INVESTIGATION OF AN ANALOG TECHNIQUE TO DECREASE PEN-TRACKING TIME IN COMPUTER DISPLAYS

by

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Submitted to the Department of Electrical Engineering on 21 January 1966 in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Many modern digital computer systems contain cathode-ray-tube display equipment to facilitate man-machine communications. Through the use of a display and a light-sensitive pen, graphical material can be directly inserted into the computer by using the pen to control the position of the electron beam at the face of the CRT--a process called pen tracking. Beam position is continually sampled by the computer, permitting continuous display of the material being sketched. In present digital pen-tracking techniques, a tracking pattern (usually a cross) with a substantial number of points is generated on the face of the CRT and the binary response of the pen to the individual points of the pattern is employed to calculate pen position. The large number of pattern points, and the phosphor decay time associated with each, yield a typical tracking cycle of 500 to 1000 microseconds. Since the cycle must be repeated about 100 times per second, 5 to 10 percent of display time is consumed.

To reduce the time required by the tracking operation, an analog technique employing a four-point tracking pattern is proposed in this study, in which the amplitude response of the pen to corresponding pairs of points is used to determine the position of the pen relative to the center of the pattern. To study the method, one channel of the proposed two-channel analog tracking system was designed, constructed, and coupled to the horizontal channel of a high-speed computer display console. To avoid the phosphor-decay limitation, an experimental "beam" pen capable of detecting the electron beam rather than the phosphor luminescence is employed. The system includes a pattern generator, sample-and-hold gates, difference amplifier, envelope detector and noise filter, and a threshold-logic analog-to-digital converter. The time required to generate the tracking pattern and develop the binary equivalent of the horizontal distance separating pen and pattern center is only 25 microseconds. Tracking is generally satisfactory, but some anomalies were noted, apparently due to the characteristics of the experimental pen being used.

It is concluded that the analog technique is feasible for improving the speed of pen tracking, but recommended that further studies be made of the limitations inherent in the method.

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ACKNOWLEDGEMENT

The author wishes to express his appreciation to Mr. John E. Ward for suggesting the topic treated in this study and for his supervision of the thesis. The author is also indebted to Dr. Donald R. Haring for his assistance with the beam pen and the suggestion of the multi-threshold-element approach to the A/D converter; and to Mr. Robert H. Stotz for his advice and assistance in integrating the experimental circuit with the ESL Display Console.

In addition, the author is grateful to Mrs. Clara Conover for typing the thesis, and to the members of the ESL Drafting Department for drawing the figures.

FOREWORD

The work reported herein represents one of the activities of the Display Group of the M. I. T. Electronic Systems Laboratory -- the search for ways to improve display performance while at the same time reducing the amount of main-frame computer time required for display operation. The Display Group is engaged in (1) further development of display consoles for Computer-Aided Design under Contract AF-33(657)-10954 with the Air Force Avionics Laboratory (the present ESL Console operating at Project MAC was designed and constructed under this contract), (2) in planning for and/or development of various classes of display systems for the future Project MAC Multics System, and (3) in display system developments for the M. I. T. Project Intrex remote-access library experiments.

John E. Ward
March 7, 1966

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CHAPTER I

INTRODUCTION

Many modern digital computer systems contain display equipment capable of facilitating the insertion of graphical material into memory. One such technique employs "pentracking", a term used to denote the ability to control the electron beam of a cathode ray tube with an external "writing" device. An example of such an equipment is the display console developed by the Electronic Systems Laboratory (ESL) of the Massachusetts Institute of Technology.[*1] Capable of being used with a high-speed digital computer, this console permits pictorial (i.e., graphical) information to be supplied to the computer, as well as allowing computer-controlled graphical presentation. Basically, a display console allows two-way communication with the computer to be accomplished through pictures as well as language (alphanumeric keyboard).[2]

In a display console, visual presentation of pictorial information, as well as text, is accomplished on a cathode ray tube (CRT). Graphical information can be inserted using a light pen as a writing device. The use of a light-sensitive pen in this manner is an established technique for guiding the motion of a CRT beam.[3,4] Through the tracking process, the pen controls the position of the electron beam by sensing the light output of the phosphor excited by this beam. To furnish a sketch to the computer, the display console is placed in the tracking mode and the operator

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[*] Superscripts refer to numbered items in the Bibliography

"draws" on the face of the CRT with the light pen. The coordinates of the path described by the pen are retained by the computer to permit continuous display of the material being sketched. The tracking operation may be under the control of a computer program, or it may be accomplished by hardware within the system.

