects were processed. All of these trials had been hand scored by the Psychology Department. The indices obtained from SCORE was compared with the hand scored indices. The following discussion shows the results of this comparison.

A. RESULTS OBTAINED FROM SCORE

The average error obtained from SCORE was compared with the integrated error score obtained from the Motor Skills system. These two indices were the same except for a constant scale factor. The accuracy of the RMS error could not be checked because it had not been obtained previously. One thing that should be noted about the RMS error is that it magnifies the larger errors and reduces the smaller errors. Since the larger errors usually occur close to the step change, the RMS error obtains meaningful information concerning this part of the trial.

In some cases the lead-lag indices which were obtained from SCORE were different from the hand scored indices. This difference was created by the difference in the definition of the indices. The hand scorer could look at a record and see the point at which the cursor signal headed for the new step position, but SCORE recorded the point that the cursor signal left LEVEL 1. This difference can be reduced by reducing the size of [illegible]; however, the number of steps that cannot be scored in regard to the accuracy for the entire trial is not increased.

The time of response, time on target, and PTEI indices could not be compared with anything. These indices are independent of the type of tracker scored so they should be fairly accurate.

A comparison of the overshoot-undershoot indices obtained from the two scoring methods showed that SCORE measured this index fairly consistently as long as the point of overshoot or undershoot was well defined. If the subject made an over-damped response to a step change, the value of OU measured by SCORE was usually different from the value measured by the hand scorer, but if the response was an underdamped response, the value measured was the same.

B. RESULTS OBTAINED FROM EAE AND THE CROSS CORRELATION OF THE TARGET SIGNAL WITH THE ERROR SIGNAL

The cross correlation of the target signal with the error signal was obtained by the cross covariance subroutine (subroutine CROSS) available in the IBM System/360 scientific subroutine package. A listing of subroutine CROSS is given in Appendix F. A description of the program can be found in the _IBM Application Program: System/360 Scientific Subroutine Package (360A-CM-03X) Version III Application Description_ (1967).

EAE was obtained from subroutine [illegible]. A listing of [illegible] is given in Appendix E. [illegible] uses the [illegible] array, SP array and NSTEP from SCORE. The ST array contains the times at which steps occur in a trial, and SP contains the step positions at the different steps. The step changes are obtained from the SP array. NSTEP is the number of steps in the trial. If the error array E is placed in the subroutine, it calculates the values described by equation 21. The maximum value of τ is read into AAEPS from NTAU, and the maximum value of τ is NTAU sample points to the right or left of the step time. AAE is the array containing the values of EAE, and NP is the number of points in this array.

Figure 7 shows the results obtained from CROSS and AAEPS for six different trials. The value of the maximum time shift (τ) fed into both programs was ten sample points which was one-half the dwell times contained in the target signal. Table 2 lists some of the points obtained from Figure 7 along with the average error and RMS error. All of the trials scored were obtained from the same target signal so a comparison of the trials can be made.

The first result that can be obtained from Figure 7 is that for all of the trials except 2X11 the $\phi_{se}(\tau)$ versus τ curve approaches a constant as τ approaches −10 and +10 which corresponds to $-d/2$ and $+d/2$. This shows that for all of the trials except 2X11 it was valid to assume that the second term of equation 17 was negligible. If the second term was not negligible, the curve for $\phi_{se}(\tau)$ would decrease for large negative τ and increase for large positive τ. The reason

