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TACTILE DISPLAY FOR AIRCRAFT CONTROL

Don H. Rosa, et al

Sanders Associates, Incorporated

Prepared for:

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TACTILE DISPLAY FOR AIRCRAFT CONTROL

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13. ABSTRACT

Nearly all flight parameter information is transmitted to the pilot visually and it is well known that instrument scanning during zero visibility flying conditions can be fatiguing. Displays using information from other modalities can alleviate the demands of this task and this program was directed towards the development of tactile displays for flight control. The results of the first phase of this program have been reported in the August '73 Final Report (AD 767 763). This report presents a description of an improved tactile display system and its evaluation as a one and two axis error display instrument during a series of manual tracking experiments. Both electrotactors and vibrotactors arrays were used. These experiments were run to obtain modeling data to predict the display performance during the forthcoming F-4 simulator evaluation phase of the program. The tracking error scores for the new tactile display are better than for the initial system. Of the four subjects employed during these tests, two preferred the electrotactor array because it provides a more clearly perceptable haptic display.

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Cutaneous Displays						
Cutaneous Communication						
Cutaneous Stimulation						
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Vibrocutaneous						
Electrical Stimulation						
Tactile Displays, Communication						
Tactual Displays, Communication						
Tactors - Electrotactor, Vibrotactor						
Touch Perception						
Skin Senses						
Multiaxis Tactile Display						
Tactile Aircraft Control						

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont)

LIST OF TABLES

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Their interest, and the effort they have invested in the program along with their constructive comments on the design and application of the tactile display has been exceedingly helpful.

SUMMARY

The purpose of this program has been the exploration of tactile flight control displays through the development of the displays and their evaluation using formal psychophysical experiments. The need for transmitting information to pilots in modalities other than visual is becoming increasingly apparent for even now the visual sense is at times overloaded; furthermore, the importance of maintaining continuous attention to the visual scene outside the cockpit is being increasingly realized for a number of situations. Tactile displays possess considerable promise of being suitable substitutes for visual displays in flight-control applications.

This work has been done under two contractual phases. The first phase probed the problems of elemental tactile transducers, display configurations, and the evaluation of man/machine tracking performance utilizing both one and two axis displays, and with and without ancillary visual tasks. The results of this phase are reported in References 1 and 2.

The second phase has been directed towards the development of an improved display system, laboratory tests to validate the improvements, and to optimize the display parameters, and then to evaluate the display using a moving base simulator with F-4 dynamics. The laboratory tests, which were conducted with four, instrument-rated pilots indicates the display performance has been improved twenty-five to fifty percent referenced to the first phase tests. The remaining work consists of evaluating the display in the simulator.

SECTION 1
INTRODUCTION

1.1 OBJECTIVES

This program is a continuation of the research on tactile flight control displays that was begun in July 1972. The program involves multiple axis tactile display development and evaluation. The initial work accomplished during the first year was conducted in three phases: (a) review and selection of elemental tactual transducers (tactors) for operation in display arrays, (b) development of the tactual displays and data coding, and (c) evaluation of the tactual displays in a series of manual tracking experiments utilizing suitable dynamic simulation of aircraft motions and rated pilots as subjects. Details on the above work are reported in references (1) and (2).

The phase of the program now underway is directed toward the refinement of the two-axis tactual display based on the operation of the intial display and then to evaluate the improved display. The evaluation is to be conducted in two parts. First of all, BBN is to provide a laboratory evaluation similar to that accomplished with the initial display system in order to assess the display improvements and update the display model.

The final evaluation is to be performed utilizing a moving base aircraft simulator with F-4 dynamics, more specifically, the simulator operated by the NMC Weapon Systems Simulation Branch at Point Mugu, California. The program will incorporate the tactual display as a flight instrument during typical flight problems. The results of these experiments will indicate how well the display will function in harmony with other visual displays and the effect of motion on the perception of tactile sensations. The model developed during the static laboratory tests is to be used to predict the display performance in the simulator experiments.

Most of the previous experiments were done utilizing bimorph (piezoelectric) vibrotactors. The present evaluation experiments are being conducted with both electrotactors and vibrotactors to obtain relative performance and acceptance data.

This report contains the description of the new tactile control system and the evaluation and results of the preliminary tests conducted at the BBN laboratory. The design of the present equipment was executed to provide a more versatile system and minimize the delay time between error detection and display. The design has four major improvements:

- a programmable tactor excitation code
- automatic stimulus intensity control for the electrotactor display
- independent axis control
- separate intensity controls for the axes and y-axis segments

The function of the laboratory tests was to sift through, select and optimize the display parameters to provide the best achievable tracking performance, and to permit prediction of the performance in the simulator. Four subjects were used for these tests.

An extensive period of laboratory testing was found most helpful in the previous effort with regard to selection of tactile-display parameters. Questions related to display geometry, display format, and to some extent display coding, were resolved.

The present laboratory study was undertaken to select and then evaluate one or two tactile display codes on the basis of their suitability for flight control tasks. Both one-axis and two-axis tracking tasks were examined, and performance comparison is made using a continuous visual display as the reference.

During the course of this program, we have always used coaxial electrodes for the electrotactors because the skin current induced from an individual tactor would be isolated by means of the common, or grounded outer electrode. This hypothesis was tested and found invalid. As this test has no connection with the program, a summary of the procedure and results are presented in Appendix 1.

1.2 FIRST PHASE SUMMARY

Most of the formal experimental time was devoted to an investigation of continuous manual tracking performance with both tactile and visual displays, in addition, combined tracking and visual monitoring tasks were studied in order to provide relative comparisons of tactual and visual tracking displays in situations imposing a high visual scanning workload. Two instrument-rated pilots served as test subjects for the entire evaluation.

The results of the evaluation have shown that the tracking error scores obtained with the tactile display were a factor of three to four times greater than scores obtained with continuous visual display. However, the results also indicate the intertask interference effects are substantially less with the tactile display in situations imposing a high visual scanning workload. The single-task performance degradation found with the tactile display appears to be a result of the display coding rather than the use of the tactual sensor mode per se. Analysis with the state-variable pilot/vehicle model shows that reliable predictions of tracking errors can be obtained for a limited set of system configurations once the pilot-related model parameters have been adjusted to reflect the pilot-display interaction. The results of this program have indicated that tactile displays appear to have the capability of alleviating the pilot's high visual workload and that with a refined display code it will be able to fulfill the requirements of single task performance and minimum task interference.

SECTION 2
EQUIPMENT DESCRIPTION

2.1 GENERAL

The Tactile Control System presented in Figure 2-1 consists of the following parts.

a. Tactile Control Unit (TCU), left in the figure, contains the logic circuitry and all the controls necessary for the functional operation of the system. The visual display in the middle of the panel is removable for remote viewing.

b. Tactile Power Supply (TPS), right in the figure, contains the system power supplies and the power control switches.

c. Two electrotactor displays, both of which have the same configuration and incorporate silver, coaxial electrotactors.

d. One vibrotactor display employing bimorphs as the electromechanical vibration transducers.

e. Two cutaneous display belts, one of which is shown under the vibrotactor display.

For this phase of the program, one display format has been selected; it is an array using eight tactors per axis, four for each axis polarity and no central common tactor. Each axis is a complete, independently controlled channel to allow simultaneous data presentation to both axes. In order to increase the versatility of the system, a switch is available to allow either independent data

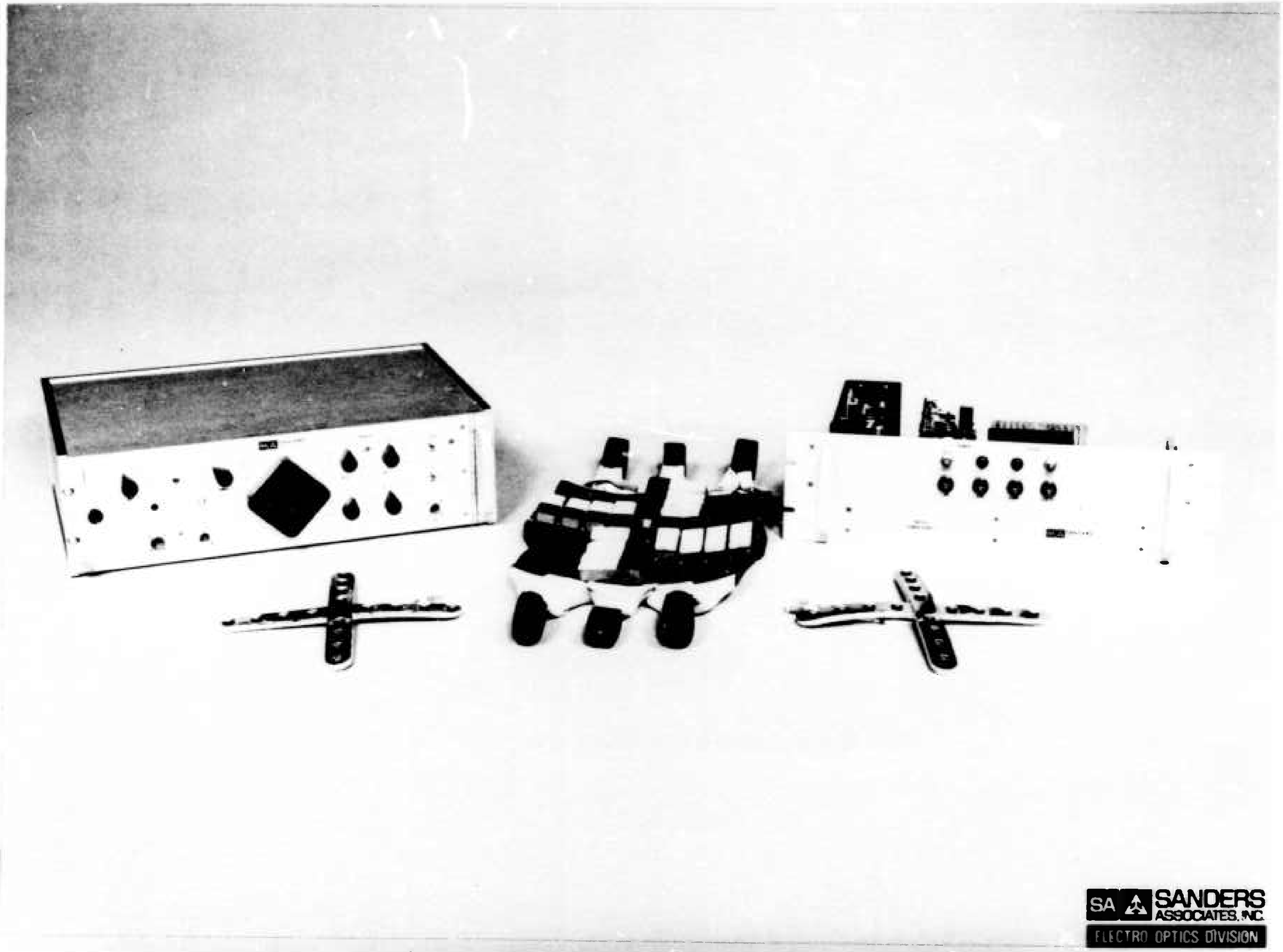

Figure 2-1 Tactile Control System.

display for each axis, or an alternate-axis display sequence. A number of tactor excitation codes are available and, if desired, each axis can have a different code.

2.1.1 TACTILE POWER SUPPLY

The front panel of the Tactile Power Supply is shown in Figure 2-2 and the top view is shown in Figure 2-3. The power switch on the front panel controls the AC input to all power supplies, each of which is fused separately. The 170 Hz power for the vibrotactors draws the greater amount of power, thus to provide optimum power efficiency a separate power switch (in series with the main power switch) regulates the operation of the 170 Hz power supply.

In Figure 2-3, the components of the power supply, beginning at the left side are as follows:

a. 24 VDC power module for the 170 Hz power supply

b. 5 VDC power module

c. $\pm$15 VDC power module

d. In front of the $\pm$15 VDC module are a transformer and two large capacitors, these are components of the $\pm$150 VDC power supply for the electro-tactor drivers.

e. The component board, transformer, and the two heat sinked transistors on the right side compose the 140 Vrms, 170 Hz power supply used to drive the vibrotactors. A trim pot near the center of the board allows control of the output voltage between 130 to 170 volts rms.

A 3-wire power cord is used in order to ground the chassis of both the power supply and the TCU. The system common is not grounded to the AC line ground in order that it can be made common to the signal ground of the equipment from which the analog control signals are derived.

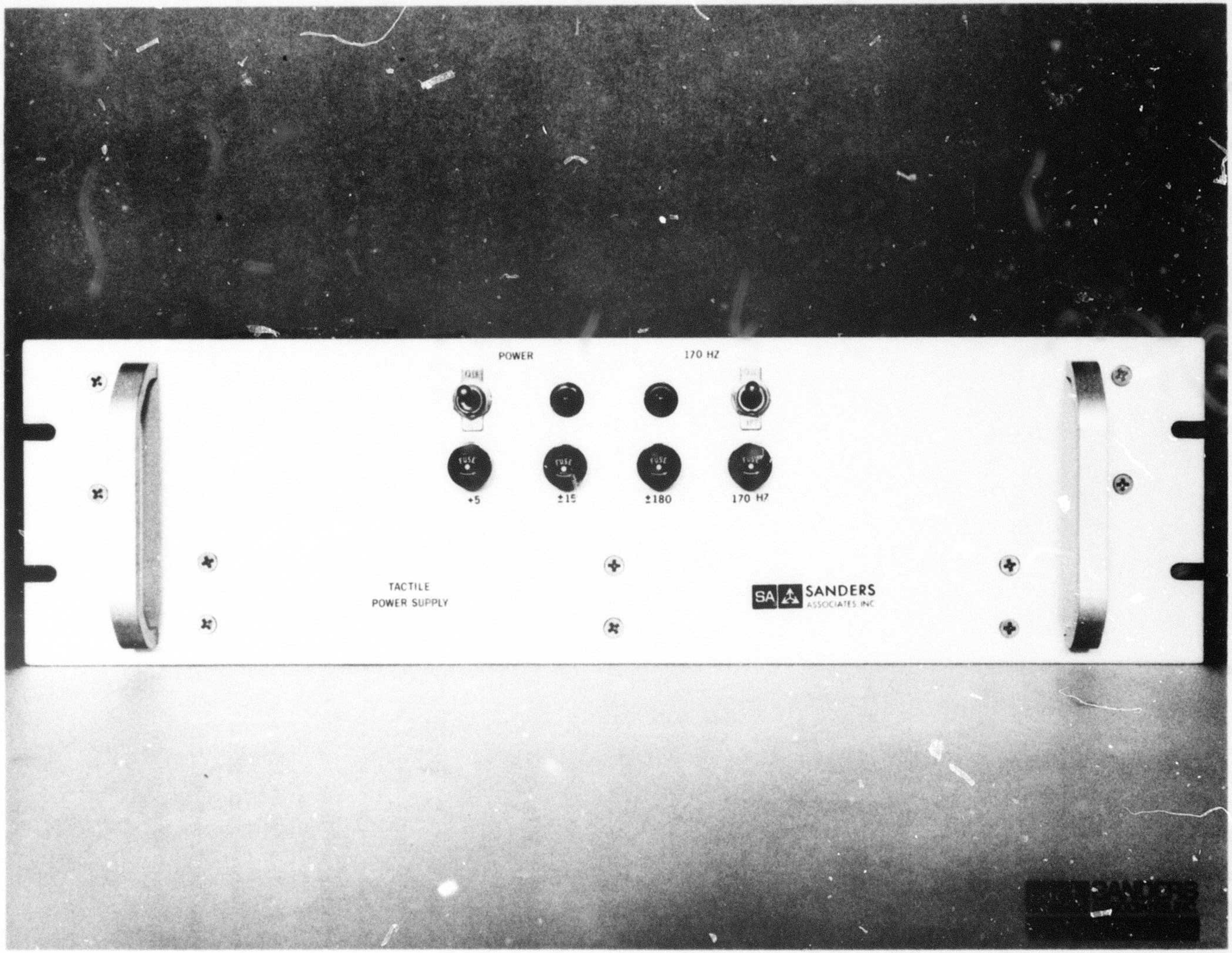

Figure 2-2 Tactile Power Supply, Front Panel.

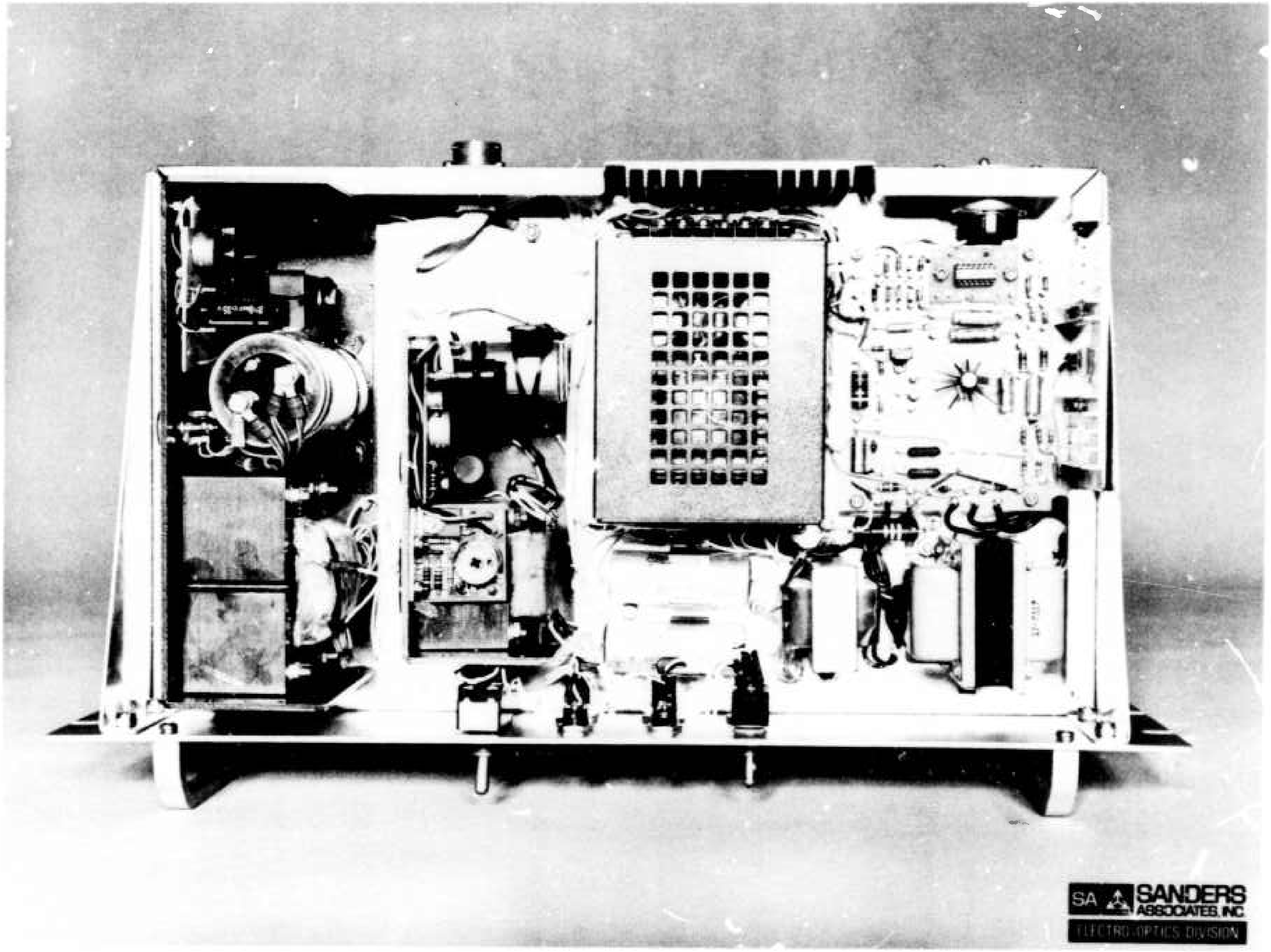

Figure 2-3 Tactile Power Supply, Top View.

2.1.2 TACTILE CONTROL UNIT

The front panel of the TCU is shown in Figure 2-4. It is hinged on the right side to allow access to the logic cards as shown in Figure 2-5. A description of the front panel controls, indicators, and cable connectors is as follows:

a. ±X INT - This control regulates the peak current delivered to the skin by the tactors forming the X-axis of the electrotactor display. The calibration points represent peak current into 5K ohms. Actual current will be less due to variations in skin impedance (5 to 10K ohms). Control should be left at CCW limit when not being used.

b. +Y INT - This control regulates the peak current delivered to the skin by the 4 tactors forming the upper half of the Y-axis of the electrotactor display. Calibration as for a. above. Control should be left at CCW limit when not being used.

c. -Y INT - This control regulates the peak current delivered to the skin by the 4 tactors forming the lower half of the Y-axis of the electrotactor display. Calibration as for a. above Control should be left at CCW limit when not being used.

d. ON-OFF - This toggle switch directly controls the ±150 VDC to the electrotactor drivers. The switch should be left in OFF position when the electrotactor display is not in use.

e. FIXED-AUTO - This toggle switch regulates the method used to control the pulse width of the constant - current skin excitation signal delivered by the electrotactors. In the FIXED position the pulses have a fixed width of 20 microseconds. In the AUTO position, the pulse width decreases from 20 to 17, to 14, to 12 microseconds as the input control signals increase in magnitude. This is a locking toggle switch and must be pulled out before toggling.

f. INDICATOR LAMP - This light signifies the system power is on.