In the particular display equipment used in this study, the ESL Console, pen tracking is accomplished by logic within the display console itself. A light pen controls the position of the electron beam, and beam horizontal and vertical coordinates are stored in registers within the console. These registers are regularly sampled by the computer. Local hardware implementation of the tracking operation frees the computer from performing this necessarily repetitive chore. In the present system, when in the tracking mode of operation, the scope display is interrupted every 10 milliseconds and a tracking cycle of approximately 1 millisecond duration is used to update pen position (a 10 millisecond interval between tracking cycles is about an upper limit if the beam is not to be lost when the pen is moved rapidly across the scope face). The tracking cycle consists of the generation and display of a tracking pattern centered at the last known position of the light pen (determined during the previous tracking cycle). Recalculation of present pen position is accomplished using the response of the light pen to this pattern. The tracking pattern is a small cross consisting of 32 points of light drawn on the CRT by the display console line generator. The points are plotted one at a time, starting at the center of the pattern, and incrementing out to describe the arms of the cross (Fig. 1).

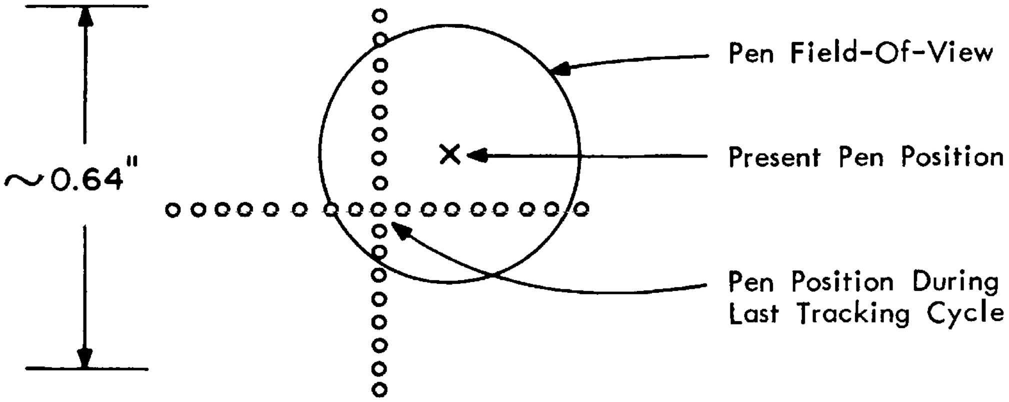


Fig. 1. Digital Tracking Cross

The light pen consists of a photoconductive sensor and associated electronics (the specific pen used with the ESL Console consists of a photomultiplier tube and threshold detector, with a fiber-optic cord linking the pen and photomultiplier). When positioned over the tracking pattern shown above, the pen yields an output pulse for each illuminated point of the cross which falls within its field-of-view. The console logic counts the points seen on each of the four arms of the cross and recalculates present pen position from this digital information. This position serves as the center of the new tracking cross to be generated in the next tracking cycle. The cycle takes approximately 1 millisecond to complete, hence, occupies about 10 percent of the total display time.

The time required for completion of a tracking cycle is limited by the phosphor response of the scope. Cathode ray tubes used in computer displays are rewritten 30 times per second, or less, and must have a persistent phosphor in order to reduce flicker to a tolerable level. The ESL Console uses type P7 phosphor, a moderate-speed blue phosphor which excites a much slower yellow phosphor. Due to this light persistence, it has been found necessary that a blanking interval of about 14 microseconds exist between successive illuminated points of the cross if the pen is to make a reliable "seen"/"not seen" decision. With 64 points being illuminated in one cycle (i.e., each of the 32 points of the cross is illuminated twice: once on the outward trace of the arm, and again when returning to the center), the resulting total pattern generation time is about 1 millisecond. This represents a considerable portion of the total time available for display. As each additional console is added to the same tracking system, operating on a time-shared basis, an additional 10 percent of display time is required, and the amount of potential display time being absorbed by the tracking operation becomes of considerable concern. The problem, then, can be very succinctly stated: the time required by the present digital technique for lightpen tracking is excessive. A faster method is needed for updating the position of a pen moving over the face of a display console.

This paper presents a technique for decreasing the time required for pen-tracking through the use of an analog, rather than digital, approach to the problem. Basically, the technique makes use of the amplitude response of a pen-sensor. A method is presented for determining positional information by obtaining the difference voltage existing between pen output pulses corresponding to pairs of points in a tracking pattern. Circuitry is developed to implement this analog concept, and the ESL Display Console is employed to test the technique. The remainder of this report is devoted to an analysis of the analog approach, the considerations and circuitry required to test the method on a specific display system, and an evaluation of the results obtained under test. The final chapter presents the conclusions derived from this investigation and recommends several areas where further study might be pursued.