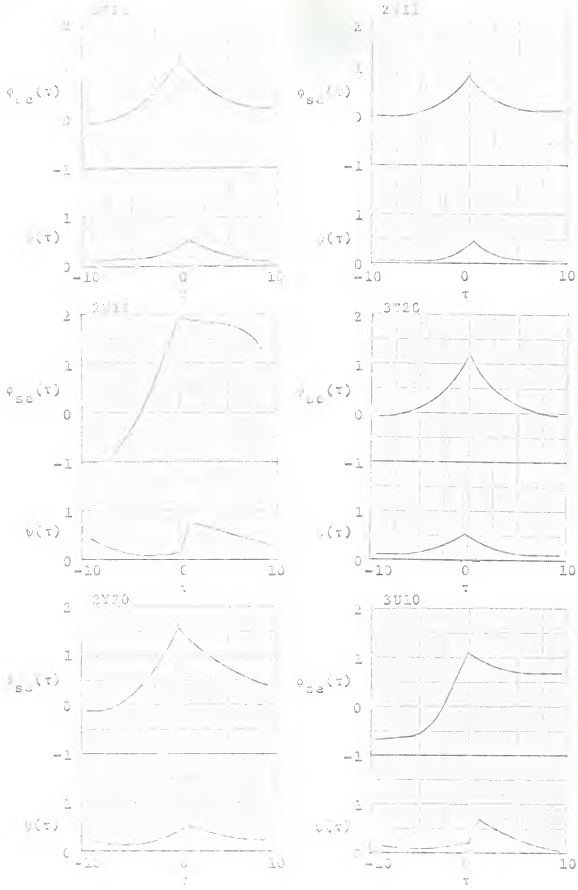


Figure 7. Plots of $\phi_{se}(\tau)$ and $\psi(\tau)$ for several trials

Table 2. List of Points Obtained from the Cross Correlation Curves Along with the Average and RMS Errors

Subject	$\phi_{se}(0) - \phi_{se}(-d/2)$	$\phi_{se}(0) - \phi_{se}(d/2)$*	$\phi_{se}(d/2) - \phi_{se}(-d/2)$	$\phi_{se}(0)$	Average error	RMS error
3T11	1.4	1.15	.25	1.35	.744	1.114
2W11	.8	.7	.1	.8	.516	.905
2X11	3.5	.7	2.8	2.0	1.106	1.692
3T20	1.25	1.2	.05	1.2	.709	1.114
2Y20	1.75	1.2	.55	1.65	.846	1.287
3U10	1.7	.4	1.4	1.1	.694	1.128

* d/2 is the same as τ = 10 sample points on Figure 7.

2X11 does not show this is because the subject had no idea of what the target pattern was; and therefore, could not anticipate on any of the steps. Subject 2X11 would be considered a poor tracker at the time this trial was obtained.

A comparison of the values listed for $\phi_{se}(0)$ and the average error on Table 2 shows that the value of $\phi_{se}(0)$ may be a function of the average error. A statement to this effect can not be made with any certainty because this value of $\phi_{se}(\tau)$ was not completely analyzed mathematically and there was not enough data scored to confirm this result. The only aspect of $\phi_{se}(0)$ that is confirmed is that this point is the maximum value of $\phi_{se}(\tau)$.

The conclusions obtained from the mathematical analysis were that the difference between $\phi_{se}(0)$ and $\phi_{se}(\tau)$ for $\tau > 0$ is a weighted average of the error which exists to the left of T_i and the difference for $\tau < 0$ is a weighted average of the error which exists to the right of T_i. An inspection of the plots of $\phi_{se}(\tau)$ and $\psi(\tau)$ on Figure 7 confirm this. The plot of $\psi(\tau)$ for 2W11 shows that the maximum average error exists to the right of T_i or $\tau = 0$ point and that this average error to the right of T_i is small. $\phi_{se}(\tau)$ for 2W11 shows this by the fact that $\phi_{se}(d/2)$ is a small amount greater than $\phi_{se}(-d/2)$. The plot for 2X11 also describes this by $\psi(\tau)$ showing that most of the average error exists to the right of T_i and $\phi_{se}(-d/2) << \phi_{se}(d/2)$. Therefore, $\phi_{se}(d/2) - \phi_{se}(-d/2)$ indicates the relative amount of error which exists to the left or right of T_i.

The magnitude of the error which exists to the right or left of T_i is indicated by $\phi_{se}(0) - \phi_{se}(-d/2)$ and $\phi_{se}(0) - \phi_{se}(+d/2)$ respectively. This can be seen by comparing the plots for 3T11 and 3U10. $\psi(\tau)$ shows that the average amount of error to the right of T_i for 3U10 is greater than the amount for 3T11. $\phi_{se}(0) - \phi_{se}(-d/2)$ for 3U10 is greater than $\phi_{se}(0) - \phi_{se}(-d/2)$ for 3T11. On the other hand the average amount of error to the left of T_i for 3U10 is less than the amount for 3T11 and $\phi_{se}(0) - \phi_{se}(d/2)$ for 3U10 is less than $\phi_{se}(0) - \phi_{se}(d/2)$ for 3T11.