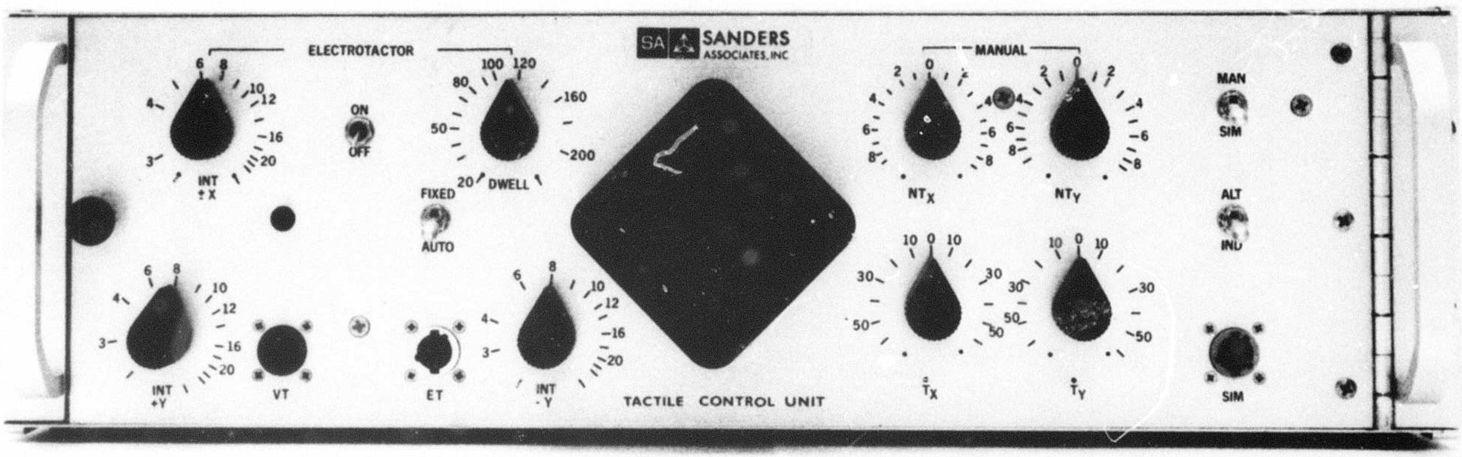

Figure 2-4 Tactile Control Unit, Front Panel.

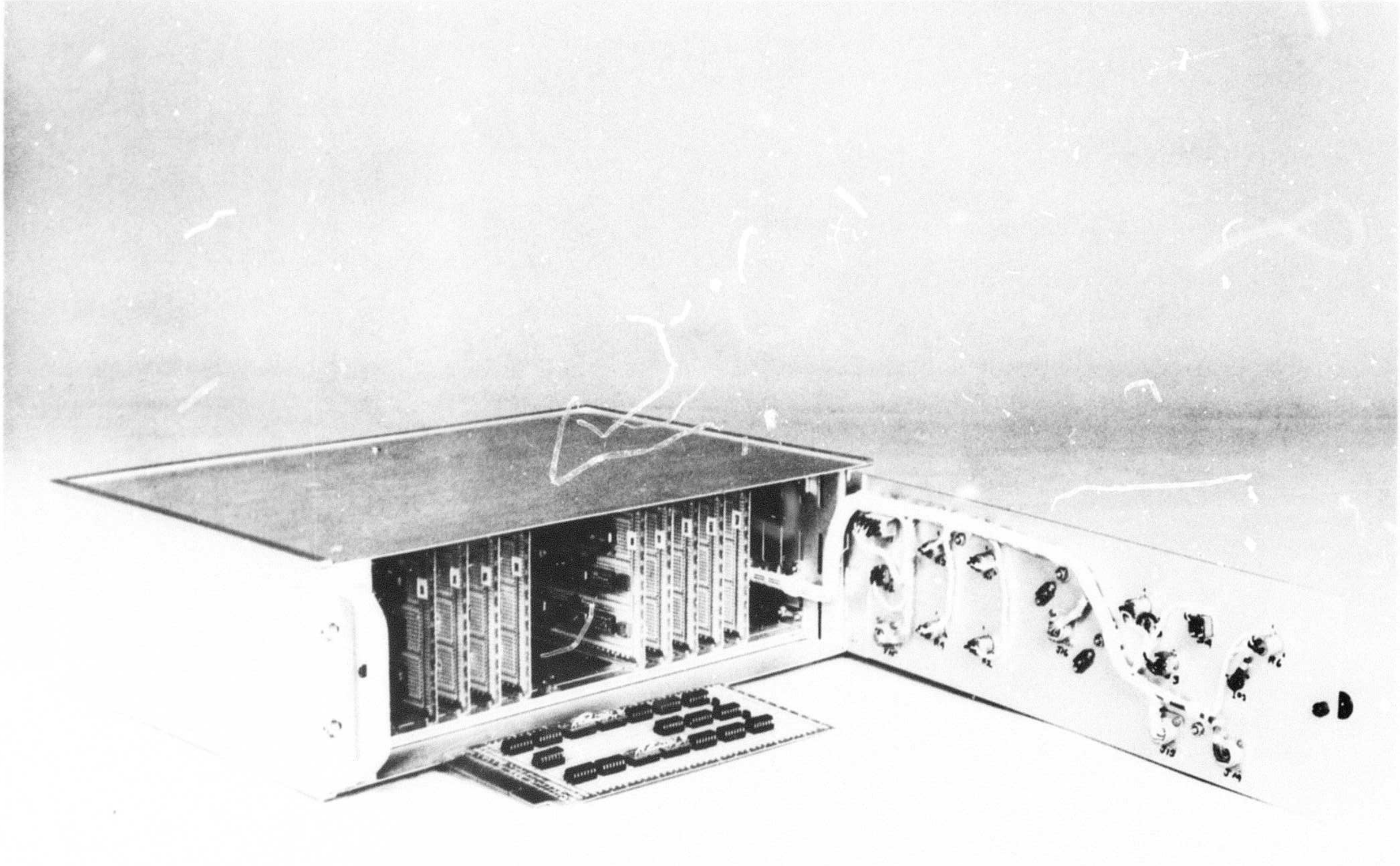

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Figure 2-5 Tactile Control Unit, Card Access.

g. DWELL - **This control** is presently disconnected and the DWELL has been fixed at 300 microseconds. DWELL is the time delay between the last excitation of one display sequence and the beginning of the next. The control when connected regulates the DWELL for both axes, it is calibrated in milliseconds, with the deviation between axes indicated by the calibration curve in Figure 2-6.

h. VT - This cable receptacle is the output connector for the vibrotactor display. It is color coded blue and keyed to accept only the vibrotactor display cable.

i. ET - This cable receptacle is the output connector for the electrotactor display. It is color coded white and is keyed to accept only the vibrotactor display cable.

j. Visual Display - This display contains an array of LED's on a one-to-one basis with the tactile displays. A LED lights when its corresponding tactor is energized. It is removable by loosening the upper right and lower left captive screws. A 10 foot cable is supplied for remote viewing.

k. MANUAL Controls - These 4 controls are active when the MAN-SIM switch is in the MAN position. They provide scaled analog signals to the display system when control loop signals are not being used.

> NT_X and NT_Y are calibrated with 10 being full scale or 100 percent. They control the quantization level of their respective channels.
>
> $\dot{T}_X$ and $\dot{T}_Y$ control the tactor ripple rates and are calibrated in hertz with DWELL set at 20 ms.

l. MAN-SIM - This toggle switch selects either the MANUAL controls, or the analog signals connected to the SIM receptacle for the control of the tactile displays. This is a locking toggle switch and must be pulled before toggling.

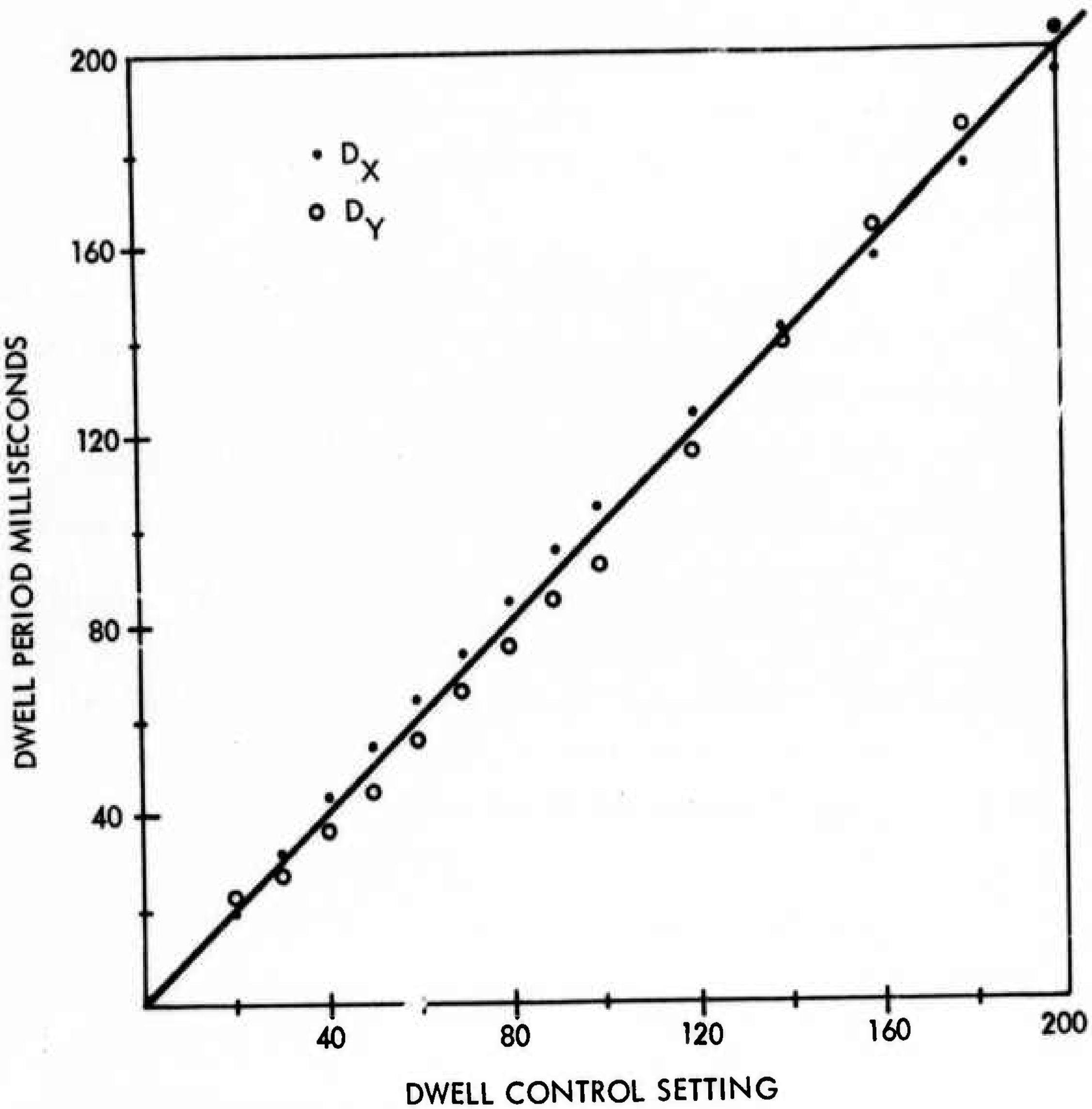


Figure 2-6 Dwell Control Calibration.

m. ALT-IND - This switch selects the display sequence. In the ALT position, the position error data is alternately displayed on one axis, then the other. In the IND position, each axis is independently controlled and the error data is displayed as it occurs.

n. SIM - This cable receptacle provides the interconnection between the tactile display and the control system. The control input and pin designations are listed in Table 2-1.

TABLE 2-1

SIM RECEPTACLE INPUTS

PIN NO.	DATA DESCRIPTION
1	$VNT_X \pm 100$ VDC
2	$VNT_Y \pm 100$ VDC
3	$V_{\dot{T}X} \pm 100$ VDC
4	$V_{\dot{T}Y} \pm 100$ VDC
5	Common
6	Spare
11	I_X, X-axis, ET Current (100 V/A)
12	I_Y, Y-axis, ET Current (100 V/A)

The input signals V_{NTX} and V_{NTY} are quantized to three levels and control the number of tactors excited during a display sequence. The input signals $V_{\dot{T}X}$ and $V_{\dot{T}Y}$ control the display ripple rate according to the calibration curve presented in Figure 2-7.

In addition to the front panel controls there are two trim-pots and five discrete component, plug-boards used to change the display programming. Most of these components can be seen in Figure 2-5. Two double plug-boards are located on Board No. 2 (lying in front of the card cage). These boards contain jumper wires which control the tactor excitation code. (See Appendix 3 for programming.) The plug-boards on the left are for the X-axis and the ones on the

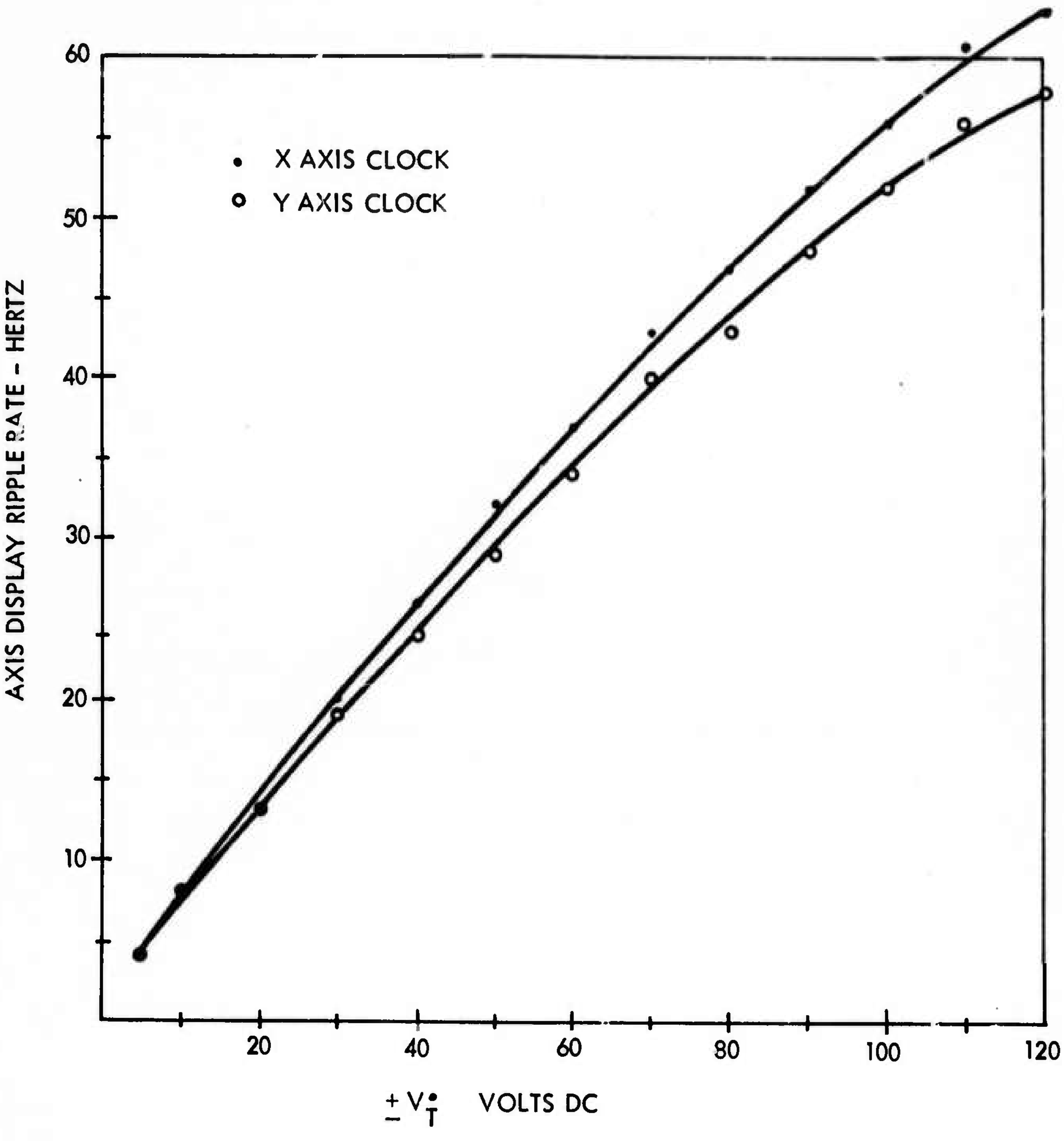


Figure 2-7 X-Y Axis Clock Period Calibration.

right are for the Y-axis. On Board No. 8 (to the right of the center opening), there are two trim-pots and two resistor plug boards. The trim pots control the biphasic stimulation pulse-pair recurrence frequencies, the upper pot controls the X-axis frequency and the bottom pot controls the Y-axis frequency. They are set at 200 Hz. The resistor board behind the upper pot controls the quantization levels of the $|\dot{T}|$ signals used in the auto-intensity control (see Appendix 4). The resistor board behind the lower pot controls the electrotactor stimulation pulse widths used during auto-intensity control. The last resistor board is located on Board No. 4 and controls the 3 quantization levels of the NT_X and NT_Y signals. (See Appendix 2.)

2.2 DISPLAY FORMAT

Only one format has been fabricated for the displays, it is an X-Y array having no central tactor and with 4 tactors in each leg as illustrated in Figure 2-8. The size of the array is fixed, i.e., the tactors are not movable. It is well known that tactile spatial resolution is generally not high, thus it is advantageous to separate the tactors as much as possible; however, for convenience, the tactile display should be small. Therefore, a compromise has been made by fixing each axis length to 9 inches. This allows 1-1/8 inches between tactors in each axis leg and 2 inches between the central tactors.

One of the final electrotactor displays is shown in Figure 2-9. The electrotactors are coaxial and have silver electrodes. The OD is 11 mm with an inner electrode area of 17 mm^2 and an outer electrode area of 57 mm^2.

Figure 2-10 is the vibrotactor display resting on one of the belts used to apply the display to the body. The 1 mm diameter probes used to vibrate the skin is driven with a piezoelectric crystal (bimorph) held as a cantelever and is capable of providing a peak force of 30 grams at 150 volts. A one-inch square pressure pad surrounds the 0.25 inch probe clearance hole in order to minimize the effects of skin wave propagation.

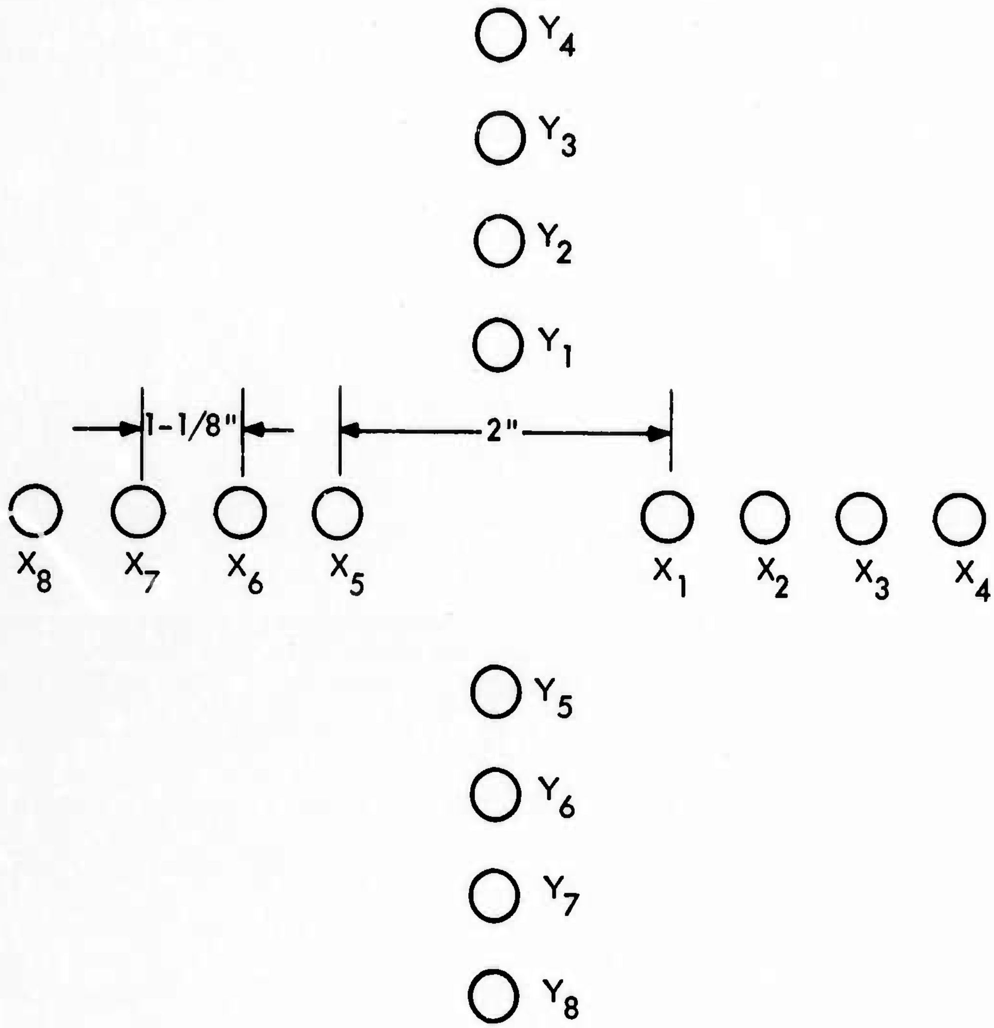


Figure 2-8 Tactile Display Geometry.