CHAPTER II

OVERALL ANALOG SYSTEM DESIGN

A. DESCRIPTION OF THE ANALOG APPROACH

The analog pen-tracking technique proposed in this study requires a considerably smaller tracking cycle time than that of the existing display system described earlier. Digital tracking operates on a points-seen-or-not-seen basis; a large number of tracking pattern points are necessary to achieve positional accuracy. The analog method differs from this in that the amplitudes of the pen responses to a small number of displayed points convey the required positional information. Rather than counting the total number of points whose responses exceed a preset threshold level, the amplitudes of the pen responses from only four points (i.e., points of light on the CRT) can be compared to provide updating of pen position.

Initially, assume the pen is placed against the CRT face and held in a fixed position while a point of light (the electron beam) sweeps past. If the output signal of the pen is plotted as a function of beam position, a curve such as that shown in Fig. 2 is obtained, the exact shape depending on the pen optics. Now, if the electron beam is deflected so as to generate two points of light in the vicinity of the pen (Fig. 3), with point 1 displayed first, followed by point 2, two corresponding pen output voltages, E1 and E2, result. The difference between these d-c amplitudes, E1 - E2, provides a measure of the distance separating the pen center from the midpoint of the line joining the two displayed points. Only when the quantity E1 - E2 is zero will the two points be symmetrically centered about the pen.