C. CONCLUSIONS

In conclusion the following remarks can be obtained from this research:

1. The best computerized scoring procedures for the human tracker are the procedures that do not require decisions made by the computer and the procedures that do not depend on the quality of the tracker.
2. The RMS error gives pertinent information about the human tracker and should be incorporated into the Motor Skills system along with the IES.
3. The indices obtained from SCORE are very useful as long as the limitations of the decisions made by the computer on lead-lag and overshoot-undershoot are kept in mind.
4. The cross correlation of the target signal with the error signal ($\phi_{se}(\tau)$) evaluated at zero may be

a function of the average error. The difference between $\phi_{se}(0)$ and $\phi_{se}(\tau)$ for $\tau > 0$ is a weighted average of the error which exists to the left of T_i, and the difference for $\tau < 0$ is a weighted average of the error which exists to the right of T_i. The cross correlation of the target signal and the error signal could be implemented into the Motor Skills system, and it would be very valuable in scoring the human tracker.

5. The ensemble average of the absolute value of the error around the step change gives valuable information about the human tracker, but the availability of the equipment to implement this into the Motor Skills system is uncertain.
6. Future studies in this area are recommended. It has been established that the cross correlation of the target signal with the error signal can be used to score the human tracker, but the relative meaning of the scores obtained has not been established. Therefore, it is recommended that the mathematical analysis be extended to find the relationship between $\phi_{se}(\tau)$ and the level of performance of the trackers, and that any results be checked experimentally. Also, it is suggested that this analysis be applied to the ramp tracking task.

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APPENDIX A

SUBROUTINE TANOST

```
      SUBROUTINE TANOST(TG,NPTS,ZERO,ONE,TWO,THREE,FOUR,FIVE,SIX,
     1SEVEN)
      DIMENSION TG(1100),STEP(10),STM(10),KE(1000)
    1 FORMAT( ERROR= ,I6)
    2 FORMAT( NUMBER OF ERRORS IS GREATER THAN 20 - NUMBER = ,I6)
      N=0
    3 FORMAT( KE( ,I4, )= ,I5)
    4 IF(ZERO)5,10,5
    5 N=N+1
      STEP(N)=0.
   10 IF(ONE)15,20,15
   15 N=N+1
      STEP(N)=.43
   20 IF(TWO)25,30,25
   25 N=N+1
      STEP(N)=.86
   30 IF(THREE)35,40,35
   35 N=N+1
      STEP(N)=1.29
   40 IF(FOUR)45,50,45
   45 N=N+1
      STEP(N)=1.72
   50 IF(FIVE)55,60,55
   55 N=N+1
      STEP(N)=2.15
   60 IF(SIX)65,70,65
   65 N=N+1
      STEP(N)=2.58
   70 IF(SEVEN)75,80,75
   75 N=N+1
      STEP(N)=3.0
   80 NSP=N-1
      DO 81 I=1,NSP
   81 STM(I)=(STEP(I)+STEP(I+1))/2.
      IF(TG(1))82,83,83
   82 SGN=-1.
      GO TO 84
   83 SGN=1.
   84 DO 85 I=1,NSP
      IF(ABS(TG(1))-STM(I))87,85,85
   85 CONTINUE
   86 TG(1)=SGN*STEP(NSP+1)
      GO TO 90
   87 TG(1)=SGN*STEP(I)
   90 DO 200 N=2,NPTS
```

```
      IF(ABS(TG(N)-TG(N-1))-.2)94,94,96
   94 TG(N)=TG(N-1)
      GO TO 200
   96 IF(TG(N))101,102,102
  101 SNG=-1.
      GO TO 105
  102 SNG=1.
  105 DO 120 I=1,NSP
      IF(ABS(TG(N))-STM(I))110,110,120
  110 TG(N)=SNG*STEP(I)
      GO TO 200
  120 CONTINUE
      TG(N)=SNG*STEP(NSP+1)
  200 CONTINUE
      I=0
      GP=TG(1)
      NPT=NPTS-2
      DO 300 N=2,NPT
      IF(TG(N)-GP)210,300,210
  210 IF(GP-TG(N+1))220,215,220
  215 TG(N)=GP
      GO TO 300
  220 IF(TG(N+1)-TG(N))235,230,235
  230 IF(TG(N+2)-TG(N))235,240,235
  235 I=I+1
      KE(I)=N
      WRITE(3,3) I,N
      GO TO 300
  240 GP=TG(N)
  300 CONTINUE
      KE(I+1)=KE(I)+10
      II=1
      DO 600 N=1,I
      IF (KE(N)+1-KE(N+1))411,410,600
  410 II=II+1
      GO TO 600
  411 IF(II-9)420,420,412
  412 IF(II-20)413,413,415
  413 NUM=KE(N)
      NBF=NUM-II+1
      DO 414 LL=NBF,NUM
  414 WRITE(2,1) LL
      II=1
      GO TO 600
  415 WRITE(3,2) KE(N)
      II=1
      GO TO 600
  420 NUM=KE(N)
      NAF=KE(N)+1
      NBF=KE(N)-II
      IF(II-1)445,425,445
  425 BF=ABS(TG(NUM)-TG(NBF))
```

```
    AF=ABS(TG(NUM)-TG(NAF))
    IF(BF-AF)430,435,435
430 TG(NUM)=TG(NBF)
    GO TO 440
435 TG(NUM)=TG(NAF)
440 II=1
    GO TO 600
445 DO 460 M=NBF,NUM
    IF(TG(M)-TG(NAF))460,450,460
450 DO 455 MM=M,NUM
455 TG(MM)=TG(NAF)
    NAF=M
    GO TO 500
460 CONTINUE
500 IF(NAF-NBF-1)599,599,510
510 TG(NAF-1)=TG(NAF)
    NAF=NAF-1
    IF(NAF-NBF-1)599,599,520
520 TG(NBF+1=TG(NBF)
    NBF=NBF+1
    GO TO 500
599 II=1
600 CONTINUE
    RETURN
    END
```