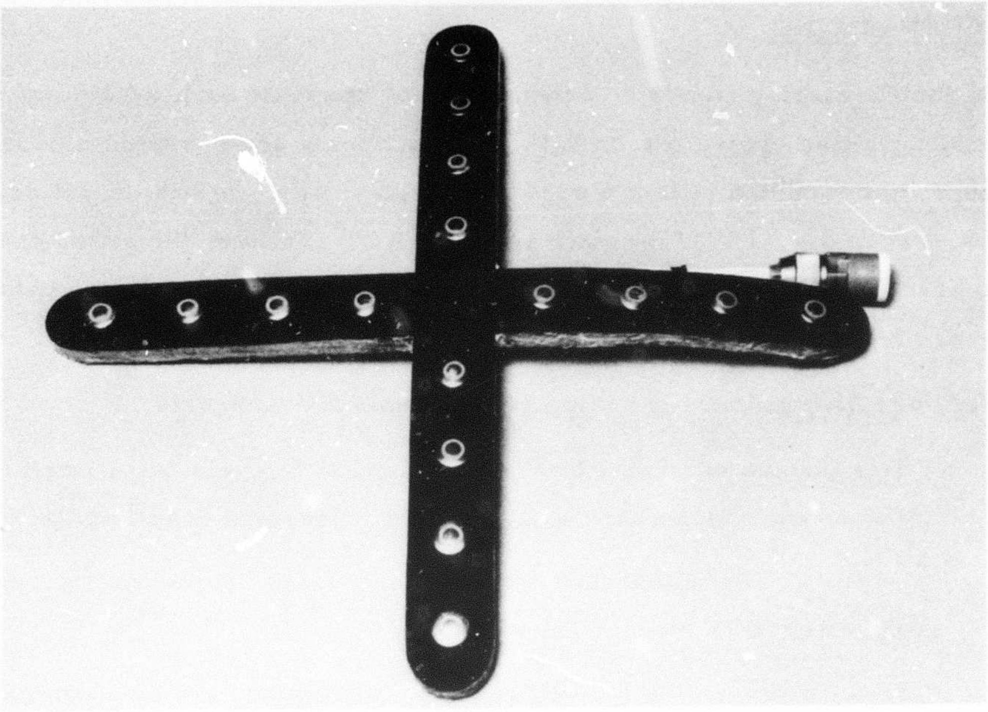


Figure 2-9 Electrotactor Display

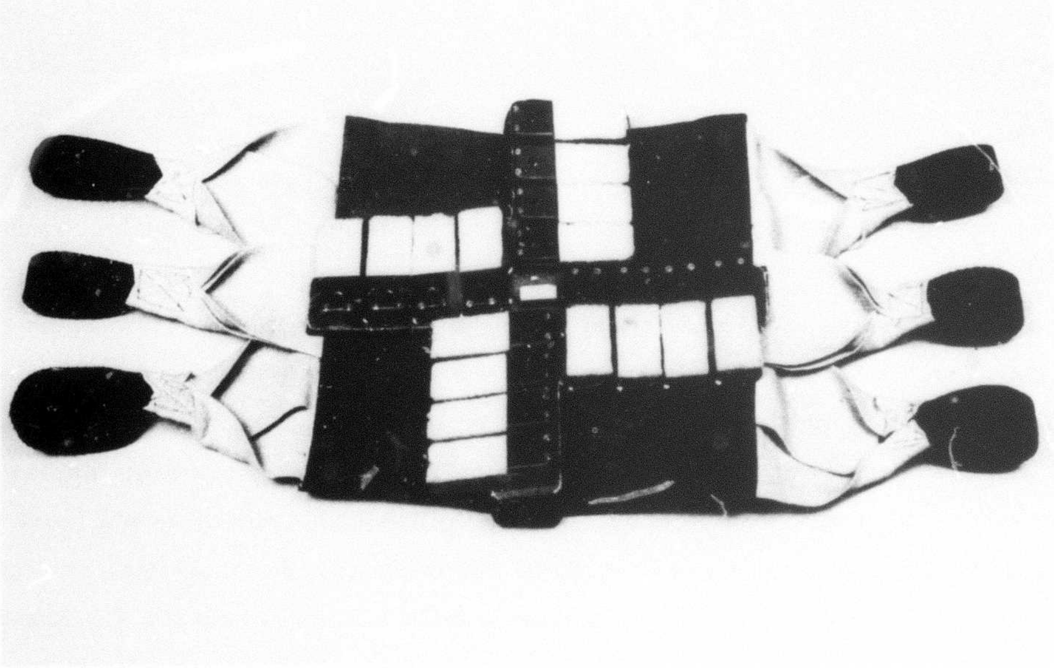


Figure 2-10 Vibrotactor Display.

2.3 DISPLAY CODING

The tactile display consists of two, parallel channels each capable of presenting polarity sensitive control error data. The channels are operated independently to the extent that each can utilize a separate display code. In one operational mode, i.e., when the ALT-IND switch is in the ALT position, the error data of one channel is held in an off state, while the other channel is displaying data, thus they alternately display their respective control data.

There are two controlling analog input signals for each axis:

- NT is the analog signal that is quantized to 3 levels (A, B, and C), presently corresponding to 5, 30, and 70 percent of full scale.
- $\dot{T}$ is the analog signal that directly controls the tactor excitation ripple rate from 4 to 60 Hz.

The three NT quantization levels for both channels are set by a precision resistor network mounted on a removable plug-board located on Board No. 4. The plug-board has two sets of resistors, one to provide levels corresponding to 5, 30, and 70%, and the other 5, 20, and 80%. To switch from one to the other the plug-board is rotated 180 degrees. If other quantization levels are desired, a new plug-board can be fabricated with the required resistors. (See Appendix 2.)

The input data directly controls the tactile display such that any control error variations will be transposed to cutaneous communication signals. During an excitation sequence of one axis, 2, 3, or 4 tactor stimulus periods can be generated as determined by what quantization level was maintained during the display period. A tactor stimulus period is the time during which a tactor can be excited. A dwell period is used between the termination of the last stimulus period and the onset of the first tactor stimulus period of the following display period; this dwell period can be controlled by the DWELL control on the front panel of the TCU through the range of 20 to 200 milliseconds, however, during the initial tests, it became desirable to eliminate the dwell and allow the $\dot{T}$ signals complete control of the display rate. The $\dot{T}$ signals regulate the display clock frequencies and for every clock pulse, a tactor stimulus period can be initiated.

The freedom within which the display can be coded is set by the following bounds.

- There are four tactors.
- There are two sequenced clock periods generated for a NT level A.
- There are three sequenced clock periods generated for a NT level B.
- There are four sequenced clock periods generated for a NT level C.

Table 2-2 illustrates some of the available codes. The clock periods are denoted as T_1, T_2, T_3, and T_4 as they are initiated by sequential display clock pulses in numerical order. The location of the dots signify the occurrence of a tactor stimulus period for the specific tactor during the selected clock period. The tactor numbers correspond to the tactor identification indicated in Figure 2-8.

The selection of tactor groups 1, 2, 3 and 4, or 5, 6, 7 and 8 is made by the polarity of the NT signal, for example:

- $+V_{NTX}$ selects tactor group X_5, X_6, X_7 and X_8
- $-V_{NTY}$ selects tactor group Y_1, Y_2, Y_3 and Y_4

Consider Code 3 and V_{NTY} equal to -10 volts. The first clock period, T_1, initiates the stimulus period for tactor No. 4 which is the uppermost tactor of the Y-axis. The second clock period initiates the stimulus period for tactor No. 3 and if the error voltage (V_{NTY}) remains within the bounds of 5 and 30 volts (5 and 30% of full scale) this sequence is repeated at a rate controlled by the $V_{\dot{T}Y}$ signal. If the error increases, one or two more tactors will be used in the display sequence.

In codes 5 through 7 more than one tactor is driven simultaneously, or as in Code 4 a single tactor is selected for each quantization level and is repeatedly driven while one tactor is never selected. Thus, in general, any code that can be defined within the bounds of the code truth table can be implemented. Implementation of the selected code is accomplished by programming the plug-boards on the Program Card (B2). (See Appendix 3.)

TABLE 2-2

TACTOR DISPLAY CODE TRUTH TABLES

Tactor	Code 1									Code 5								
	A		B			C				A		B			C			
	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4
1, 5	●		●			●				●	●	●	●	●	●	●	●	●
2, 6		●		●			●				●		●	●		●	●	●
3, 7					●			●						●			●	●
4, 8									●									

Tactor	Code 2									Code 6								
	A		B			C				A		B			C			
	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4
1, 5		●			●				●		●			●				●
2, 6	●			●				●		●	●		●	●			●	●
3, 7			●				●					●	●	●		●	●	●
4, 8						●									●	●	●	●

Tactor	Code 3									Code 7								
	A		B			C				A		B			C			
	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4
1, 5									●									●
2, 6					●			●						●			●	●
3, 7		●		●			●				●		●	●		●	●	●
4, 8	●		●			●				●	●	●	●	●	●	●	●	●

Tactor	Code 4									Code 8								
	A		B			C				A		B			C			
	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4
1, 5																		
2, 6	●	●																
3, 7			●	●	●													
4, 8						●	●	●	●									

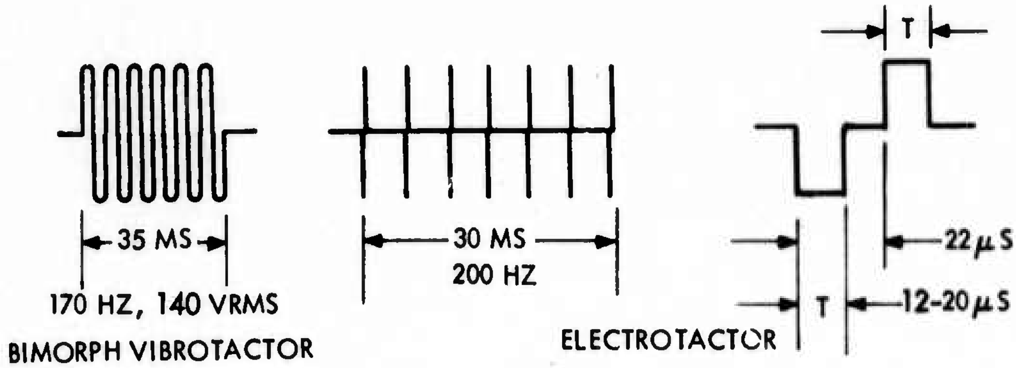
2.4 TACTOR EXCITATION

The tactile displays are fabricated using two different tactor types, bimorph (piezoelectric) vibrotactors and electrotactors. The bimorph excitation signal is a six cycle burst of 170 Hz, 140 Vrms; and the electrotactors are excited with seven cycles of biphasic constant current pulses. Representative sketches of these signals are illustrated in Figure 2-11(a). The resulting stimulus period for either of these signals is 30 milliseconds or about twice as long as the 60 Hz period occurring at the maximum ripple rate, consequently for ripple frequencies greater than 30 Hz, the tactor stimulus periods will begin to overlap and two adjacent tactors will be on simultaneously. In Figure 2-11(b), the X-axis tactor (1, 2, 3) stimulus periods are shown for Code 1, level B presentation with the ripple rate less than 30 Hz, and the Y-axis stimulus periods are shown for Code 1, level B presentation with the ripple rate greater than 30 Hz.

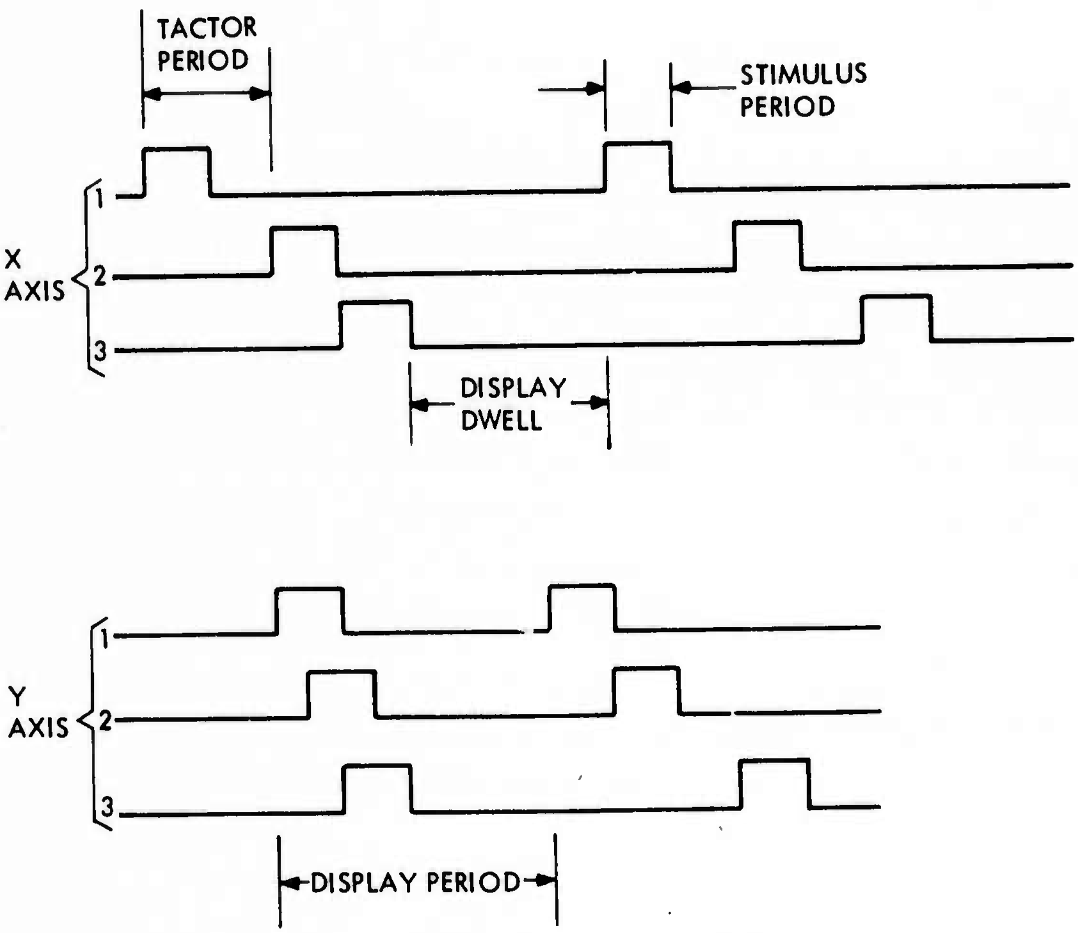
If, during an initiated display period, the $\dot{T}$ or NT input signals change, the change will be directly transferred to the tactile display. The $\dot{T}$ input continuously controls the tactor ripple rate. There are two conditions to satisfy for changes in the NT signal after a display period has been started: What happens when the quantization level jumps to a higher level (A to B or B to C) and what happens when the reverse occurs? The jump to a higher level will allow the excitation of the tactors required for the higher level. The jump to a lower level has two cases. If the last stimulus period had not been started, the newly required number of periods will be generated and the display period will be terminated. If, for instance, a display period for a B level presentation was started and during the third stimulus period would be immediately terminated, thus ending the display period. The loss of the A quantization level at any time will terminate the data display.

2.5 SYSTEM DESCRIPTION

The tactile display system block diagram is presented in Figure 2-12. As stated, each axis is independently controlled, thus the system basically consists of



(a) TACTOR STIMULUS SIGNALS



(b) TACTILE DISPLAY PERIODS

Figure 2-11 Tactor Stimulus Signals and Display Periods.

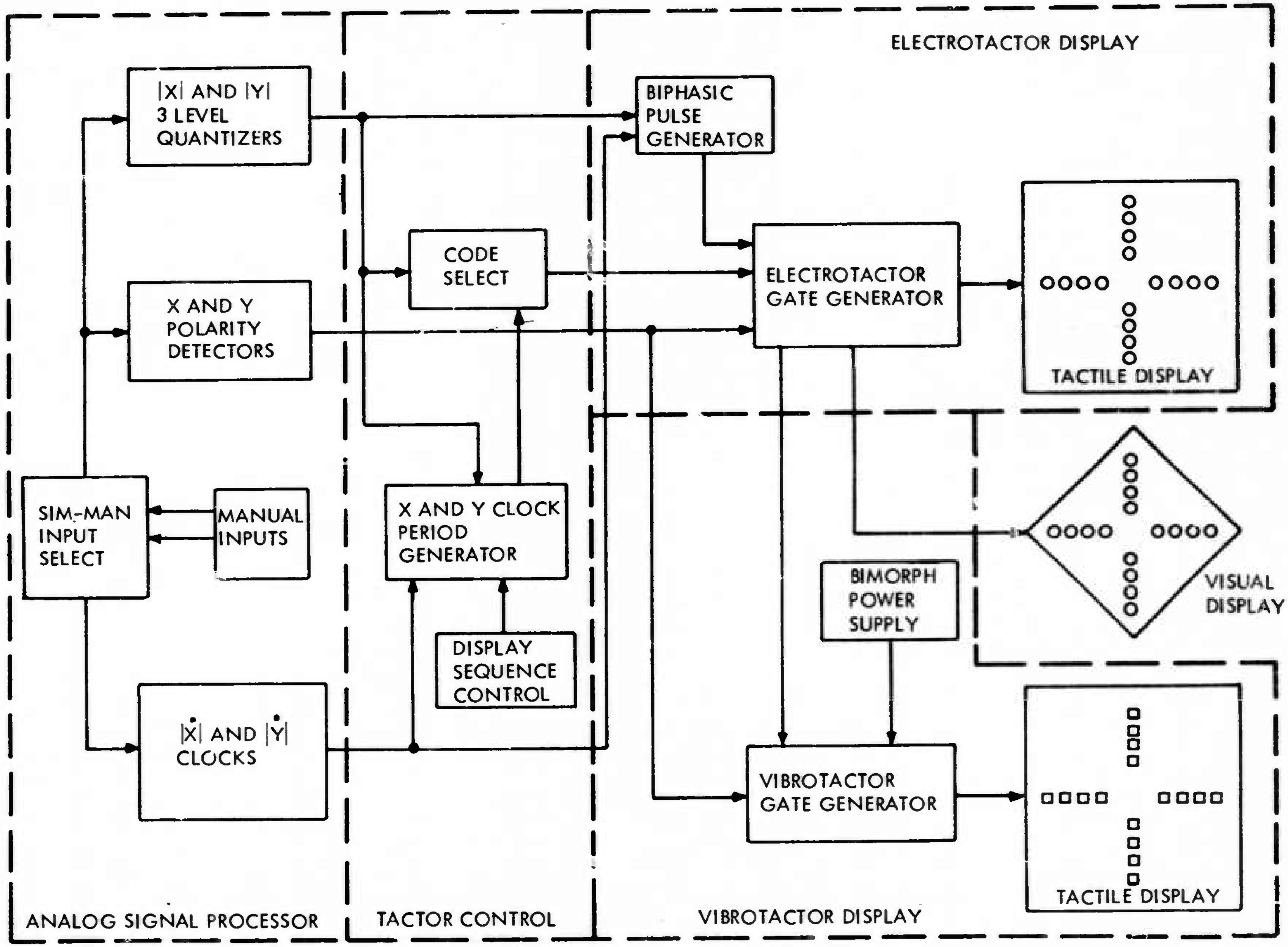


Figure 2-12 Tactile Display Block Diagram.

two parallel data channels, the X-axis and the Y-axis. They are synchronized only when the alternate axis display mode is selected. The system description is presented in four parts: analog signal processor, tactor control, electrotactor display and the vibrotactor display.

2.5.1 ANALOG SIGNAL PROCESSOR

The analog signal processor derives its inputs from either the manual controls on the front panel of the Tactile Controle Unit (TCU) or from an external control system such as the F-4 simulator which is utilized in the display evaluation as discussed in paragraph 2.3. For each tactile display axis, two analog signals are required, V_{NT} and $V_{\dot{T}}$.