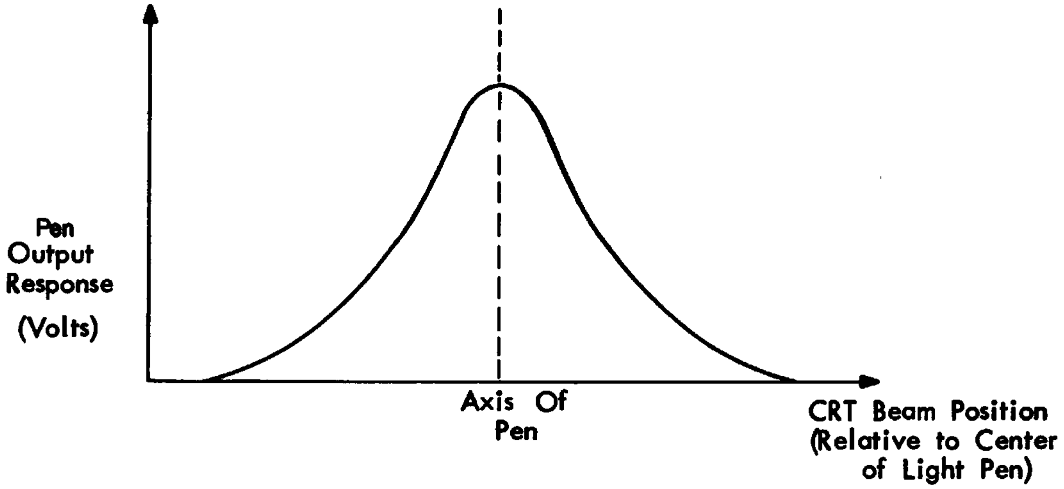


Fig. 2. Typical Pen Amplitude-Position Response Curve

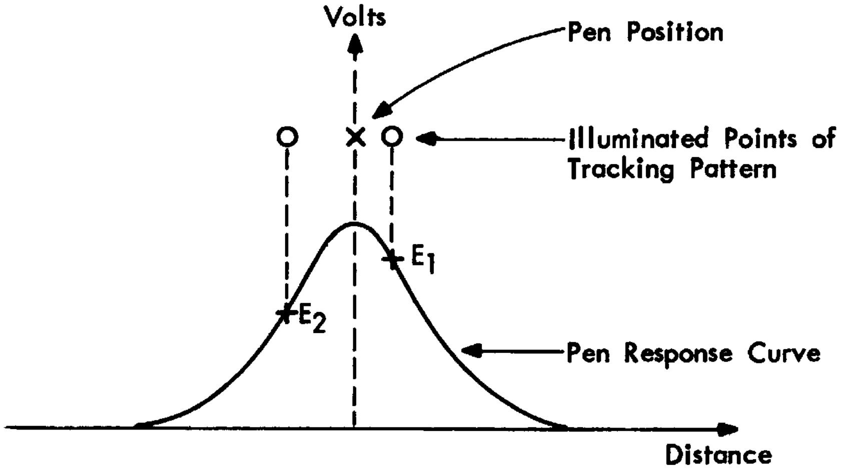


Fig. 3. Developing the Analog Difference Voltage

An analog tracking pattern can consist of four points (Fig. 4). Point 1 is illuminated first, followed by points 2, 3, and 4. With a pen placed over this pattern, the horizontal pair provides a horizontal error voltage, ΔEh, and the vertical pair, ΔEv. Converting these orthogonal difference voltages to error distance (specifically, increments of distance along the horizontal and vertical axes of the CRT face), and adding them to the coordinates of the pattern center, establishes the position of the pen. Moving the cross center to this new position centers it about the axis of the pen. Repeating this "tracking cycle" at periodic intervals would permit the cross, hence the CRT beam, to follow a pen moving over the scope face. The time interval between tracking operations is utilized to display the graphical material being described by the pen.

B. CHOICE OF PEN-SENSOR

Two choices presently exist for the pen-sensor. The established device is the light pen. The unit presently used with the display console is constructed as follows: a metal cylinder, physically about the size of a large fountain pen, houses one end of a fibre-optic cord. A thumb-actuated shutter seals the end of the cord from the open end of the pen. When tracking, the pen is placed against the plastic protective faceplate of the CRT and the shutter depressed, allowing light from the CRT to fall on the exposed end of the fibre optic bundle. The other end of this flexible cord is placed above the anode of a photomultiplier tube housed within the console. The output of the photomultiplier is fed into a voltage threshold detector circuit. With a point of light displayed on the CRT, and the shutter depressed, the threshold circuit will fire when the pen aperture moves over the point.

Since this pen responds to light excitation, an output can exist for some time after the electron beam has been turned off. As previously mentioned, the CRT face is coated with a high-persistence phosphor to avoid flicker. The light output (as detected by the light pen) for a 1/2 microsecond unblanking pulse is depicted in Fig. 5. If intensify pulses occur too closely spaced in time, the pen output will be influenced not only by the immediate pulse, but also by those earlier pulses whose light output has not yet decayed to zero. To avoid this response integration, which can bias the phototube into a saturation region, sufficient time must be allowed between pulses to ensure the complete decay of the preceding pen signal. When dealing with phosphor response, this delay time can be considerable.

In an effort to overcome this difficulty experienced with light pens, a second writing instrument, the "beam pen", has recently been developed at ESL.[5] This device relies on capacitive pickup to detect the electron beam itself, rather than the light it creates. The desirable feature of the beam pen is that its output is independent of phosphor decay time. Two undesirable features of the present experimental model of the beam pen are, (1) the pen field-of-view response curve is considerably broader than that of the light pen because the charge generated by the beam can be detected over an area larger than that occupied by the illuminated spot, and (2) in a stationary situation, a pulse-to-pulse output fluctuation equal to approximately 10 percent of the d-c output amplitude is present. The result is a fairly low signal-to-noise ratio. However, the prospect of fast response time, of the same order as the intensify pulse itself, argues strongly in favor of this device. For this reason of speed, the beam pen

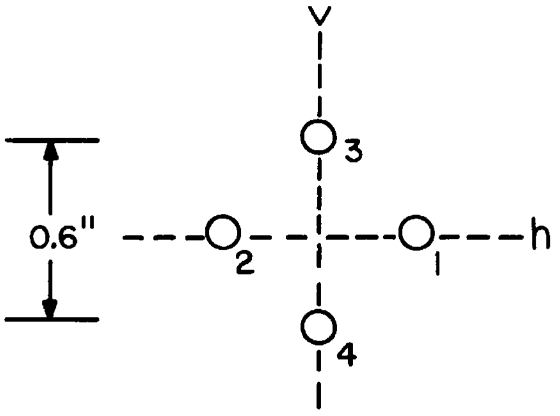
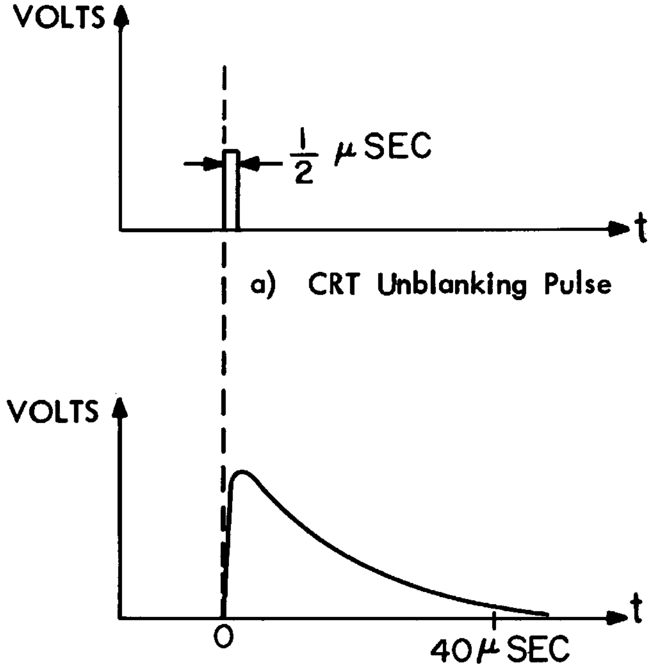