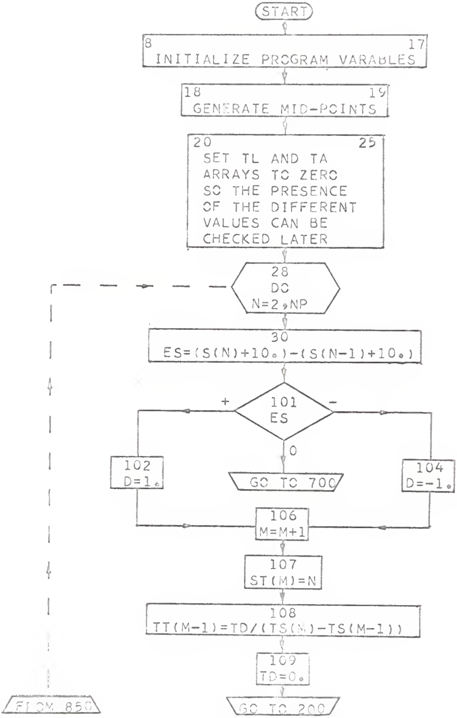
APPENDIX B

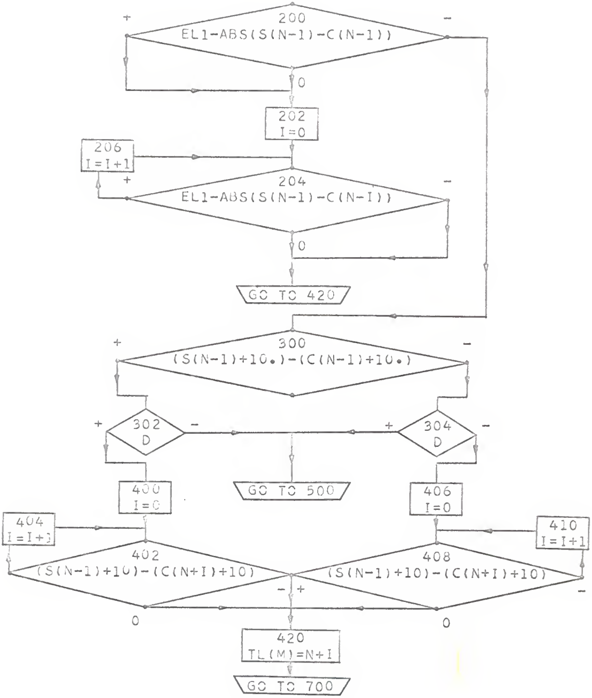
SUBROUTINE CUNO

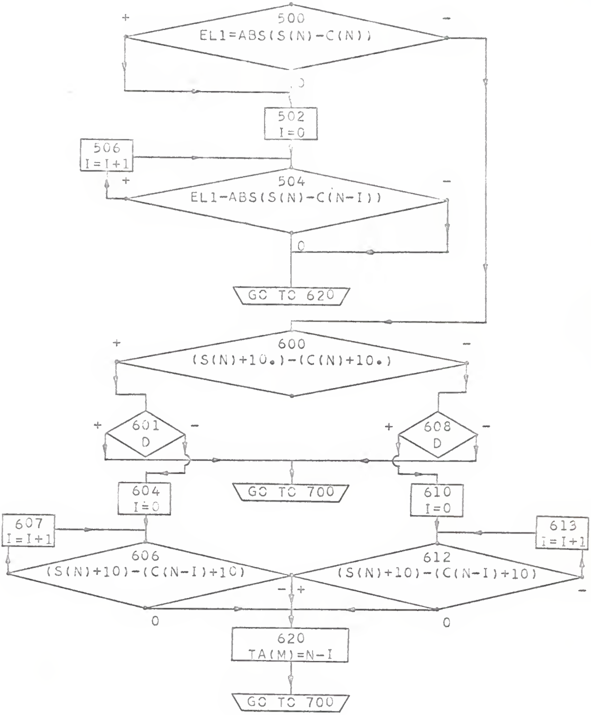
```
      SUBROUTINE CUNO (CR,NPTS)
      DIMENSION CR(1100)
      IF((CR(2)+10.)-(CR(1)+10.))1,2,2
    1 SGN=-1.
      GO TO 3
    2 SGN=1.
    3 NN=NPTS-1
      DO 100 N=2,NN
      IF((CR(N)+10.)-(CR(N-1)+10.)) 4,6,6
    4 IF(SGN)100,8,8
    6 IF(SGN)8,100,100
    8 AV1=(CR(N+1)+CR(N-1))*.5
      AV2=(CR(N)+CR(N-2))*.5
      D1=ABS(AVI-CR(N))
      D2=ABS(AV2-CR(N-1))
      IF(D1-D2)10,12,12
   10 IF(D2-.2)18,14,14
   12 IF(D1-.2)18,16,16
   14 CR(N-1)=AV2
      GO TO 18
   16 CR(N)=AV1
   18 IF((CR(N)+10.)-(CR(N-1)+10.)) 20,22,22
   20 SGN=-1.
      GO TO 100
   22 SGN=1.
  100 CONTINUE
      RETURN
      END
```