The F-4 simulator computation voltages are ± 100 Vdc full scale; they are rescaled to the ± 8 Vdc full scale voltage used in the tactile display. The MAN-SIM switch on the TCU front panel selects either the analog signals from the SIM receptacle or from the four potentiometers located on the front panel.

The V_{NT} signal for each channel (X, Y) is the input for the three level quantizer and the axis polarity control. The three levels (A, B, C) for both axes are set by the same voltage divider network. The initial quantization level reference voltages are $A \geq 0.4V$, $B \gtrsim 2.4V$, and $C \gtrsim 5.6V$, which correspond to 5, 30 and 70 percent of full scale. This resistor network is mounted on a plug board to facilitate changing the reference values when desired. To minimize the number of comparators, the absolute value of the analog signal is used. The quantization levels (A, B, C) control the number of generated clock periods (2, 3, or 4) used as variables for the tactor period logic in the selection of various tactor excitation codes. The levels are also inputs to the automatic electrotactor intensity control. The polarity signal (P_X or P_Y) is used in its respective tactor gate generator to determine which of the two, four tactor sets of one axis is to be used to display the error data, i.e., is the data polarity positive or negative.

The absolute values of the $\dot{T}$ data signals ($|\dot{X}|$) and ($|\dot{Y}|$) are used to control the clock rates at which the tactor stimulus periods are generated. The minimum clock pulse rate is set at 4 Hz in order to eliminate excessive display time delays that would occur at lower rates. The maximum clock rate is 60 Hz. The $|\dot{X}|$ and $|\dot{Y}|$ signals are also used in the auto-intensity control for the electrotactors.

2.5.2 TACTOR CONTROL

The function of the tactor control section is to generate the number of clock periods determined by the quantization level (A, B, C) at the rate decreed by the $\dot{T}$ input. This is done by counting the clock pulses and generating gates equal to the interval periods between sequential clock pulses.

The four possible clock periods (T_1, T_2, T_3 and T_4) are combined to form six multiple period combinations (i.e., T_2T_3, $T_1T_2T_3$, etc.). The four clock periods and their combinations serve as inputs to the code selector where they are programmed by the selected code plug-boards, and combined with the quantization levels to produce the desired tactor gate sequence. There are four outputs for each axis, T_{15}, T_{26}, T_{37} and T_{48}. Each output controls one of two tactors pending the polarity of the NT signals, for instance T_{15} will control tactor No. 1 if the axis V_{NT} signal is negative and will control tactor No. 5 if the polarity is positive.

The X and Y clock period generators are designed to operate independently, however, the ALT-IND switch on the front panel provides the option of selecting independent operation or an alternate-axis display mode. During the alternate-axis display mode, the clock period generator of one axis is held in its DWELL or reset state while the other is presenting its data, then when its DWELL is initiated, the held-off axis is allowed to operate in its turn.

The DWELL period is presently fixed at 300 microseconds such that there is no delay between display periods, however a DWELL control exists on the front panel which will allow a controlled delay of 20 to 200 milliseconds. A wiring change on Boards No. 1 and 3 is required to reconnect the DWELL control.

varies, requiring separate intensity controls for the upper and lower halves of the array. It is probable that in a future operational system, the individual tactor drivers could be trimmed to the relative mean threshold of its location; then with one intensity control all tactors could be optimally controlled.

Prior data has indicated that the electrocutaneous sensation increases proportionately to the number of tactors being excited and the rate of excitation, or, in other words, proportional to the power dissipated in the skin. With the range of excitation codes and ripple rate, it would be impossible to maintain a single, constant level of cutaneous sensation, thus a feed-forward intensity control is used to control the excitation pulse width. If the pulse widths are reduced to about 5 μs, the touch sensation is extremely low even when peak currents of 20 to 25 milliamperes are used, hence controlling the pulse width between 20 and 5 μs provides a very affective intensity control. The pulse width control has been quantized such that 20, 17, 14, or 12 μs pulses will be generated. (Appendix 4 describes procedure for setting pulse widths.) The decision logic used to select the pulse width is based on the quantization level, ripple rate, and inter-axis intensity magnitudes. The logic signals for the NT quantization levels (A, B and C) already exists. The $\dot{T}$ data is quantized to furnish two levels.

F_1 when $\dot{T} > 20$ Hz

F_2 when $\dot{T} > 40$ Hz

The pulse generator is designed to provide 20 μs pulses unless one of the following logic equations are satisfied:

$$X_{17} = A_x F_{2x} + B_x F_{1x} + C_x F_{1x} \qquad (1)$$

$$X_{14} = B_x F_{2x} + C_x F_{1x} + X_{17} Y_{17} \qquad (2)$$

$$X_{12} = C_x F_{2x} + X_{14} Y_{14} \qquad (3)$$

These equations are for the X-axis. As an example, take equation (2); this states that the X-axis biphasic pulse width will be 14 μs (X_{14}) if NT_X is quantized in the

2.5.3 ELECTROTACTOR DISPLAY

The electrotactor gate generator accepts the clock gates from the code selector, the polarity signals, and the biphasic pulse pairs. Its function is to generate the tactor stimulus period from the clock gate, then, with the polarity signal, route the biphasic pulses to the proper tactor drivers.

The clock gate onset is coincident with the leading edge of the clock pulse. A post clock pulse is generated coincident to the trailing edge of the clock pulse. The post clock pulse is ANDed with the clock gates to produce the SOS (stimulus onset signal) for the tactor pair (such as T_{15}) having its related clock gate at a "1" level. The SOS resets the stimulus pulse counter which then begins to count the pulse pairs, and gates the pulse pairs, in conjunction with the polarity signal, to the proper tactor drive circuit. When seven pulse pairs have been delivered, the counter is turned off, awaiting its next SOS. The tactor driver converts the low level logic signals to the required high level constant current pulses required to exceed touch threshold. The conversion from clock gates to stimulus gates is necessary because at $\dot{T}$ rates greater than 30 Hz the stimulus periods overlap the clock gates, hence, during these periods, two tactors in one axis can be on simultaneously for up to one-half the stimulus period of 30 ms.

The biphasic signal described in reference (2) is used as the tactile stimulus. The signal consists of a short burst of seven negative and positive, square constant current pulse pairs at a 200 Hz rate, as illustrated in Figure 2-11(a).

The maximum pulse widths are 20 μs and there is a fixed period of 22 μs between the beginning of the negative and the positive pulses. The constant current magnitude of the pulses is controllable from the front panel which is accessible to the subject. An operating peak current range of 3 to 20 milliamperes is provided.

There are 3 current level controls, one for the X-axis and two for the Y-axis. The X-axis is applied laterally on the abdomen and when centrally located, the average touch threshold of the two 4-tactor bits is equal and a single control is adequate. For the Y-axis, which is oriented longitudinally, the touch threshold

B level and $\dot{T}_x$ is equal to or greater than 40 Hz, or that NT_X is quantized in the C level and $\dot{T}_x$ is equal to or greater than 20 Hz, or that the NT and $\dot{T}$ signals of both the X and Y axes are such that X_{17} and Y_{17} are fulfilled, i.e., each individually qualify for 17 μs pulses. Satisfying the X_{14} equation implies the X_{17} equation is also balanced.

2.5.4 VIBROTACTOR DISPLAY

The vibrotactor display accepts the SOS from the electrotactor gate generator, the polarity signals, and the bimorph power (170 Hz, 140 Vrms). As for the electrotactor channel, the SOS resets a counter which in turn opens the related vibrotactor gate. The gate is ANDed with the polarity signal to turn-on the desired tactor via its driver. The tactor driver converts the logic level vibrotactor gate to the power level necessary to turn on the triac used to switch the 140 Vrms of the selected tactor. With the gate open, the bimorph excitation begins with the next 170 Hz zero-cross-over point. When the counter reaches its full count of six cycles, the vibrotactor gate is closed by the next 170 Hz zero-cross-over, thus terminating the stimulus period.

2.5.5 VISUAL DISPLAY

The LED (light emitting diode) display has three main functions: as a monitor to establish proper system operation, as an aid in training subjects, and as an operational display to establish a performance reference for the selected display format and code. The LED visual display has the same format as the tactile displays but with the lights closer together. The display is fabricated such that it can be mounted on the front panel, or used with an extension cable for remote viewing. The drive signals for the LED's are derived directly from the electrotactor gate generators.

SECTION 3

DISPLAY EVALUATION - LABORATORY

3.1 GENERAL

The laboratory study consisted of optimizing the tactile display, comparing two tactor types (electrotactor and vibrotactor), and evaluating the optimized display. In optimizing the display, a number of alternative coding schemes were investigated and various values of the display parameters were explored. In comparing the two tactor types, both objective and subjective measures of tactor suitability were obtained. In evaluating the display, the performance of four trained subjects was measured in tactile and visual tracking tasks.

The laboratory tracking tasks were designed to explore the limits of performance with the various tactile display configurations.* Accordingly, the subjects performed a simulated wide-band attitude tracking task of the type used in the previous study.** It was hoped that this experimental situation would encourage the subjects to work hard at the tracking task, and allow measurements of pilot performance over a reasonably wide frequency range using both electrotactors and vibrotactors.

*We assume that the displays which provide best performance in a somewhat stressful tracking task will also be the ones that provide best performance in less severe tasks of the type contemplated for ultimate application.

**See reference 2.

In addition to performing the tracking task, the subjects filled out a three-part questionnaire consisting of a comparison of the two tactor types, suggested improvements, and potential use in flight.

Four instrument rated pilots served as test subjects for the experimental program. Subject DE (who had participated last year) and subject RF were commercial airline pilots with over 1000 hours and 330 hours respectively of instrument flight time. Subjects BO and JK were flight instructors with over 360 hours and 150 hours respectively of instrument flight time.

The explicit goals of the study were the following:

a. Determine the most suitable code for a one-axis tactile display.

b. Determine the most suitable code for a two-axis tactile display [if different than a.].

c. Find optimal settings of the display parameters for both one- and two-axis displays.

d. Quantify performance differences, if any, between electrotactor and vibrotactor displays.

e. Explore differences in pilot acceptance and ease of use between electrotactors and vibrotactors.

f. Explore the extent to which pilots would accept a tactile display which had been optimized and modified to their specifications.

g. Obtain a full set of performance measures for the tactile displays and compare with visual tracking performance measures.

h. Predict performance in tasks to be explored in the F-4 simulation.

The following detailed description of the laboratory study has been divided into four parts: (1) display optimization, (2) training, (3) comparison of tactor types, and (4) performance measurement. The pilot questionnaire is discussed in Appendix 5, while the performance prediction has not yet been completed and will be included in the final report.

3.2 DISPLAY OPTIMIZATION

Since a formal study could not be performed for each display parameter, a small informal study was conducted, using Sanders and BBN technical personnel, to make a preliminary selection of the most promising codes and parameter values. In addition, because test subject DE had participated in last year's tracking experiment, he required far less time to train than did the three other subjects. Consequently, he was able to participate with us in the preliminary definition phase while the other subjects were completing their training.

The data obtained in this phase of the study consist of some objective measurements of tracking performance as well as subjective impressions of display effectiveness and comfort. Although we generally did not obtain statistically valid data, we made observations and drew tentative conclusions in a number of areas.

3.2.1 RIPPLE RATE RANGE

One of our first observations on trying out the tactile displays was that a maximum ripple rate of 60 hz seemed to be somewhat too high. We felt that it was too intense, and that it made distinguishing between large and small errors difficult. After a bit of testing, we reduced the maximum rate to 15 hz by attenuating the analog input signal $\dot{T}$ by a factor of four.

This arrangement was kept throughout almost the entire training period until just prior to the final test. An additional experiment was then conducted to see whether 15 hz was, in fact, a good choice for the maximum ripple rate. This experiment consisted of a series of one- and two-axis tracking runs performed by all four subjects. The results showed that in the one-axis case, increasing the maximum ripple rate from 15 hz to 60 hz improved the rms tracking scores by about 20 percent on the average. (Significant at the .01 level.) In the two-axis case, however, such as increase in the ripple rate produced virtually no change in the tracking scores.

Considering these test results, while keeping in mind the high stimulation intensity experienced at high ripple rates, we decided to compromise; we set the maximum ripple rate to 30 hz by attenuating the analog input signal $\dot{T}$ by only a factor of two.

3.2.2 CODE SELECTION

Code 3 (see paragraph 2.3) seemed a priori to be the most promising code for several reasons. First of all, because large errors are displayed by rippling over four tactors the highest possible ripple rate is permitted and the possibility of overstimulating a small area is minimized. In addition, because the outermost tactor (4 or 8) is always excited first, maximum spatial separation for even small errors is obtained. A possibly objectionable consequence of exciting the outer tactor first, however, is that the ripple direction is reversed from normal (i.e., from the outermost tactor to an inner tactor). We felt that this was a relatively unimportant drawback, since we found that sensing the direction of ripple is very difficult at high ripple rates.

In order to examine a large number of aspects of tactor coding in a short time, we decided to compare Code 3 with one other code that (a) seemed promising, and (b) differed from Code 3 in many respects. Code 4 (see paragraph 2.3) fit these requirements. It requires only three tactors per arm; it provides the additional cue of distance of the excited tactor from the center of the array increasing with increasing error; and there is no rippling.

A brief comparison of Codes 3 and 4 in a series of one-axis tracking tasks using subject DE indicated little difference in performance between the two codes. This result was in agreement with our subjective reaction that despite the large difference in the way the two codes felt, they seemed about equally effective in displaying tracking error. We eventually chose Code 3 over Code 4 because of the lesser chance of overstimulating a small region, and because it permits the freedom of using a higher maximum ripple rate.

3.2.3 SIMULTANEOUS OR SEQUENTIAL PRESENTATION OF TWO-AXIS ERRORS

One conclusion of last year's study was that in an improved display for two-axis tracking, the errors should be presented simultaneously on both axes, rather than sequentially on alternate axes. With the sequential presentation algorithm, such as the one used last year, the time between successive presentation of error on a given axis is increased by about 20 percent on the average. It was concluded that this increased display delay time caused a performance degradation beyond that normally associated with the requirement of the pilot to share attention between two tasks.

Despite this conclusion, however, it remained to be seen whether simultaneous presentation would introduce confusion into the subjects' perceptions, thereby negating its advantage of diminished display delay. Thus, this year, the tactile display was modified to allow either simultaneous or sequential presentation of two-axis errors.

A brief comparison of simultaneous versus sequential presentation, in a series of two-axis tracking tasks using subject DE, indicated roughly a 15 percent improvement in rms tracking score in the simultaneous mode. Although this result was only marginally significant (only 95 percent confidence) and represents a total of only twelve runs of 3 1/2 minutes each, it was in agreement with our subjective reaction that the simultaneous mode would provide a better display.* We therefore decided to adopt the simultaneous display for the remainder of our experimental work.

3.2.4 AUTO OR FIXED PULSE WIDTH

Preliminary work with electrotactors indicated that it would probably be necessary to automatically reduce the width of the biphasic pulses with increasing

*Subject DE also felt that in the simultaneous mode, the tactile sensation on one axis helped to locate the center of the other axis.

ripple rate in order to prevent excessive cutaneous sensation. We wondered, however, whether such a pulse width reduction would counteract the effect of encoding error magnitude in ripple rate, and thereby wash out the perceptual difference between errors of different magnitudes. To provide some flexibility regarding the pulse widths, the electrotactor control unit included a switch which either fixed the pulse widths at 20 usec (FIXED mode), or caused them to be automatically reduced from 20 usec to as short as 12 usec depending on the error magnitude (AUTO mode).

A brief comparison of the FIXED vs AUTO mode of pulse width control in a series of two-axis tracking tasks, again using subject DE, indicated virtually no difference in performance achieved using between the two modes. As expected, however, the electrotactile display was far more comfortable in the AUTO mode. Consequently, we adopted the AUTO mode for the remainder of the tests run with the electrotactile display.

3.3 TRAINING

3.3.1 EXPERIMENTAL PROCEDURE

Experimental runs of continuous tracking were typically grouped into "sessions" of three 4-minute runs each. A rest period of about 1 minute was provided between runs in a single session; a substantially longer rest period between sessions (10-15 minutes) was provided for each subject.

The subjects were informed of their performance after each training run (although no such feedback was provided during the formal data sessions). The subjects were instructed to minimize mean-squared tracking error when tracking a single axis, and to minimize the sum of the mean-squared pitch and roll errors when tracking the two axes jointly.

The subjects wore earphones while using the vibrotactile display in order to prevent them from obtaining auditory cues from sounds produced by the vibrotactors.

Wide-band noise was played through the earphones at a level that was comfortable and sufficient to prevent the localization of external sounds. Earphones were worn for the other conditions as well to provide proper experimental control.

3.3.2 TRAINING PROCEDURE

The test subjects were given considerable training on the simulated pitch and roll tracking tasks. They were trained first with the visual display to facilitate rapid learning of the vehicle dynamics and the characteristics of the simulated gust disturbance. Each subject performed about thirty runs of two-axis tracking with the visual display, after a bit of practice on one-axis tracking. This was enough training to yield reasonably stable performance scores on the order of what we had expected from past levels of pilot proficiency.

The four subjects were then trained with both electrotactor and vibrotactor displays, receiving a total of about 120 training runs on the average with the tactile displays. Roughly equal training was provided with each of the two tactor types, and about equal effort was devoted to each of the three task conditions (i. e., pitch, roll, and pitch+roll). To facilitate the adjustment to the tactile displays, the subjects performed about the first quarter of their tactile training runs on the easier single-axis tasks. From that point on, however, the 1- and 2-axis tasks were mixed.

3.3.3 TRAINING RESULTS

The training histories of the four subjects illustrated in Figures 3.1 - 3.4. For each condition, the first five runs and the last five runs of the training period are plotted. The double-axis scores represent the sum of the mean-square error scores (i. e., the mean-square pitch score plus the mean-square roll score) from 2-axis runs; while the single axis scores represent the sum of mean-square error scores from pairs of 1-axis runs. Since the rms input level was varied during training, all performance scores have been normalized with respect to the input levels used for the visual task so that the meaningful learning curves can be

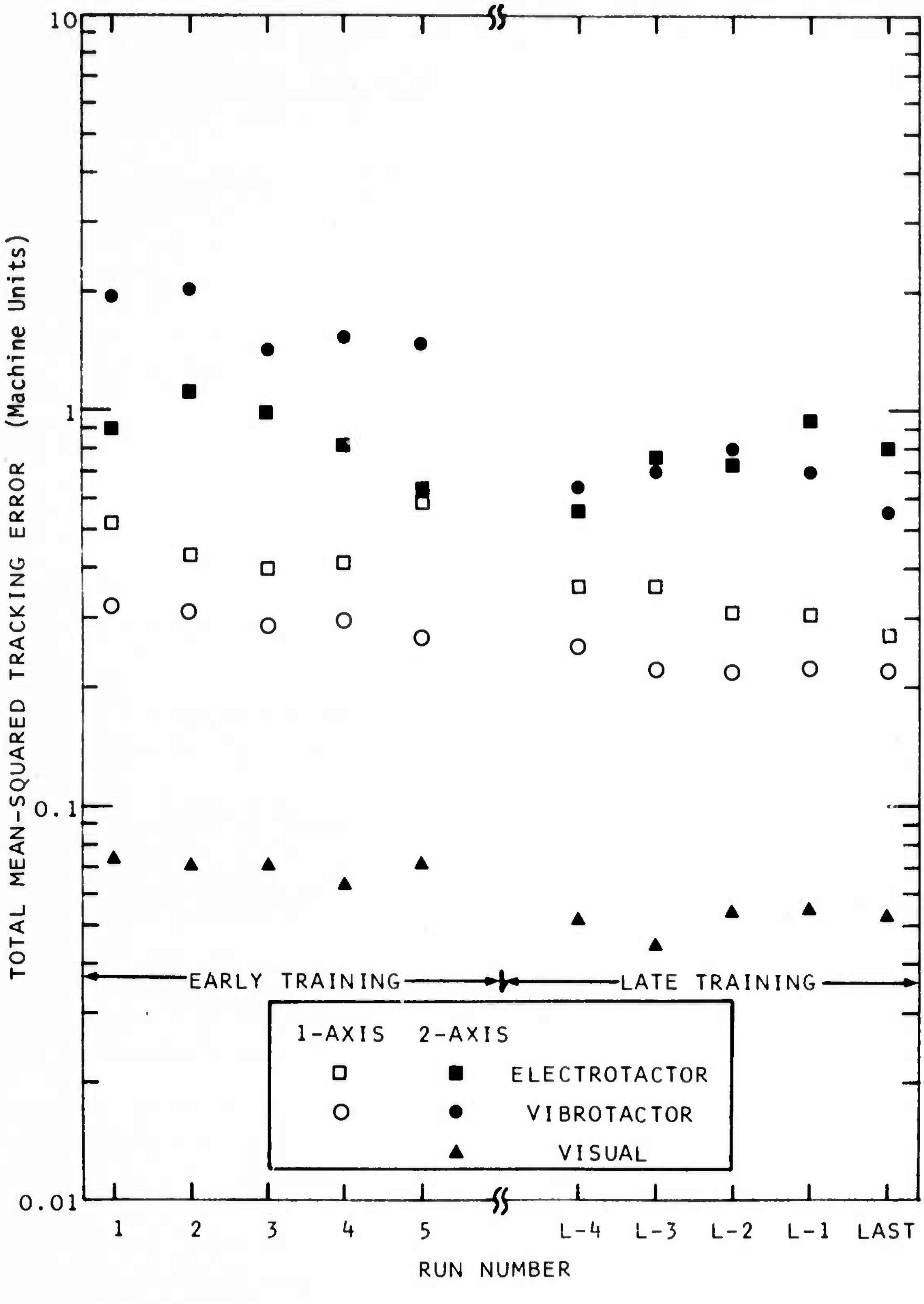


Figure 3.1 Training History of Subject DE.