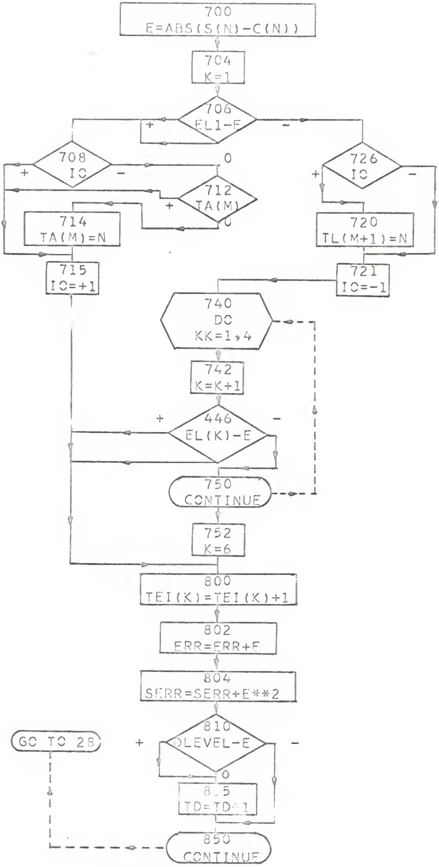
APPENDIX C

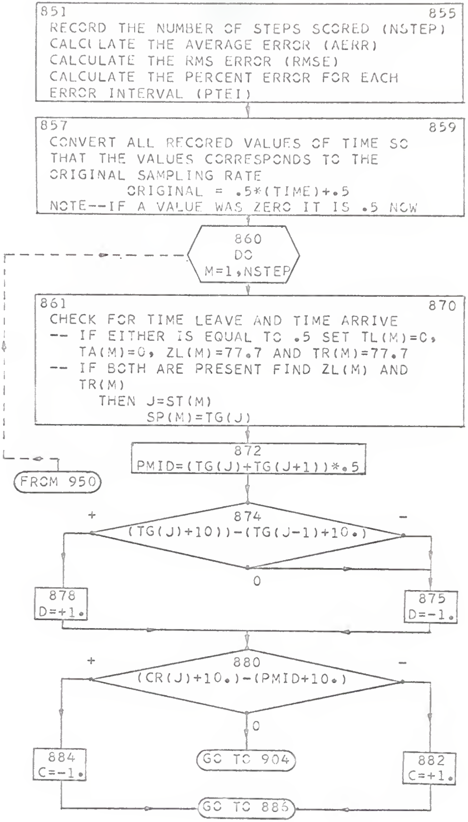
SUBROUTINE SCORE FLOW CHART

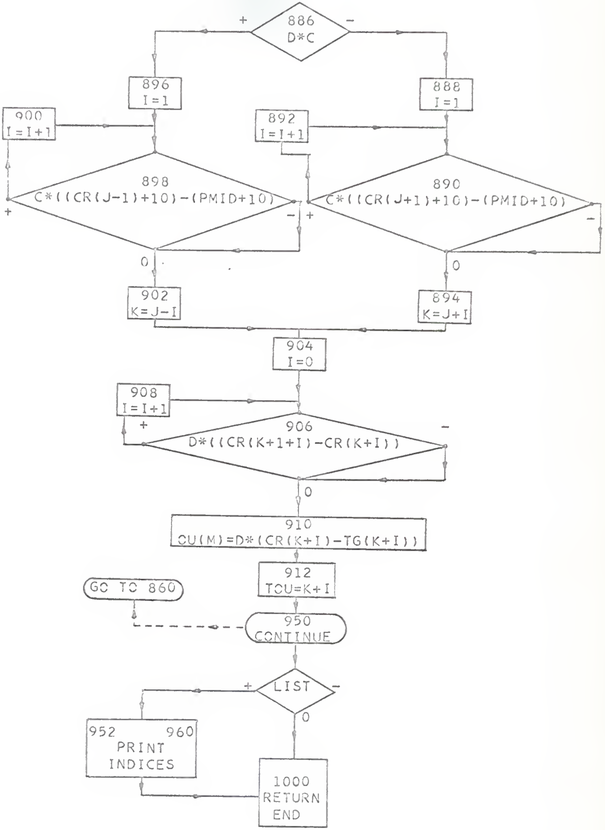



+
200
EL1-ABS(S(N-1)-C(N-1))
−
0
202
I=0
206
I=I+1
+
204
EL1-ABS(S(N-1)-C(N-I))
−
0
GO TO 420
+
300
(S(N-1)+10.)-(C(N-1)+10.)
−
+
302
D
−
+
304
D
−
400
I=0
GO TO 500
406
I=0
404
I=I+1
402
(S(N-1)+10)-(C(N+I)+10)
408
(S(N-1)+10)-(C(N+I)+10)
410
I=I+1
−
+
−
0
0
420
TL(M)=N+I
GO TO 700


500
EL1=ABS(S(N)-C(N))
+
-
0
502
I=0
506
I=I+1
504
EL1-ABS(S(N)-C(N-I))
+
-
0
GO TO 620
600
(S(N)+10.)-(C(N)+10.)
+
-
601
D
+
-
608
D
+
-
GO TO 700
604
I=0
610
I=0
607
I=I+1
613
I=I+1
606
(S(N)+10)-(C(N-I)+10)
612
(S(N)+10)-(C(N-I)+10)
-
+
-
0
0
620
TA(M)=N-I
GO TO 700