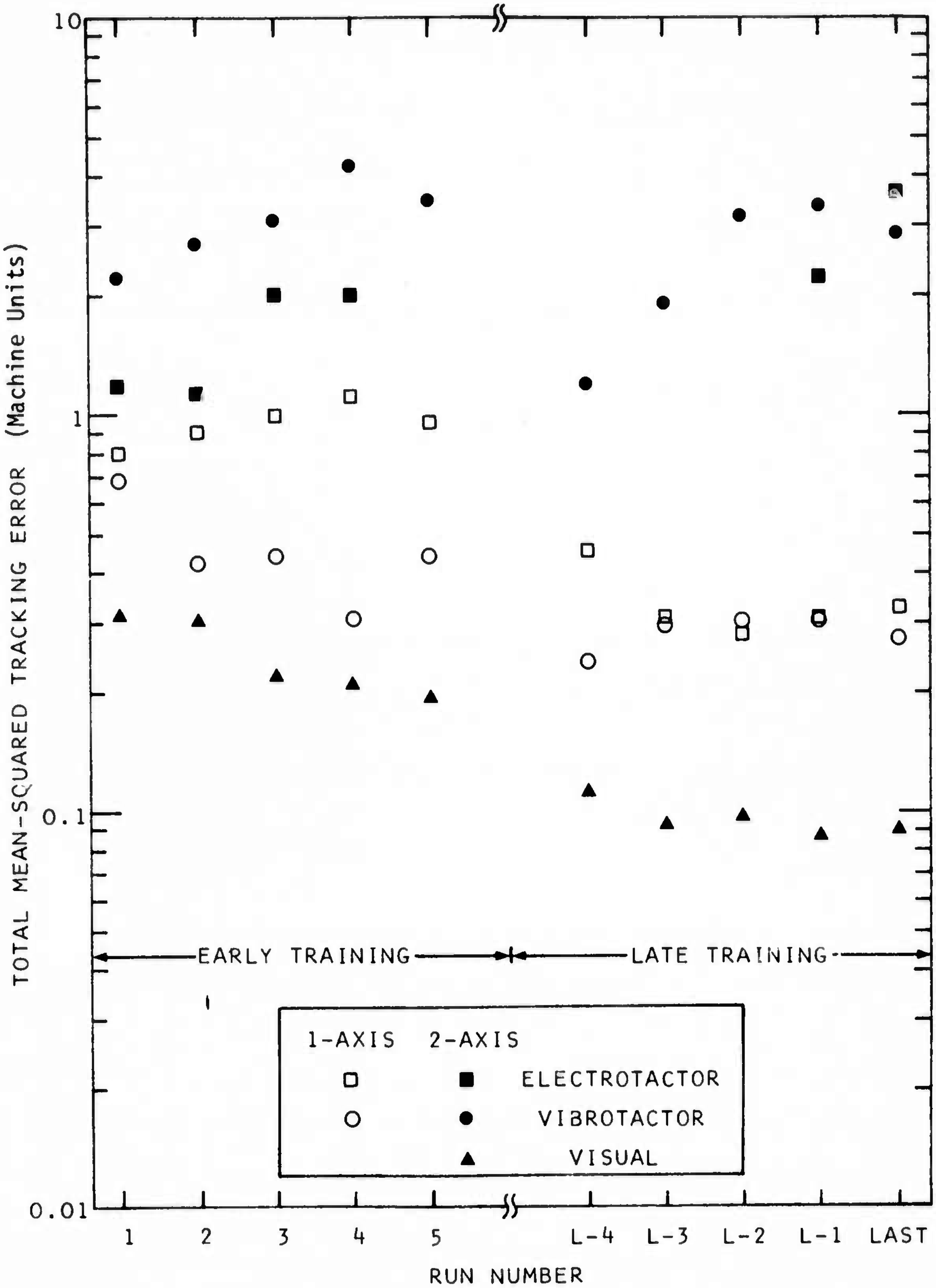


Figure 3.2 Training History of Subject R.F.

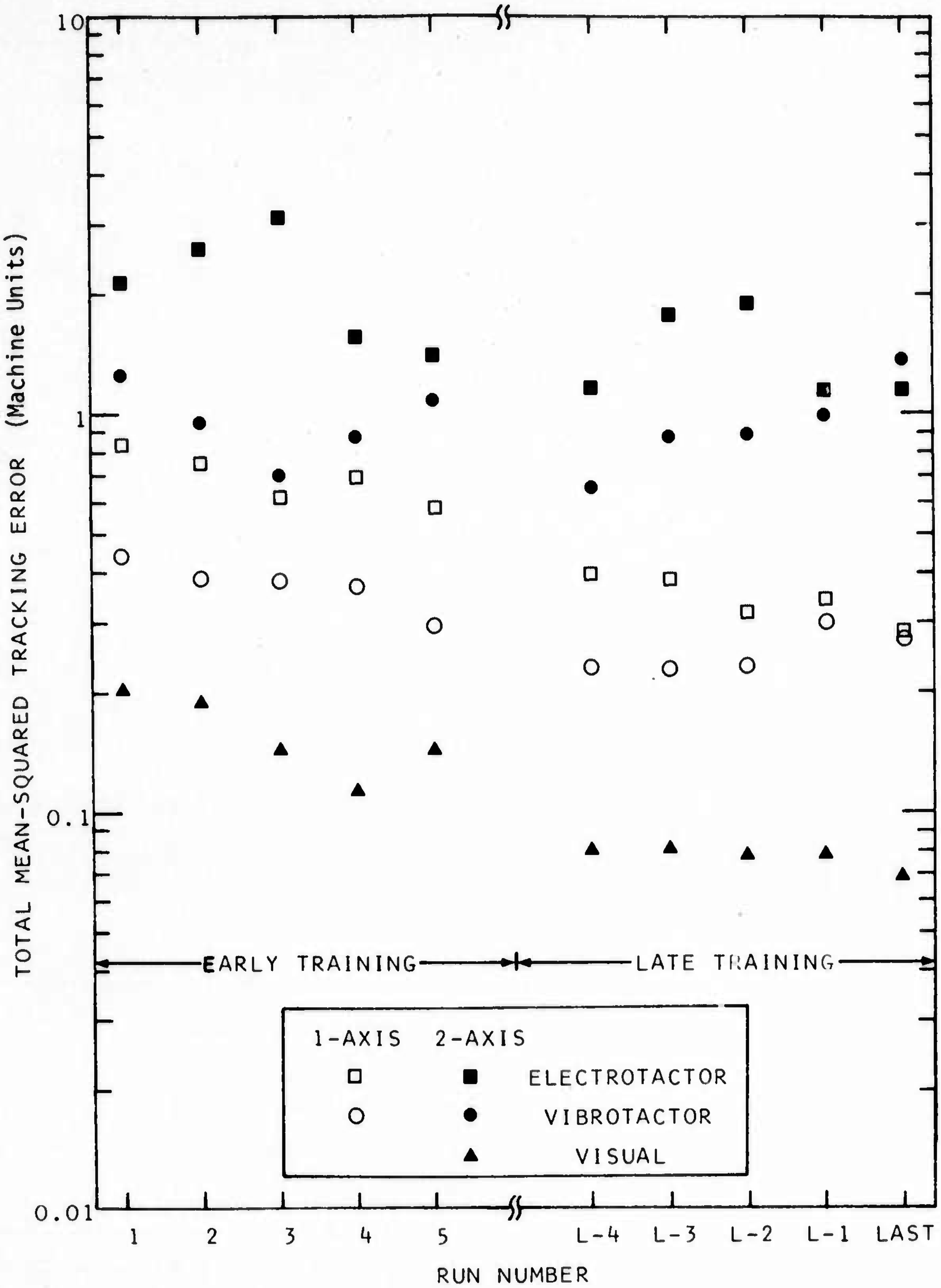


Figure 3.3 Training History of Subject BO.

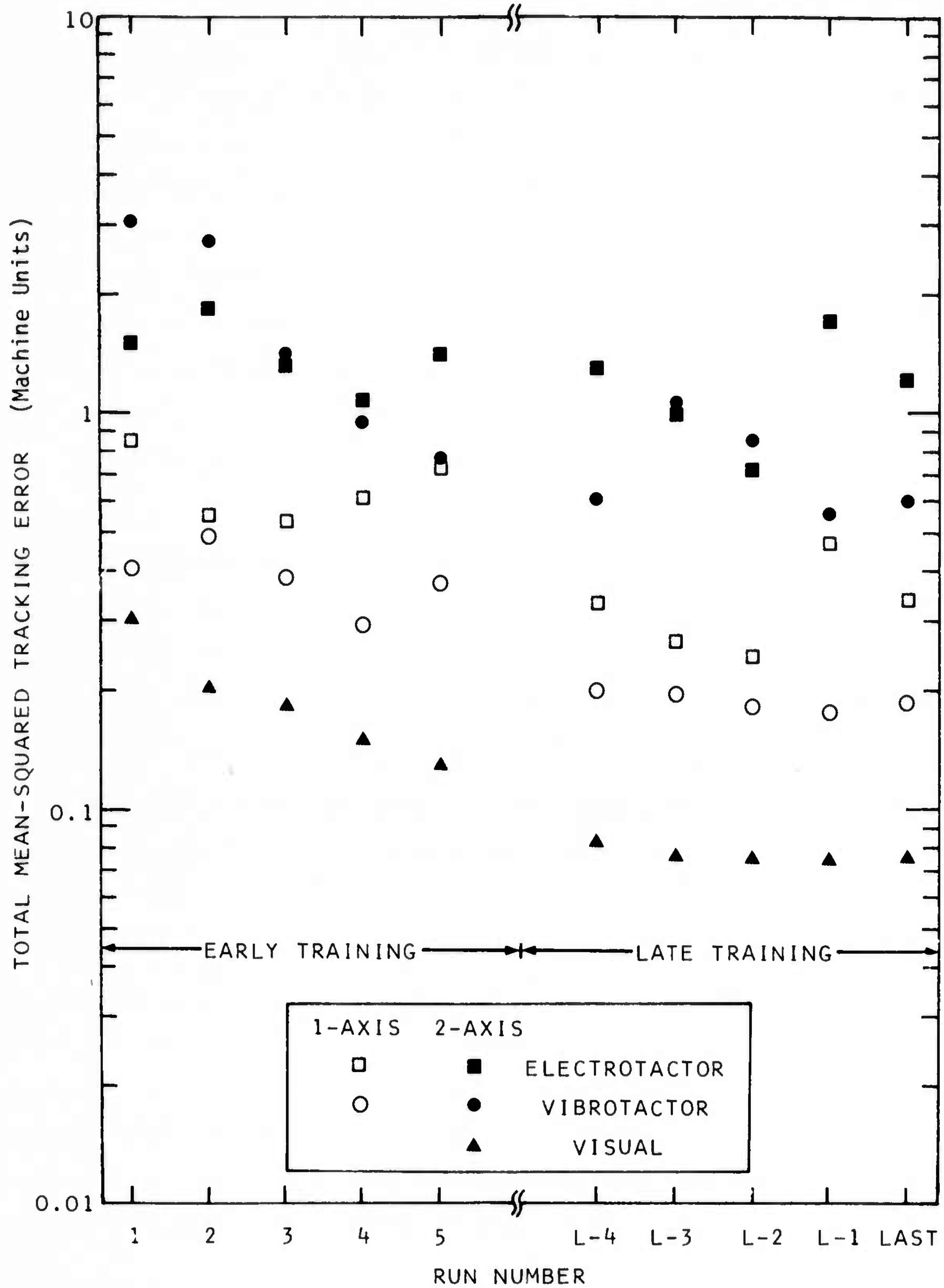


Figure 3.4 Training History of Subject JK.

shown. Because of the considerable variation in scores for the different conditions, the performance scores are plotted on a logarithmic scale.

The average percent reduction in error scores from the early training to the late training provides one useful summary of the training results. These reductions are about 50 percent for the 2-axis visual scores; 36 percent and 35 percent, respectively, for the 1- and 2-axis vibrotactile scores; and 49 percent and 4 percent, respectively, for the 1- and 2-axis electrotactile scores. The performance of subject RF is responsible for the small average improvement in the 2-axis electrotactile score. He, unfortunately, joined the program late, and was able to spend considerably less time than the others on the 2-axis tactile tasks, particularly with the electrotactors. Furthermore, he experienced more difficulty than the others in learning the 2-axis control task, even with the visual display.

It may be seen from Figures 3.1 - 3.4 that subject DE, who had participated in last year's study, held a considerable advantage in the early training. It appears that he retained some of the skills he had developed last year. His advantage in the single-axis tactile tasks virtually disappeared by the late training, although he retained his advantage in all the 2-axis conditions.

Another feature to note of the late training period, is the somewhat wider fluctuations of the 2-axis tactile scores, both within and between subjects, and the tendency of some of these scores to increase with time. These phenomena probably reflect the greater difficulty of the 2-axis tactile control task, and may be caused by the subjects experimenting with various control strategies.

Although not visible in these figures, the subjects required somewhat longer training time to reach stable performance levels with the electrotactors than with the vibrotactors. The difference was more pronounced in the single-axis situation, the bulk of which was performed before the two-axis tracking began. On the average, about 25 single-axis runs (split between pitch and roll) were needed to reach a stable performance level with the electrotactile display, while only about 15 runs were needed with the vibrotactile display.

A major factor seemed to be that the subjects had little prior experience with electrical stimulation, and that whatever prior experience they had had been unpleasant. As a result, they were, at first, very conservative in adjusting the electrotactile intensity control. During the first several practice sessions, the subjects used settings between 6 and 10 milliamperes. By the end of the training, however, they had adapted to the electrotactors, and the settings they used were between 13 and 15 milliamperes. Their best scores were achieved with their highest settings; the error scores increased if the intensity settings were reduced.

3.4 COMPARISON OF ELECTROTACTORS AND VIBROTACTORS

Following the completion of training, an informal comparison was made between performance with the electrotactors and vibrotactors. Each of the four subjects performed two replications each of the pitch, roll, and pitch+roll tasks. The results of this experimental comparison, summarized in Table 3.1, are that the subjects performed better with the vibrotactile display, and that the difference was more pronounced in the pitch axis than in the roll axis. Analysis of variance indicates that, except for the 2-axis roll condition, the differences between tactor types were significant at the 0.01 level, while the differences between subjects were only weakly significant.

Remarks by the subjects, as well as our own experience with the electrotactile display, pointed up a problem which we now consider to be one major reason for the electrotactor scores being worse than the vibrotactor scores. This problem was the inequality of the sensations on the different arms of the display, especially on the pitch (vertical) axis. It was typical to find that at a particular setting of the electrotactor intensity control, the sensation on the upper vertical arm was at a comfortable level while the sensation on the lower vertical arm was below threshold. Increasing the intensity to bring the sensation on the lower arm above threshold tended to increase the sensation on the upper arm above an unacceptable level. This inequality of sensation necessitated a compromise setting of the intensity control, and was, we feel, the primary reason for the greater percent difference between electrotactile and vibrotactile scores in the pitch axis.

TABLE 3.1

EFFECT OF TACTOR TYPE ON TRACKING PERFORMANCE

(a) Mean Square Error Scores* (Average of 4 Subjects)

Experimental Condition	Axis	Display		Relative Difference
		Electrotactile	Vibrotactile	(VT-ET)/ET
1-Axis	Pitch	0.189	0.118	-37%
	Roll	0.140	0.112	-20%
2-Axis	Pitch	0.898	0.498	-45%
	Roll	0.699	0.555	-21%

(b) Summary of Analysis of Variance-Significance of Significance of Sources of Variation

Experimental Condition	Axis	Source of Variation		
		Tactor Type	Subject	Tactor Type X Subject
1-Axis	Pitch	0.01	NS	0.05
	Roll	0.01	0.05	NS
2-Axis	Pitch	0.01	0.05	NS
	Roll	NS	0.05	NS

2 replications per subject

*The performance scores are normalized to the input levels used for the visual task.

Consequently, the subjects, who were all well aware of this inequality of sensation, suggested in response to the questionnaires that separate intensity controls be provided for each arm of the electrotactile display. On the basis of these experimental results, and the subjects suggestions, it was agreed that the electrotactile display would be modified before the simulator evaluation to provide more flexible control of intensity. To minimize the hardware involved, however, and because the sensations on the two arms of the roll axis were judged about equal, three controls have been provided: one each for the upper and lower arms of the pitch axis, and one for the entire roll axis.

Although there was insufficient time for an evaluation of the modified electrotactile display, one subject (DE) tried out the display, adjusting the new intensity controls in an attempt to equalize the sensations on all four arms of the display. After some adjustment, he felt that he had achieved this equalization with the following settings: 16 and 18 milliamperes on the upper and lower arms respectively, and 15 milliamperes on the roll arms. For comparison, during the training period, when only one intensity control was available, DE had normally used a setting of 15 milliamperes.

Judging from the t [illegible] ype comparison summarized in Table 3.1, it is our expectation that this modified electrotactile display would yield improved pitch scores, and that for all conditions the difference in the mean square error would be about 20 percent, corresponding to only about a 10 percent difference in rms error.

There is another factor which would appear to be a major factor contributing to this remaining difference. All the subjects, at one time or another, reported large variations in the electrotactile sensation strength during the course of an experimental session. It was not uncommon for a subject to report that the sensations on one or both axes seemed to disappear during a large part of a run, and that these sensations reappeared after adjusting or repositioning the electrotactile array. These reports, as well as our own experiences, have led us to suspect that the problem lies in intermittencies in the electrode-skin contact as a result of small body motions and hair interference.* It seems that a redesign of the electrodes and possibly the harness would be needed to solve this problem. Although we have some ideas about this, such redesign is beyond the scope of the current project.

Problems with sensation strength were not restricted to the electrotactors. Each of the subjects, at one time or another, reported, especially after a difficult run, that they had found the vibrotactile sensations to be overly strong. Not only was this unpleasant, but it made localizing the sensation difficult. The two subjects who experienced the most trouble with this problem, BO and JK, found relief and improved their scores by wearing the vibrotactor array over their t-shirts instead of directly on their skin.

Another difference between the tactor types was the greater time required by the subjects to adapt to the electrotactors. In addition to the long-term adaptation effect discussed in Section 3.3.3, the subjects experienced a period of adaptation to the electrotactors each day. At first, it took many minutes for them to reach the intensity setting used in the previous session. By the end of the training, however, they would adapt to their normal settings within a minute or less.

The questionnaires provided other information regarding a comparison of the tactor types. The subjects were asked which tactor type they felt allows best performance, which tactor type is most comfortable to use, and which tactor type they prefer overall. Despite the measured performance advantage of the vibrotactors, the subjects were evenly split on their ratings of which type would allow best performance. It is possible that they were not considering the electrotactile display they had actually used, but rather a display incorporating the modifications described above. Three of the subjects felt that the vibrotactors were more

*One subject even shaved a portion of his chest in an attempt to relieve this problem. It is uncertain whether this improved his scores, and he did not consider it worthwhile to shave again as his hair grew back.

comfortable to use, while the fourth found no difference in comfort, Despite this difference in rated comfort, however, the subjects were evenly split on which tactor type they preferred overall, these votes correlating with the votes regarding performance. One subject had a strong preference for the vibrotactors, while the other three preferences were rated as mild.

We chose the vibrotactors for use in the final laboratory performance measurement on the basis of our comparison of the tactor types. However, it was decided to include both the vibrotactile display and the intensity-control-modified electrotactile display in the simulator evaluation for the following three reasons: (1) the differences in performance between the vibrotactors and the modified electrotactors are expected to be small (but real); (2) the differences in the subjects' preferences were relatively small; and (3) it seems likely that a future operational version of the electrotactile display, being lighter, more compact and probably more reliable (having no moving parts) than a future operational version of the vibrotactile display, would be judged superior for operational use.

3.5 PERFORMANCE MEASUREMENT

The primary objective of the formal experiment was to quantify the interaction between the pilot and tactile display in terms of pilot-related model parameters. A secondary objective was to provide a comparison of tactile tracking performance to performance with a continuous visual display.

3.5.1 EXPERIMENTAL CONDITIONS

The simulated attitude regulation task was performed alternately with the tactile and continuous visual displays. Performance measures were obtained for each axis tracked separately, as well as for the combined pitch-roll task.

Two levels of input amplitude were employed for tactile tracking so that display-related threshold effects could be quantified. Because of the high performance scores obtained with the tactile display, input amplitudes used with this display were lower than the level used with the visual display.

The various conditions explored in this experiment are listed in Table 3.2. Input amplitudes are shown relative to the amplitude used with the visual display. To the extent possible, the various tasks were presented in a balanced order.

TABLE 3.2

EXPERIMENTAL CONDITIONS

Display	Tasks (P=Pitch; R=Roll)	Rel. Input Amplitude	No. Replications Per Condition Per Subject
Visual	P, R, P+R	1.00	2
Tactile	P, R, P+R	0.50	3
Tactile	P, R, P+R	0.25	3

3.5.2 TRACKING PERFORMANCE

Average standard deviation (SD) scores for error are shown in Figure 3.5. Pitch- and roll-axis scores are given separately; they have not been combined into a single total-performance measure.

The performance scores shown in this figure and throughout the report are given in terms of analog machine units. One machine unit of error corresponds to 2 cm vertical deflection of the visual error presentation for pitch, and about 50 degrees rotation for roll. One unit of control effort represents approximately 7.7 newtons of force.

The tactile tracking performance was poorer than performance with the visual display. When corrected for differences in input amplitude, the single-axis tactile scores were found to be about 1.9 times as large as the visual scores; this is a considerable improvement over the corresponding figure from last year of 3.5. The two-axis scores, however, were found to be about 3.6 times as large as the visual scores; only a small improvement over the figure of 4.8 from last year.

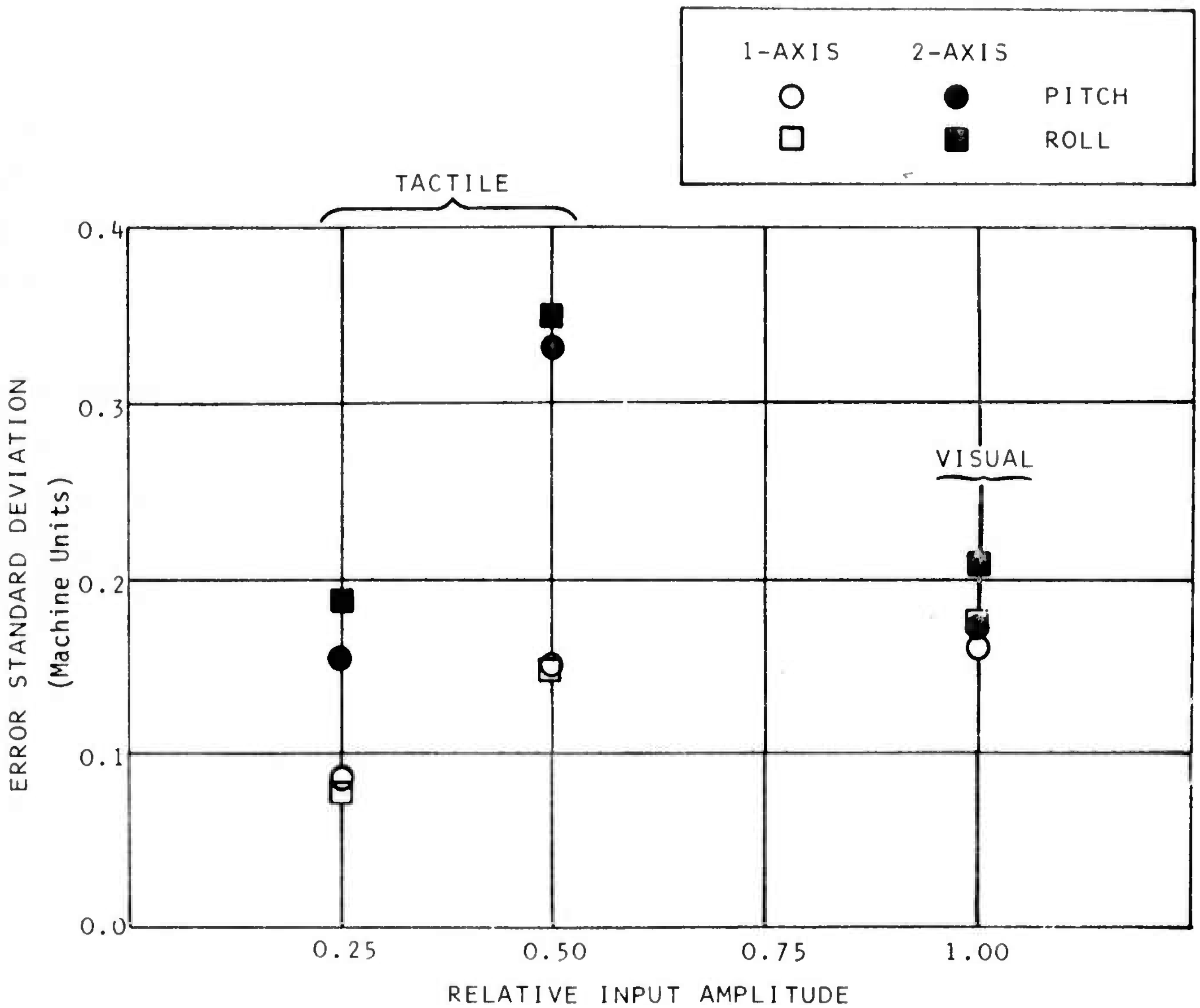


Figure 3.5 Effect of Input Amplitude on Error SD Scores
(Average of Four Subjects)

The scores associated with the tactile display were considerably closer to varying proportionately with input amplitude, than last year's scores. Extrapolation to zero input yields a smaller (positive) non-zero score, suggesting that the thresholdlike effects are reduced.

Significant inter-axis interference effects were found with both the visual and tactile displays, although the size of the effect was much larger with the tactile display than with the visual display. With the visual display, the 2-axis pitch and roll scores were about 7 percent greater and 20 percent greater, respectively, than the corresponding 1-axis scores; while with the tactile display (averaging over the two values of input amplitude), the 2-axis pitch and roll scores were about 100 percent greater and 140 percent greater, respectively, than the corresponding 1-axis scores. The large increase in relative difference from last year (when the 2-axis tactile scores were about 35 percent greater than the 1-axis scores) is due to the substantial decline seen this year in the 1-axis tactile error scores, while the 2-axis scores diminished only slightly.

As was the case last year, use of the tactile display often resulted in pulse-like control inputs, whereas the visual display allowed continuous-looking control activity. However, the tendency towards pulsed control was somewhat reduced from last year, at least in the single-axis runs, despite the fact that the subjects were again instructed to use whatever strategy they felt gave the best performance.

We made a limited examination of this aspect of the data and noted what appeared to be generally three types of control activity: pulsed, oscillatory, and continuous. Data collected during the final testing period which illustrate these different control techniques are shown in Figures 3.6 - 3.10. Figures 3.6 - 3.8 are sample time histories of error and control signals in tactile tracking, while Figures 3.9 and 3.10 contain amplitude densities of control input.

Figure 3.6 Time Histories of Error and Control Signals.
Subject RF; Task = Pitch+Roll
Relative Input Amplitude = 0.25

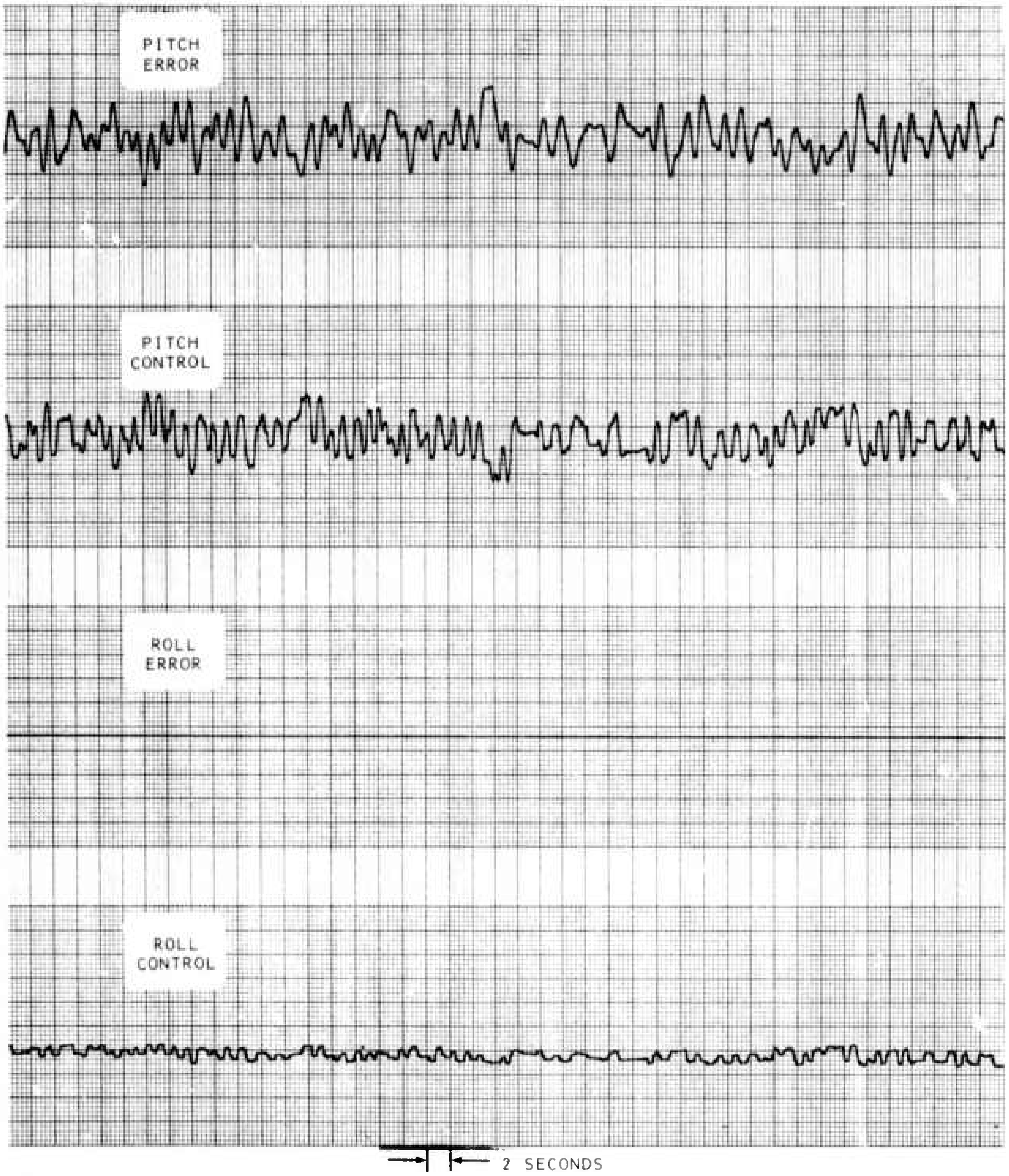


Figure 3.7 Time Histories of Error and Control Signals.
Subject JK; Task = Pitch
Relative Input Amplitude = 0.50

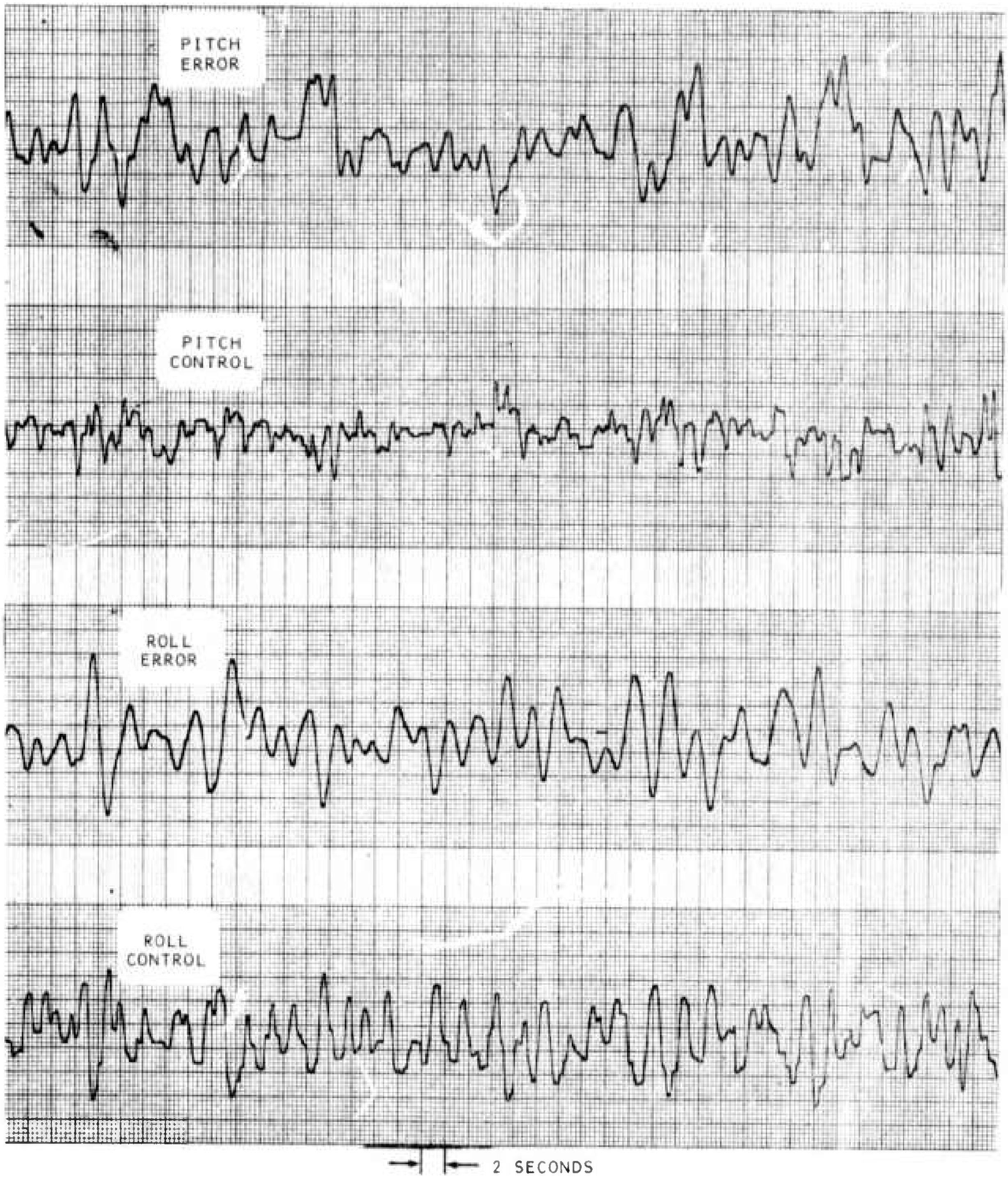
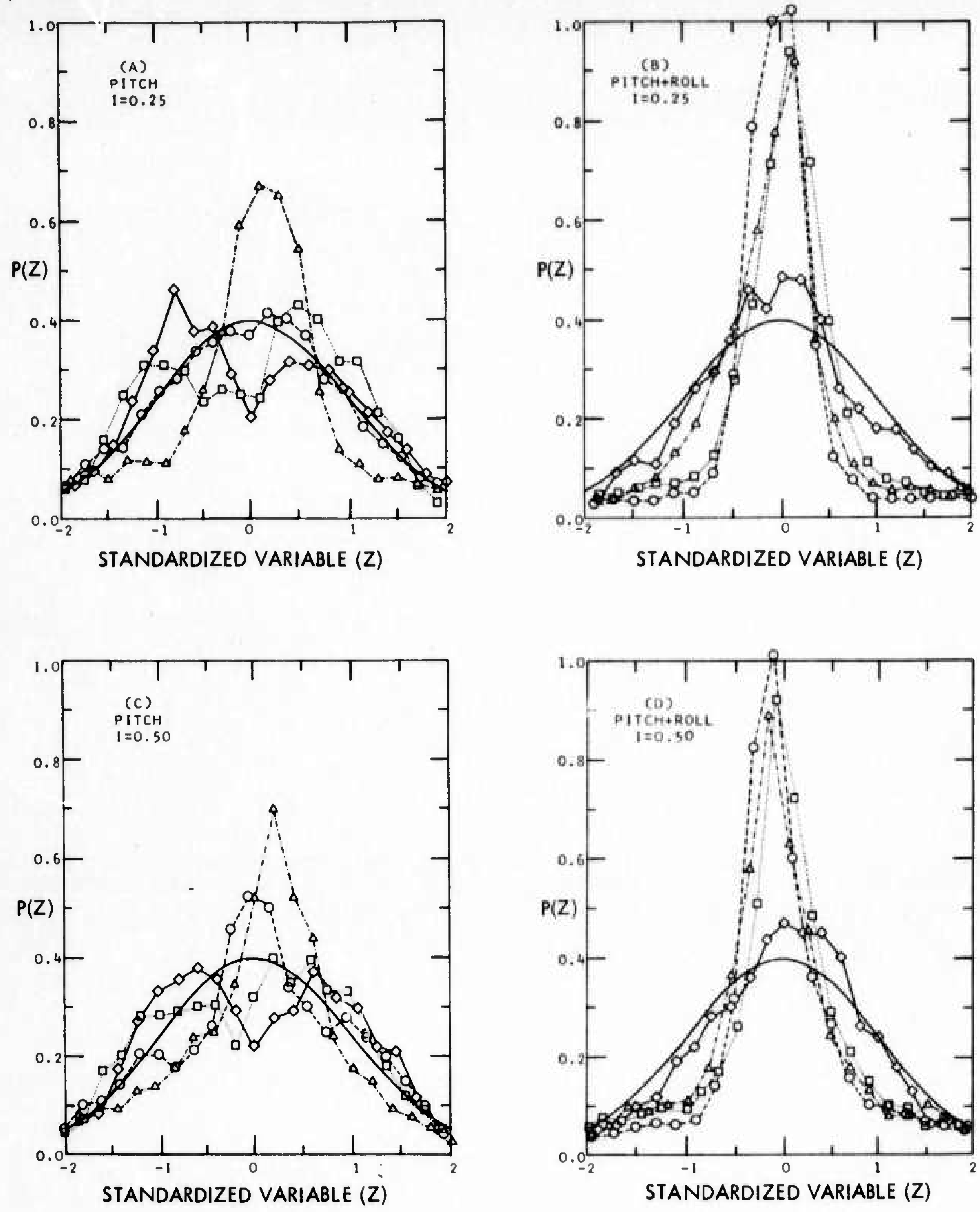


Figure 3.8 Time Histories of Error and Control Signals
Subject JK; Task = Pitch+Roll
Relative Input Amplitude = 0.50



(A) TASK=PITCH; RELATIVE INPUT AMPLITUDE=0.25
(B) TASK=PITCH+ROLL; RELATIVE INPUT AMPLITUDE=0.25
(C) TASK=PITCH; RELATIVE INPUT AMPLITUDE=0.50
(D) TASK=PITCH+ROLL; RELATIVE INPUT AMPLITUDE=0.50

Figure 3.9 Pitch Axis Control Amplitude-Density Distributions in Tactile Tracking.