700
E=ABS(S(N)-C(N))
704
K=1
706
EL1-E
+
-
708
IO
+
-
0
726
IO
+
-
712
TA(M)
+
0
714
TA(M)=N
720
TL(M+1)=N
715
IO=+1
721
IO=-1
740
DO
KK=1,4
742
K=K+1
446
EL(K)-E
+
-
750
CONTINUE
752
K=6
800
TEI(K)=TEI(K)+1
802
ERR=ERR+E
804
SERR=SERR+E**2
810
DLEVEL-E
GO TO 28
+
-
0
815
TD=TD+1
850
CONTINUE


851
855
RECORD THE NUMBER OF STEPS SCORED (NSTEP)
CALCULATE THE AVERAGE ERROR (AERR)
CALCULATE THE RMS ERROR (RMSE)
CALCULATE THE PERCENT ERROR FOR EACH ERROR INTERVAL (PTEI)
857
859
CONVERT ALL RECORED VALUES OF TIME SO THAT THE VALUES CORRESPONDS TO THE ORIGINAL SAMPLING RATE
ORIGINAL = .5*(TIME)+.5
NOTE--IF A VALUE WAS ZERO IT IS .5 NOW
860
DO
M=1,NSTEP
861
870
CHECK FOR TIME LEAVE AND TIME ARRIVE
-- IF EITHER IS EQUAL TO .5 SET TL(M)=0, TA(M)=0, ZL(M)=77.7 AND TR(M)=77.7
-- IF BOTH ARE PRESENT FIND ZL(M) AND TR(M)
THEN J=ST(M)
SP(M)=TG(J)
FROM 950
872
PMID=(TG(J)+TG(J+1))*.5
874
(TG(J)+10))-(TG(J-1)+10.)
+
-
0
878
D=+1.
875
D=-1.
880
(CR(J)+10.)-(PMID+10.)
+
-
0
884
C=-1.
GO TO 904
882
C=+1.
GO TO 886


886
D*C
+
-
896
I=1
888
I=1
900
I=I+1
892
I=I+1
898
C*((CR(J-1)+10)-(PMID+10)
+
-
0
890
C*((CR(J+1)+10)-(PMID+10)
+
-
0
902
K=J-I
894
K=J+I
904
I=0
908
I=I+1
906
D*((CR(K+1+I)-CR(K+I))
+
-
0
910
CU(M)=D*(CR(K+I)-TG(K+I))
912
TCU=K+I
GO TO 860
950
CONTINUE
LIST
+
-
0
952
960
PRINT
INDICES
1000
RETURN
END