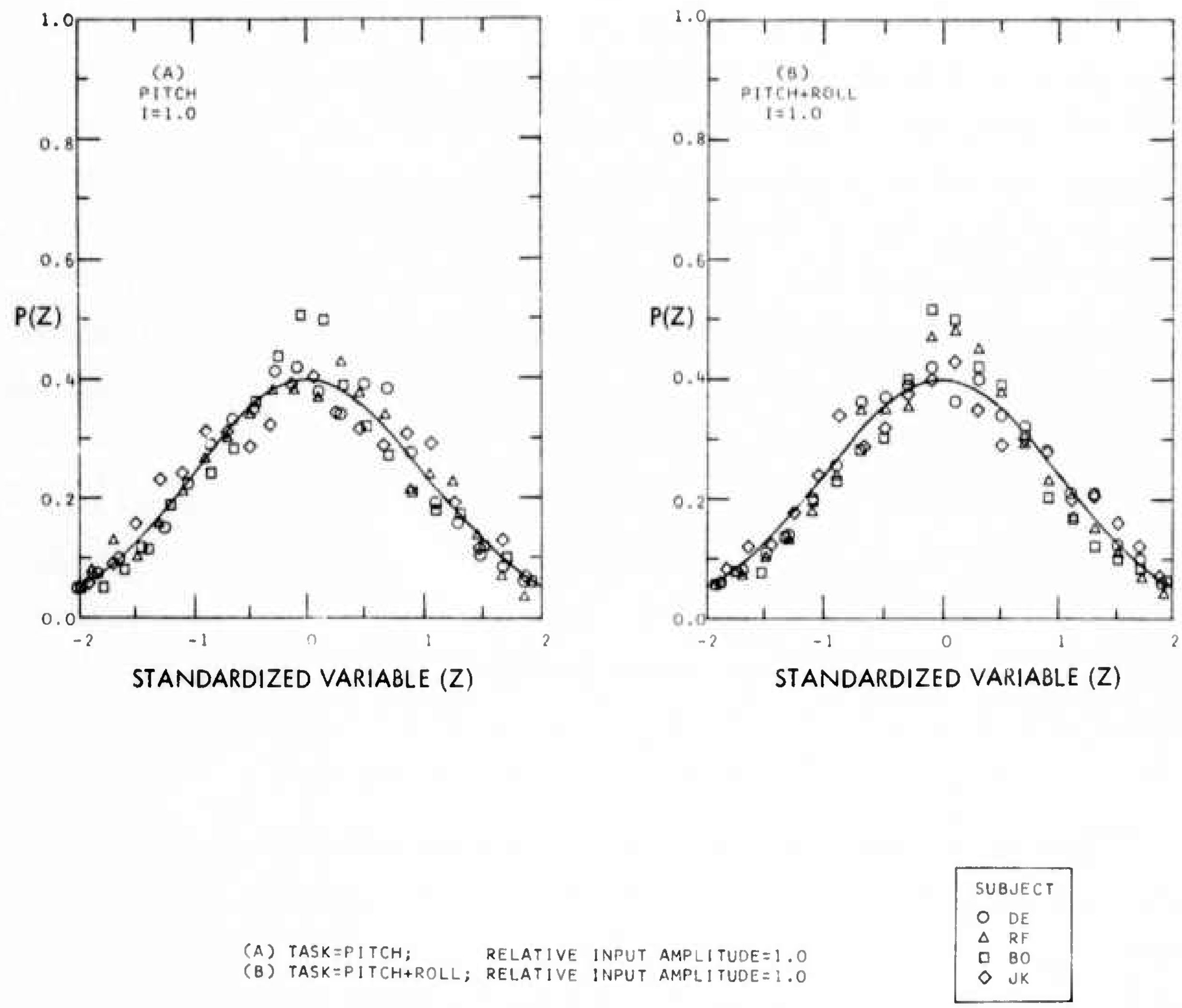


Figure 3.10 Pitch Axis Control Amplitude-Density Distributions in Visual Tracking

Figure 3.6 represents a two-axis tactile tracking run in which pulsed control behavior is evident. Control pulses were typically applied in a sequence of single pulses to alternate axes, with occasional bursts of pulses on a single axis. Pulses within a sequence were separated by about 0.8 second. The amplitude density of the pitch control signal corresponding to this run is included in Figure 3.9B as subject RF (triangles). As expected, the pulsed control behavior produced a highly non-Gaussian amplitude density having a large peak associated with zero control activity.

Figure 3.7 represents a single-axis tactile pitch tracking run in which large portions of the control signal appear oscillatory. Although the boundaries of the individual oscillatory segments are sometimes ill-defined, we would judge that intervals between oscillatory segments ranged up to about 10 seconds, and the duration of individual segments ranged up to about 15 seconds. The period of the oscillations is on the order of 1 - 1.2 second, a frequency in the neighborhood of 5.7 rad/sec. The amplitude density of the control signal corresponding to this run is included in Figure 3.9C as subject JK (diamonds). The oscillatory control behavior produced a highly non-Gaussian bimodal density, with the two peaks associated with the limits of the oscillatory control motions.

Figure 3.8 represents a two-axis tracking run in which the pitch control activity appears continuous, although the roll control appears oscillatory. The amplitude density of the pitch control signal corresponding to this run is included in Figure 3.9D as subject JK (diamonds). As expected, the continuous control behavior produced an approximately Gaussian amplitude density.

Although not shown in these figures, different segments of some individual runs contain different types of control behavior. For example, in one run the subject began by pulsing, switched to oscillations, and then returned to pulsing. As a result, the control amplitude density from that run was roughly Gaussian, although the control activity was definitely not continuous.

Keeping in mind that Figures 3.9 and 3.10 consist of data from only one eighth of the runs performed during the final testing period, and that combinations of the different control strategies may exist within an individual run, we make some general observations regarding control behavior. Both one- and two-axis tracking with the visual display produced continuous control activity with Gaussian amplitude densities. (See Figure 3.10.) Tracking with the tactile display produced various types of control activities. (See Figure 3.9.) Two-axis tactile tracking produced mostly pulsed control behavior with peaked amplitude densities. Single-axis tactile tracking produced a mix of pulsed, oscillatory and continuous control behavior. The amplitude of the input disturbances had little effect on control behavior in tactile tracking.

The reasons for the different types of control behavior are not altogether clear, although it is possible to make some judgments about them. In the two-axis control situation the pulsing seemed to be a means of dividing control activity between the axes. Apparently, subjects who used a pulsed control switched their attention and their control efforts back and forth between the two axes, while the subject who responded continuously, without pulsing had learned to monitor and control both axes simultaneously.

It appeared that the oscillatory control inputs and the corresponding bimodal control amplitude densities may have resulted from a resonance in the closed-loop man-machine system. For example, consider the run plotted in Figure 3.7. A comparison of the pilot describing function relating pitch error to pitch control with the vehicle dynamics transfer function, shows that at a frequency of about 5.6 rad/sec, where the phase shift around the loop is about 360°, the loop gain is about -1.8 dB, a gain margin of less than 2 dB. Consequently, there is a resonance in the closed-loop system at about a frequency of 5.6 rad/sec. This is in agreement with the periodicity seen in the control waveform of Figure 3.7. Furthermore, the driving noise was, in fact, not Gaussian white noise, but rather a sum of 12 sinusoids, one of which had a frequency of about 5.6 rad/sec. Consequently, this component of the input disturbance may have excited the corresponding resonance in the closed-loop system, thereby dominating the control input waveform, and producing the bimodal control input amplitude density.

Additional information regarding the pilot describing functions, along with an analysis of the tracking data based on our pilot/vehicle model and our predictions concerning pilot performance in the F-4 simulation tasks, will be presented in the final report.

SECTION 4
CONCLUSIONS

The laboratory evaluation of the tactile display system has shown that the tracking scores of the subjects have been improved over those recorded for the system tested last year. Best improvement was observed with the tests incorporating only a single-axis tracking task, the two-axis tracking performance improved only half as much and this is due to the complexity of the task and the limited training.

The use of tactile displays have always resulted in greater tracking errors when compared to a continuous analog visual display, we do not have the tactile dual of the visual display. The tactile display is quantized, and as presently programmed, no data is displayed until the error is already greater than five percent.

The most suitable tactor excitation code tested to date has been one in which the outermost tactor is always excited first, thus providing maximum spatial separation for even small error displays. The code was best for both one-axis and two-axis tracking tasks.

Although the maximum tactile ripple rate was scaled for 60 Hz, it was found that a maximum rate of 15 Hz was good for training and 30 Hz adequate for the formal tests. An underlying reason for this may well be the overlapping of tactor-ON periods which begins to occur at 30 Hz, and at 60 Hz, two adjacent tactors are excited simultaneously during one-half of their ON periods.

The simultaneous or independent operation of the two data channels proved to be superior to the sequential operation but not to the expected degree. What may be a more important conclusion is the fact that the subjects did not exclusively use control pulsing for error correction as they had last year when only the sequential display mode was used.

The auto-intensity control for the electrotactor display proved very beneficial in maintaining the electrocutaneous sensations within the comfort range. The variation of comfort level with body location was resolved to some degree by providing one intensity control for the X or roll axis and individual controls for the upper and lower halves of the Y or pitch axis. With sufficient data, it may be possible to adjust the gain of the elemental tactor drivers such that a single intensity control could provide uniform excitation levels for all the tactors in a specified array.

Since the additional intensity controls were not added until after the formal tests were run, a final performance comparison between electrotactor and vibrotactors cannot be made at this time, but the comparison is expected to be close. The problem encountered with the skin contact variation may be eliminated by employing a different shape for the electrode pairs. Since the coaxial configuration does not localize skin current, a flat surfaced tactor may no longer be necessary.

APPENDIX A1
SKIN CURRENT ISOLATION

During the course of this program, we have always used coaxial electrodes for the display tactors. The reason for this was that the skin current induced from an individual tactor would be isolated from all other tactors by means of the common or grounded outer electrode. The idea had further merit because it would eliminate current distribution throughout large areas of the body. A test has been conducted to determine the isolation characteristics of the coaxial tactor and the data indicates the isolation, for all practical considerations is nonexistent.

INITIAL EXPERIMENT

The initial experiment was not run to determine the isolation characteristics of the coaxial electrotactors, its purpose was to determine the effects of line length on the current and voltage waveshapes at the tactor location. Two tactors were used, one with 40 inch leads and the other with 140 inch leads. In order to monitor the current at the tactor, a 100 ohm resistor was connected to each outer electrode in series with the common lead, and again, the two common leads were connected together in series with another 100 ohm resistor to ground. The tactors were excited sequentially with a biphasic, capacitively coupled, constant current drive circuit. The tactors were applied to the abdomen at two separation distances, 1 inch and 8-7/8 inches, in the case of the wider separation, the tactors were equidistant from the navel in a horizontal plane.

The results satisfied the primary reason for the experiment by indicating the line length had a negligible effect on the current or voltage waveforms or the haptic perception. The data did show that the pulsed current into the center electrode of one tactor returned through the common electrode of both tactors in just about equal amounts.

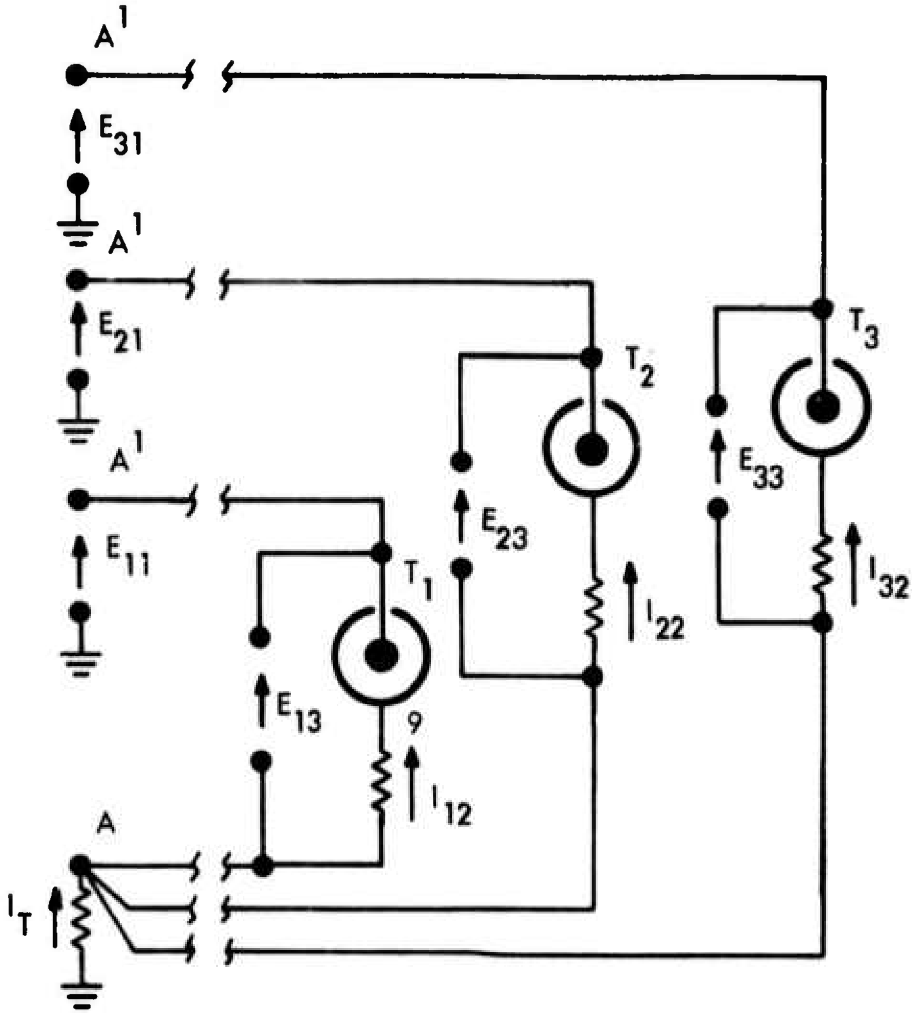
ISOLATION EXPERIMENT

Three tactors were modified such that skin voltage and the outer electrode current could be measured at the tactor. The tactor wiring and signal definition are presented in Figure A1-1. The biphasic signal used throughout this experiment had peak current values limited to 10 ma, 20 microsecond pulse widths and a 10 microsecond dwell between the negative and positive current pulses. The experiment consisted of operating one, two and three tactors at various intertactor spacings.

Figure A1-2 illustrates the skin voltage and current waveforms obtained when using one tactor and having no other part of the body grounded. The waveforms are the same whether they are observed at the drive circuit or 40 inches away at the tactor.

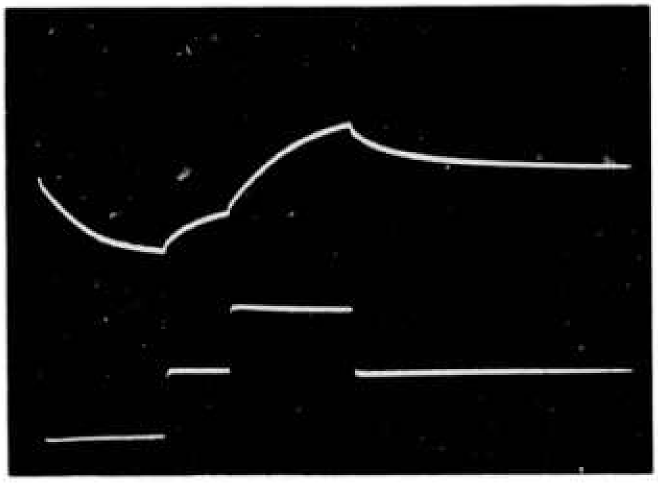
The two sets of current waveforms presented in Figure A1-3 show the current division between two tactors for two different tactor separations, 4-3/4 inches and 36 inches. Each photo shows the individual current at the tactors and their sum at the common tie point. At the close separation the current split is about 5.5 and 4.5 ma, favoring the driven tactor, and at 36 inches the split is 6.5 and 3.5 ma. In either case there is little indication of isolation. The leading time constant indicated by the driven tactor current waveforms is probably due to the interelectrode capacitance of the tactor.

The last two photos presented in Figure A1-4 show the current distribution between three in-line tactors with the center tactor being driven. The current division is quite proportional whether the tactor spacing is 0.6 or 7 inches.



- All resistors: 100 OHMS
- Line Length: 40" from points A & A[1] to tactors
- Tactors: See Paragraph 2.2

Figure A1-1 Tactor Wiring for Isolation Experiment.

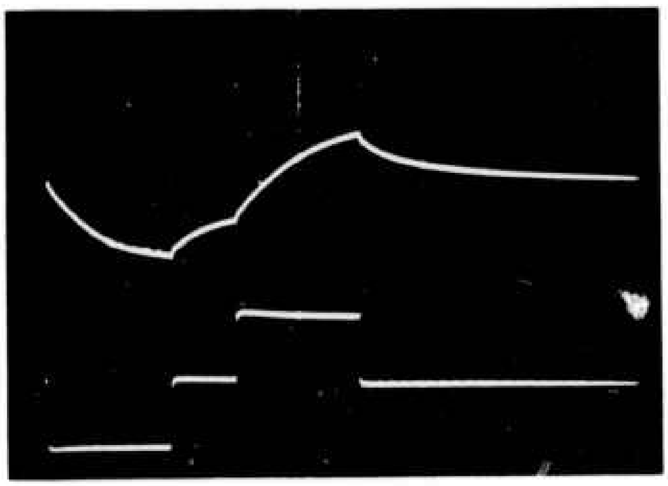


HOR: $10 \mu s/cm$
SYNC: T_1

E_{11}: 50 V/cm

I_T: 10 ma/cm

a) Skin voltage and current using one tactor; measured at a line length of 40 inches.



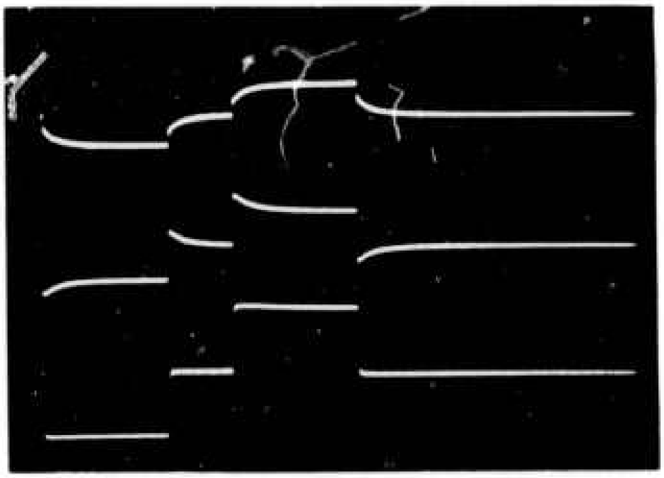
HOR: $10 \mu s/cm$

E_{13}: 50 V/cm

I_{12}: 10 ma/cm

b) Skin voltage and current measured at tactor.

Figure A1-2 Tactor Drive Signals.



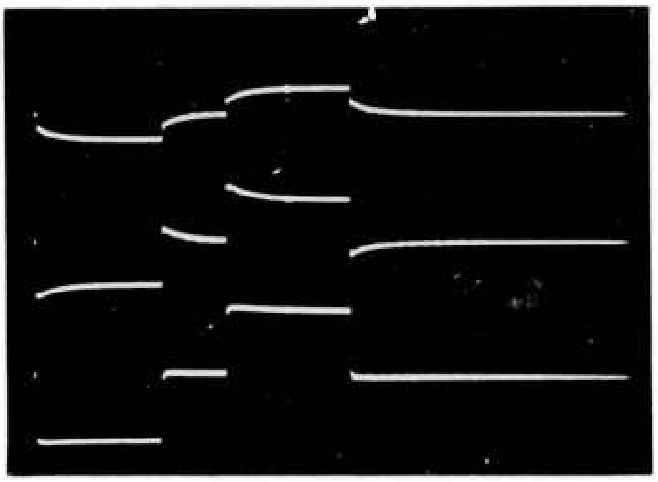
HOR: $10 \mu sec/cm$
SYNC: T_3

I_2: 10 ma/cm

I_3: 10 ma/cm

I_T: 10 ma/cm

a) Two tactor current division where T_2 is located just above navel and T_3 is 4-3/4 inches to the right. Tactor T_3 is the driven and referenced tactor.



HOR: $10 \mu sec/cm$
SYNC: T_1

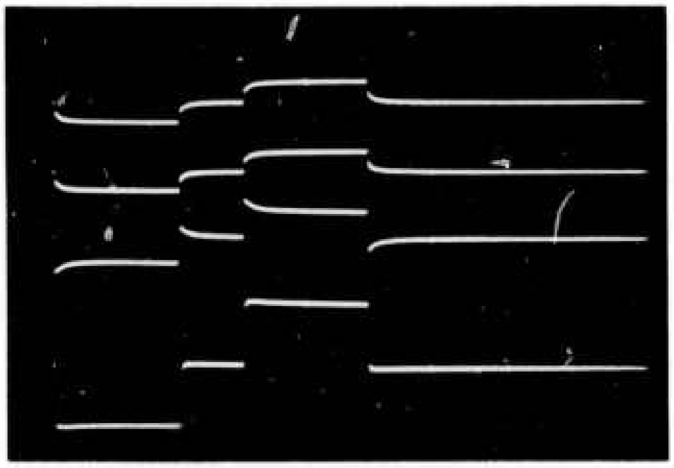
I_2: 10 ma/cm

I_1: 10 ma/cm

I_T: 10 ma/cm

b) Two tactor current division where T_2 is located on left forearm and T_1 is to the right of the navel on the abdomen. Tactor T_1 is the driven and referenced tactor.

Figure A1-3 Two Tactor Current Division.



HOR: 10μ sec/cm
SYNC: T_3

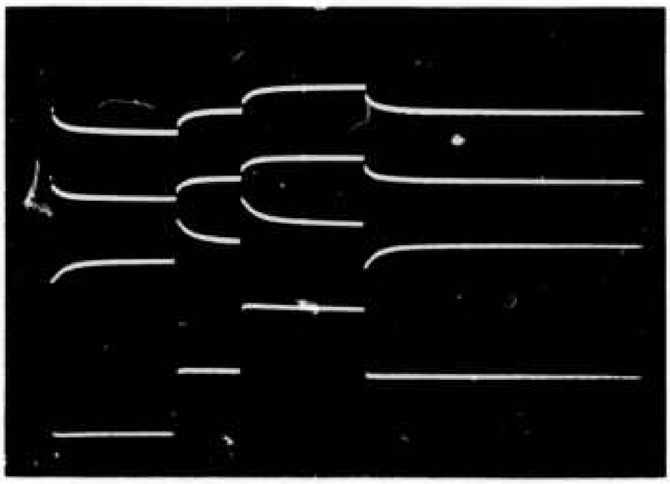
I_1: 10 ma/cm

I_2: 10 ma/cm

I_3: 10 ma/cm

I_T: 10 ma/cm

a) Three tactor current division where tactor T_3 is located 3 inches to the right of the navel and T_1 and T_2 are on either side 0.6 inch center-to-center from T_3. Tactor T_3 is the driven and referenced tactor.



HOR: 10μs/cm
SYNC: T_3

I_1: 10 ma/cm

I_2: 10 ma/cm

I_3: 10 ma/cm

I_T: 10 ma/cm

b) Three tactor current division where T_3 is located just above navel, T_1 is 8-3/4 inches to the left and T_2 is 7-1/4 inches to the right. Tactor T_3 is the driven and referenced tactor.

Figure A1-4 Three Tactor Current Division.

SUMMARY

The data has been taken on one subject to determine whether or not coaxial electrodes can restrict the induced skin current within the local of the electro-tactor. It has been shown that the injected skin current is quite uniformly distributed to all common electrodes in contact with the skin, thus coaxial electrodes do not provide skin current isolation or prevent through-body current flow. It is important to note however that the haptic perception only occurs at the driven tactor.

APPENDIX A2
QUANTIZATION LEVELS

The 16 pin plug board, SA104 (U12 of Board 4) contains two sets of precision resistors, each set can be derived to determine the three quantization levels (A, B and C). The resistor layout of SA104 is as shown in Figure A2-1.

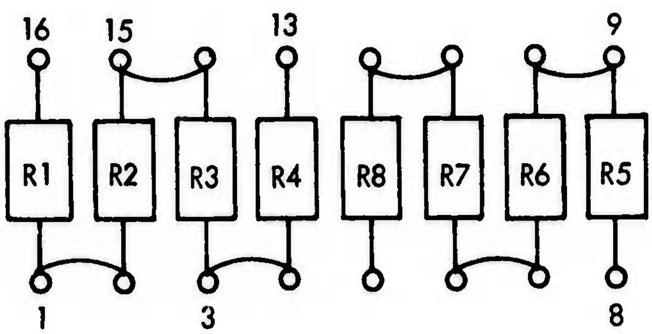


Figure A2-1 Wiring Diagram of Plug Board SA104.

Pin 16 is connected to +15 Vdc and pin 13 is ground. The voltage at Pin 3 determines A level; pin 15, B level and pin 1, C level. The active set of resistors control both the X and Y axis comparators. Note that R5 through R8 corresponds directly to R1 through R4 when the plug board is rotated 180 degrees. Use a 5 ma current to determine the required resistor values.

The scale voltage is 8 Vdc. The data in Table A2-1 identifies the resistor values on the delivered plug board.

TABLE A2-1

RESISTOR VALUES FOR SELECTED QUANTIZATION LEVELS

A = 5% = 0.4V	A = 5% = 0.4V
B = 20% = 1.6V	B = 30% = 2.4V
C = 80% = 6.4V	C = 70% = 5.6V
R_1 = 82.2 ohms	R_5 = 82.2 ohms
R_2 = 261 ohms	R_6 = 422 ohms
R_3 = 1000 ohms	R_7 = 681 ohms
R_4 = 1780 ohms	R_8 = 1960 ohms

APPENDIX A3

CODE PROGRAMMING

The code programming for each axis is determined by a pair of plug-boards on the Program Card (B2) as shown in Figure 2-5 and illustrated in Figure A3-1. The procedure for wiring these boards is as follows.

The table shown in Figure A3-2(a) is used to illustrate a tactor excitation sequence. The tactors for a single polarity are indicated by the vertical column (1, 2, 3, 4). Enter a selected code number in top horizontal space. The three letters A, B and C signify the NT quantization levels, and the clock periods T_1, T_2, T_3 and T_4 shown under each level are those generated for each quantization level. Now, place a mark (x) corresponding to when a specific tactor is to be on, for example, for an A level quantization (and not B or C) tactor 2 will be activated during both T_1 and T_2. It is best to note here that when B equals one, A also equals one, furthermore, the truth table for A, B and C is as follows.

	NT Increase →			
A	0	1	1	1
B	0	0	1	1
C	0	0	0	1

With the code defined as illustrated in Figure A3-2(a), the wiring matrix of Figure A3-2(b) is completed. The symbols JP1 and JP2 identify the pair of plug boards, the numbers 1-16 closest to the grid are the pin numbers of each plug board and the remaining symbols define the function at each terminal. The columns are the outputs and the rows are the inputs. Each tactor is controlled by a combination of three signals, i.e., for tactor 1: 1A, 1B and 1C. If 3 arbitrary logic inputs are N, M and R, then tactor 1 would be controlled by the logic equation,

$$NA + MB + RC$$

The next part of the procedure is to write the logic equations for each tactor using Figure A3-2(a) as reference.

$$\text{Tactor 1} = \bar{B}\, T_2 A + \bar{C}\, T_3 B + T_4 C$$

$$\text{Tactor 2} = \bar{B}(T_1 + T_2)A + \bar{C}(T_2 + T_3)B + (T_3 + T_4)C$$

$$\text{Tactor 3} = OA + \bar{C}(T_1 + T_2 + T_3)B + (T_2 + T_3 + T_4)C$$

$$\text{Tactor 4} = OA + OB + (T_1 + T_2 + T_3 + T_4)C$$

From these equations the appropriate wiring connections can be indicated in the wiring matrix.

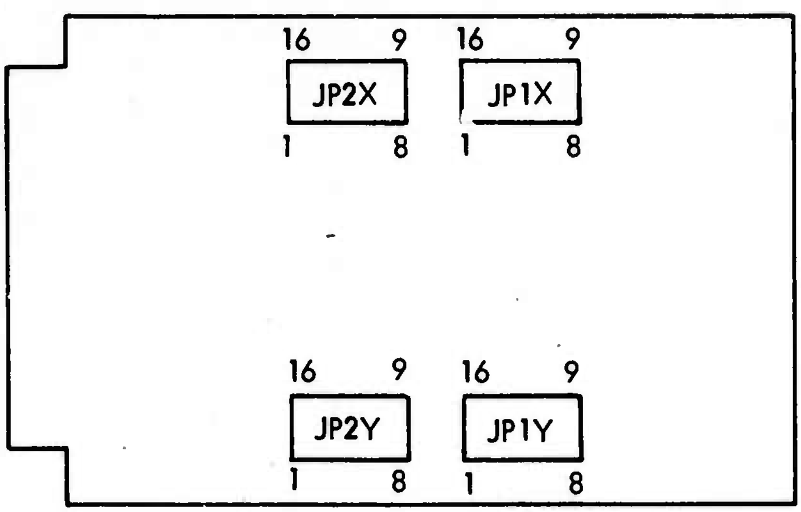


Figure A3-1 Code Plug-Board Location on Program Card B 2.

TACTOR	CODE (NO.)								
	A		B			C			
	T_1	T_2	T_1	T_2	T_3	T_1	T_2	T_3	T_4
1		X			X				X
2	X	X		X	X			X	X
3			X	X	X		X	X	X
4						X	X	X	X

(a) TACTOR EXCITATION

JP2		JP1 →	1_A	1_B	1_C	2_A	2_B	2_C	3_A	3_B	3_C	4_A	4_B	4_C
			1	2	3	4	5	6	7	8	9	10	11	12
JP1	+5VDC	13												
JP1	GND	14							O			O	O	
JP1	T_1	15												
JP1	T_2	16												
JP2	T_3	1												
JP2	T_4	2			O									
JP2	$T_1 + T_2$	3												
JP2	$T_2 + T_3$	4												
JP2	$T_3 + T_4$	5						O						
JP2	$T_1 + T_2 + T_3$	6												
JP2	$T_2 + T_3 + T_4$	7									O			
JP2	$T_1 + T_2 + T_3 + T_4$	8												O
JP2	$\overline{B}(T_1 + T_2)$	9				O								
JP2	$\overline{B}\,T_2$	10	O											
JP2	$\overline{B}\,T_1$	11												
JP2	$\overline{C}\,T_1$	12												
JP2	$\overline{C}\,T_2$	13												
JP2	$\overline{C}\,T_3$	14		O										
JP2	$\overline{C}(T_2 + T_3)$	15					O							
JP2	$\overline{C}(T_1 + T_2 + T_3)$	16								O				

(b) WIRING MATRIX

Figure A3-2 Code Programming Data.

For example, take Tactor 3, it is not turned on during A level-connect 3A (Pin 7 of JP1) to ground (Pin 14 of JP2). In level B it is to be turned on for all three T periods, but T_1 is not to be used during a C level - connect 3B (Pin 8 of JP1) to $\bar{C}(T_1 + T_2 + T_3)$ (Pin 16 of JP2). In level C, it is on for T_2, T_3 and T_4 - connect 3C (Pin 9 of JP1) to $(T_2 + T_3 + T_4)$ (Pin 7 of JP2). The other tactor codes are wired in like manner.

APPENDIX A4
AUTO-INTENSITY CONTROL

The stimulus pulse width for the electrotactor excitation in the AUTO mode is controlled by the quantization levels A, B, C (NT) and two $|\dot{T}|$ levels (F_1 and F_2) determined by levels set by the resistors of SA106 which is identified as U16 on Board 8. These data are combined to determine which of 4 pulse widths is used. The logic is such that as the number of energized tactors increase and/or the ripple rate increases, the pulse width is made to decrease, thus providing a nearly constant stimulus level.

The pulse generator is designed to provide 20 μs pulses unless one of the following logic equations are satisfied:

$$T_{x2} = A_x F_{2x} + B_x F_{1x} + C_x F_{1x} \quad (1)$$

$$T_{x3} = B_x F_{2x} + C_x F_{1x} + T_{x2} T_{y2} \quad (2)$$

$$T_{x4} = C_x F_{2x} + T_{x3} T_{y3} \quad (3)$$

These equations are for the X-axis. As an example, take equation (2): this states that the X-axis biphasic pulse width will be T_{x3} if NT_x is quantized in the B level and $\dot{T}_x$ is equal to or greater than 40 Hz (F_{2x}); or that NT_x is quantized in the C level and $\dot{T}_x$ is equal or greater than 20 Hz (F_{1x}); or that the NT and $\dot{T}$ signals to both the X and Y axes are such that T_{x2} and T_{y2} are fulfilled, i.e., each individually qualify the T_2 pulses. Balancing the T_{x3} equation implies the T_{x2} equation is also balanced.

The comparator reference voltages used to set the two $\dot{T}$ breakpoints F_1 and F_2 are determined by the components on plug board SA106. Component location is shown in Figure A4-1(a). R_1, R_4 and R_7 are the resistors determining the reference voltages with pin 1 connected to -15 Vdc and pin 8 grounded. The voltage at pin 7 sets F1 and at pin 14, F2. The voltage scale is 0.133 V/Hz. The 10K ohm resistors are part of the hysterisis circuitry of the comparators and play no part in determining the reference voltages.

The resistor values

R_1 = 1800 ohms
R_2 = 510 ohms
R_3 = 510 ohms

provide reference frequencies of

F_1 = 20 Hz
F_2 = 40 Hz.

The plug board SA107 identified as U24 of Board 8 contains the resistors which control the pulse widths. The layout is shown in Figure A4-1(b). Resistors R_1 through R_4 control the X-axis pulse widths and R_5 through R_8 control the Y-axis pulse widths. Pins 12 and 13 are connected to +5 Vdc. The pulse width is controlled by opening the normally grounded resistors at Pins 14, 15 and 16 and 9, 10, and 11.

The resistors are selected by experiment because of the electrical output characteristics of the control gates and the tolerance of the capacitors. The steps are as follows.

a. Place the FIXED-AUTO switch in the FIXED position - this grounds the normally grounded pins through the control gates.

b. Determine required pulse widths: 12, 14, 17, 20 microseconds.

c. Using a value of 1500 ohms for R_4 (and R_5) calculate the capacitance required to obtain the shortest period (12 µs) with the equation:

$$C = \frac{3T}{R + 3}$$

when

T is in nanoseconds

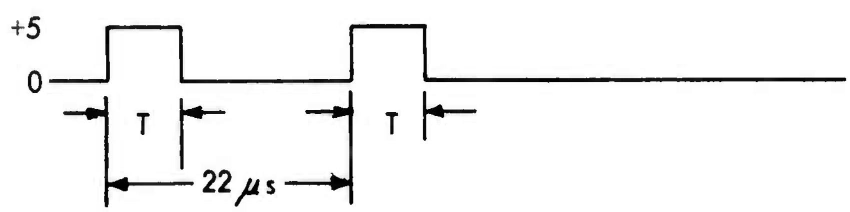
R is in K ohms

C is in picofarads.

There is a 470 Pfd capacitor on Board 8 near U15 for the X-axis and U23 for the Y-axis. If necessary, shunt this capacitor with another to come close to the calculated value.

d. Run a shorting wire from Pin 1 through Pin 4, and Pin 5 through Pin 8 on a 16 pin discrete component plug board.

e. Place the 1500 ohm resistor in the position for R_4. Signals from the SIM receptacle (pin 14 for C_{Dx} and pin 15 for C_{Dy}) can be used to monitor the generated pulses.

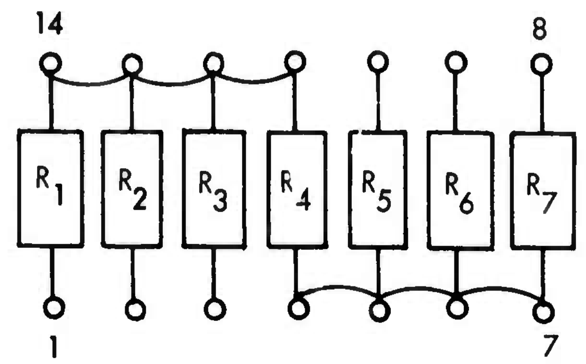


Select R_4 (R_5)($\pm 5\%$) to obtain T = 12 µsec.

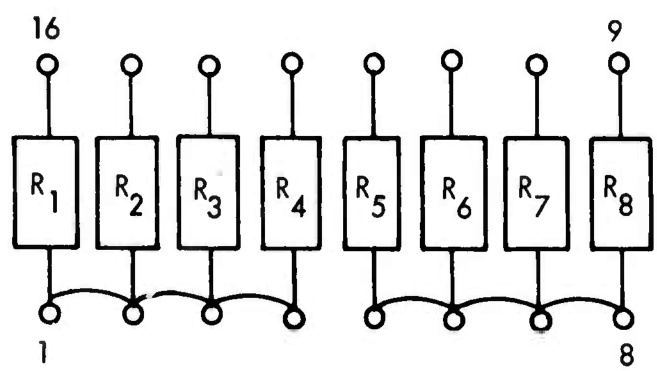
f. Select R_1 (R_8) to obtain T = 14 µsec.

g. Select R_2 (R_7) to obtain T = 17 µsec.

h. Select R_3 (R_6) to obtain T = 20 µsec.



a) RESISTOR PLUG BOARD SA106



b) RESISTOR PLUG BOARD SA107

Figure A4-1 Resistor Plug Boards Used to Control the Electrotactor Stimulus Pulse Width.

APPENDIX 5
QUESTIONNAIRE RESULTS

A three part questionnaire was filled out by each subject following the completion of the training and prior to the main performance measurement experiment. The results concerning a comparison of tactor types has been discussed in Section 3.3. The remaining results, dealing with suggested improvements and with the potential for use in flight, are discussed here. The text of the questionnaire is given at the end of this appendix.

A.1 SUGGESTED IMPROVEMENTS

One suggested improvement, providing a separate intensity control for each arm of the electrotactile display, was discussed in Section 3.4, and has been partially implemented.

A group of suggestions related to the overly strong vibrotactile sensations. Two subjects suggested wearing the array over a t-shirt (as they themselves did), one subject suggested providing an intensity control for the vibrotactors, and one suggested enlarging slightly the diameter of the vibrotactile probe to dull the sensations somewhat.

Each of the subjects had a suggestion concerning the size of the tactile arrays. Three suggested spacing the individual tactors more widely (especially along the pitch axis) to improve the ability to identify the error.* The fourth subject, however, suggested reducing the size of the somewhat bulky vibrotactile array.

There were two suggestions relating to the occasional intermittency of the electrotactor-skin contact. One subject suggested shaving the chest, which he did as mentioned earlier. The other suggestion was to use a conductive gel be used with the electrotactors. Although such a gel would short out these electrotactors, it might be used to advantage in conjunction with a different electrotactor array.

One subject, who felt that the high ripple rates were somewhat confusing, suggested that the error be encoded in the duration of each tactor excitation period as well as in the ripple rate, and that the maximum ripple rate be reduced. Finally, one subject wanted the vibrotactors made less noisy.

A.2 POTENTIAL FOR USE IN FLIGHT

The portion of the questionnaire dealing with the potential of the tactile display for use in flight was divided into two parts. They first dealt with the potential for use as a supplement to the visual pitch/roll display. Although only one subject expressed willingness to use the displays as currently configured, all of the subjects said they would be willing to use either the electrotactile or the vibrotactile display if some of their suggested improvements were adopted. The only condition was that the displays be used to display pitch and roll error, and not absolute pitch and roll.

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* Although this suggestion was made and adopted during last year's experimental program, and resulted in about a 15 percent improvement in tracking performance, we reverted this year to the smaller array. We felt that the more compact array, being less cumbersome and offering less interference with other gear worn by a pilot, would be operationally superior.

The remaining part dealt with other potential in-flight uses of the tactile displays. All four subjects responded affirmatively when asked whether profitable use could be made of the tactile display for each of the following in-flight functions: (1) to present emergency warning signals indicating a critical situation (e.g., engine temperature too high, impending stall, etc.); (2) to provide (on one axis only) continuous monitoring of airspeed or angle-of-attack errors; and (3) to present ILS-type information (2-axis).

Additional applications of the tactile display suggested by the subjects included use as a low altitude warning, as a supplement to a helicopter hovering aid, and as an alert to a group of instruments (e.g., electrical system, hydraulic system, etc.) instead of to a particular instrument.

A.3 TEXT OF QUESTIONNAIRE

(See attached)

QUESTIONNAIRE: USE OF TACTILE DISPLAYS

Name____

Part I: Comparison of Tactor Types

1. Which tactor type do you feel allows best performance?
   (Check one.)
   Electrotactor:
   Vibrotactor:
   No difference:

2. Which tactor type is most comfortable to use?
   (Check one.)
   Electrotactor:
   Vibrotactor:
   No difference:

3. Which tactor type do you prefer overall?
   (Check one.)

   Electrotactor:
   Vibrotactor:
   No preference:

4. If you answered "no preference" to question 3, skip to Part II. Otherwise, please state the strength of your preference
   (Check one.)
   Mild preference:
   Strong preference:

5. If you responded "strong preference" to the preceding question, please state the reason for this preference below. Otherwise, proceed with Part II.

   Reason for strong preference:

Name ____

Part II: Suggested Improvements

If necessary, you may use additional paper to answer the questions in this part of the Questionnaire.

1. List below any improvements you can suggest with regard to design, format, coding, etc, that apply to both electrotactors and vibrotactors:

2. List suggestions that apply specifically to electrotactors:

3. List suggestions that apply specifically to vibrotactors:

Name ______________________________________

Part III: Potential Use in Flight

A. Potential Use and Pitch/Roll Display

1. Would you be willing to use the electrotactor display as a supplement to the visual pitch/roll in actual flight?

   a. As currently configured (check one).

      Yes:

      No:

   b. If you answered "no" to part (a) above, then would you be willing to use the display for pitch and roll under certain conditions or with certain modifications? (Check one.)

      Yes:

      No:

   c. If you answered "yes" to part (b) above, what conditions and/or modifications are required?:

2. Would you use the vibrotactor display as a supplement to the visual pitch/roll display in actual flight?

   a. As currently configured?

      Yes:

      No:

   b. If you answered "no", then would you use this display for pitch and roll under certain conditions or with certain modifications?

      Yes:

      No:

   c. If you answered "yes" above, please elaborate:

Name ______________________________

B. Other Potential In-flight Uses for Tactile Displays

Assume that you have a choice of either electrotactors or vibrotactors and assume that your recommendations for display improvement have been carried out. What other use can be profitably made of the tactile display in flight? Specifically:

1. Would the display be suitable for presenting emergency warning signals to indicate a critical situation (e.g., engine temperature too high, impending stall, etc.)?
   Yes:
   No:

2. Could the display (1-axis only) be used to provide continuous monitoring of airspeed or angle-of-attack?
   (Check one of the following.)
   Airspeed: Yes:
   Airspeed: No:

   (Check one of the following.)
   Angle-of-attack: Yes:
   Angle-of attack: No:

3. Could the tactile display be used profitably to present ILS-type information (2-axis)?
   Yes:
   No:

4. Please list any other uses you can think of:

5. If you cited two or more potential uses for the tactile display when answering the preceding questions, then which single use would provide the greatest reduction in visual scanning workload?

REFERENCES

1. Ross, D, R. Sanneman, W.H. Levison, R. Tanner, and T. Triggs, "Tactile Display for Aircraft Control", Semi-Annual Technical Report, Sanders Associates, Inc., Nashua, N.H. (AD757-344) January 1973.

2. Ross, D., R. Sanneman, W. Levison, R. Tanner, and T. Triggs, "Tactile Display for Aircraft Control", Final Technical Report, Sanders Associates, Inc., Nashua, N.H. (AD767-763) August 1973.