APPENDIX D

SUBROUTINE SCORE

ARGUMENTS

TG-------TARGET ARRAY

CR-------CURSOR ARRAY

ELEVEL---ARRAY OF ERROR LEVELS
ELEVEL(1)=VALUE OF ERROR LEVEL ONE
.
.
.
ELEVEL(5)=VALUE OF ERROR LEVEL FIVE

DLEVEL---VALUE OF TIME ON TARGET LEVEL

NPTS-----NUMBER OF POINTS IN THE TARGET AND CURSOR ARRAYS

ST-------ARRAY CONTAINING THE TIMES AT WHICH THE DIFFERENT STEPS OCCUR

TL-------ARRAY CONTAINING THE TIMES AT WHICH THE CURSOR LEAVES ERROR LEVEL ONE OF THE PREVIOUS STEP

TA-------ARRAY CONTAINING THE TIMES AT WHICH THE CURSOR ARRIVES AT ERROR LEVEL ONE OF THE NEXT STEP

TT-------ARRAY CONTAINING THE TIME ON TARGET FOR EACH STEP

ZL-------ARRAY CONTAINING THE LEAD-LAG FOR EACH STEP

TR-------ARRAY CONTAINING THE TIME OF RESPONSE FOR EACH STRP

SP-------ARRAY CONTAINING THE STEP POSITION FOR EACH STEP

OU-------ARRAY CONTAINING THE OVERSHOOT-UNDERSHOOT FOR EACH STEP

TOU------ARRAY CONTAINING THE TIMES AT WHICH THE OVERSHOOT-UNDERSHOOT OCCURS FOR EACH STEP

NSTEP----NUMBER OF STEPS SCORED

LIST-----PRINTING INSTRUCTION
VALUE OF ONE = PRINT INDICES
VALUE OF ZERO = DO NOT PRINT INDICES

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      SUBROUTINE SCORE(TG,CR,ELEVEL,DLEVEL,NPTS,ST,TL,TA,TT,ZL,TR,
     1SP,CU.TCU,NSTEP.LIST)
      DIMENSION TG(1),CR(1),ST(1),TL(1),TA(1),ELEVEL(1),TT(1),ZL(1)
      DIMENSION TR(1),CU(1),SP(1),TCU(1)
      DIMENSION S(2100),C(2100),TEI(6),PTEI(6),EL(6)
    1 FORMAT( 1 ,9X, AVERAGE ERROR = ,F7.3,9X, RMS ERROR = ,F7.3)
    2 FORMAT(10X, ERROR LEVEL  ,I1,- =  ,F4.1,   )
    6 FORMAT(3X,I5,3(2X,F6.1),3X,F4.1,6X,F4.1,5X,F4.2,8X,F5.2,9X,
     2F6.1,5X,F6.1)
    8 M=1
      D=1
      FRR=0
      SFRR=0
      TD=0.
      ST(1)=0.
      DO 10 K=1,6
   10 TEI(K)=0.
   14 DO 15 K=1,5
   15 EL(K)=ELEVEL(K)
   16 EL1=ELEVEL(1)
   17 IO=-1
   18 TG(NPTS+1)=TG(NPTS)
      CR(NPTS+1)=CR(NPTS)
      J=-1
      DO 19 N=1,NPTS
      J=J+2
      C(J)=CR(N)
      C(J+1)=.5*(CR(N)+CR(N+1))
      S(J)=TG(N)
   19 S(J+1)=TG(N+1)
      NP=J
   20 DO 25 J=1,100
      TL(J)=0.0
   25 TA(J)=0.0
      DO 850 N=2, NP
   30 ES=(S(N)+10.)-(S(N-1)+10.)
  101 IF(ES) 104,700,102
  102 D=1.
      GO TO 106
  104 D=-1.
  106 M=M+1
  107 ST(M)=N
  108 TT(M-1)=TD/(ST(M)-ST(M-1))
      TD=0.
  200 IF (EL1-ABS(S(N-1)-C(N-1))) 300, 202, 202
  202 I=0
  204 IF (EL1-ABS(S(N-1)-C(N+I))) 420, 420, 206
  206 I=I+1
      GO TO 204
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ABSTRACT

The limitations of the human when operating as part of a control system are becoming more apparent every day. This has prompted considerable research in the area of human behavior in control systems. Research in this area is being performed by the Psychology Department at Kansas State University by presenting a tracking task to numerous subjects. The main deficiency in the present tracking system is in the equipment which scores the subjects. Therefore this research was performed to obtain better scoring methods.

In the past the only index of performance obtained from the tracking system was the integrated error score (IES). To obtain more information on a subject the response of the subject was recorded and other indices of performance were measured. These measurements were made by hand which is time consuming and in many cases called for the scorer to make a judgement on the relative scores obtained. To obtain a better scoring procedure these indices were redefined so they could be measured by a computer. Then a computer program was written to obtain these redefined indices. Also a few indices that had not been obtained before were measured by the computer.

The indices obtained by the computer gave valuable information on the human tracker. Some of these indices were lead-lag, overshoot-undershoot, average error, RMS error and time on target. One index of performance which was of special interest was the RMS error. This index indicates the performance of a

tracker close to a target change. This index was of special interest because the RMS error could be implemented into the present tracking system. The other indices measured by the computer gave information concerning the cause of a certain IES or RMS error, but the equipment required to obtain these indices could not readily be built into the tracking system.

To obtain more information on scoring methods for the human tracker the tools used in communication theory were applied to an assumed mathematical model of the human being. The model was a second order system with a time shift placed at the input to simulate a lead or a lag in the response. The application of the tools of communication theory showed that the cross correlation of the target signal with the error signal gave a weighted average of the error about a target change. Another function considered was the ensemble average of the absolute value of the error close to target change, but equipment to obtain the cross correlation of two signals is easier to obtain.

The conclusions obtained from this research are that the equipment required to obtain the RMS error and the cross correlation of the target signal with the error signal should be implemented into the present tracking system. The equipment required is readily available and should not be too difficult to install.