Fig. 4. Analog Tracking Pattern



a) CRT Unblanking Pulse

b) Light Pen Output

Fig. 5. Light Pen Output Pulse (Photomultiplier-Type Light Pen and P7 Scope Phosphor)

was selected to provide the input signal to the analog pen-tracking circuit.

Figure 6 is a plot of the field-of-view of the present model of the beam pen. It was obtained by moving the electron beam out from the center of the stationary pen and recording output voltage as a function of position. The abscissa is scaled in units of display console increments, one increment equaling 1/100 of an inch. With a tracking cross 6/10 of an inch wide (60 increments), the region of the curve with which we are dealing during normal tracking is that within the range of about -60 to +60 increments. To a good engineering approximation, this portion of the curve can be linearized as in Fig. 7.

Consider the two-point horizontal arm of the pattern. When this arm is centered exactly about the pen, the difference voltage $\Delta V = V_1 - V_2$ is zero. When the pen is moved into a position as shown in Fig. 7, an error voltage ΔV occurs, where,

$$\Delta V = V_1 - V_2 = 2\ md$$

m = slope of response curve

d = distance between center of tracking pattern and pen axis.

Thus, the error distance, d, existing between tracking cross arm and pen is uniquely determined by the sign and magnitude of the difference voltage ΔV. Converting ΔV to the binary equivalent of its corresponding error distance, and adding this to the contents of a register containing the position of the tracking cross, will yield the present position of the pen. This is the method used in this study. At the close of each tracking cycle,

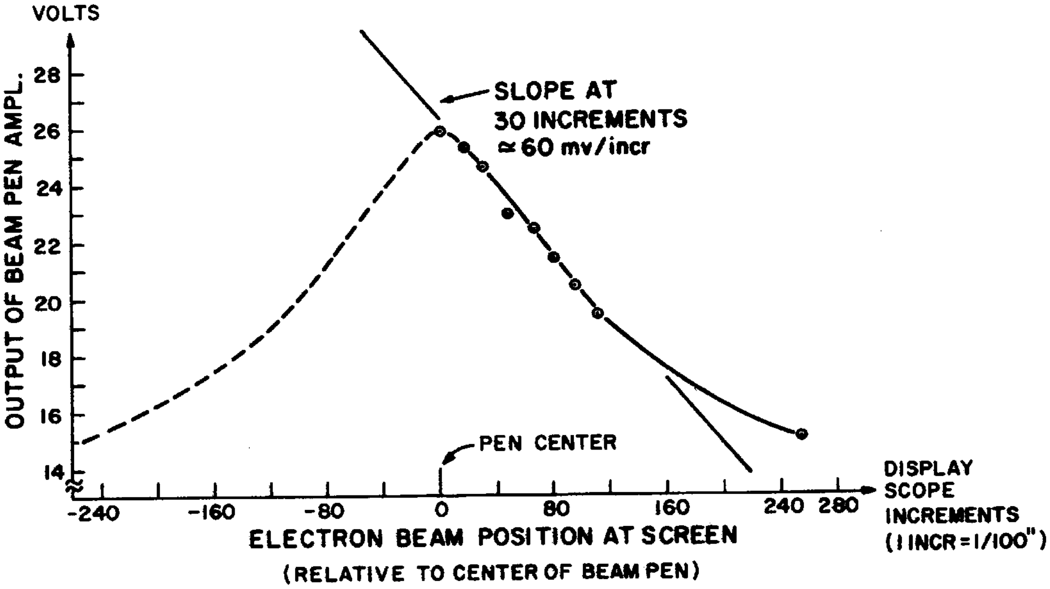


Fig. 6. Beam Pen Amplitude-Position Response Curve

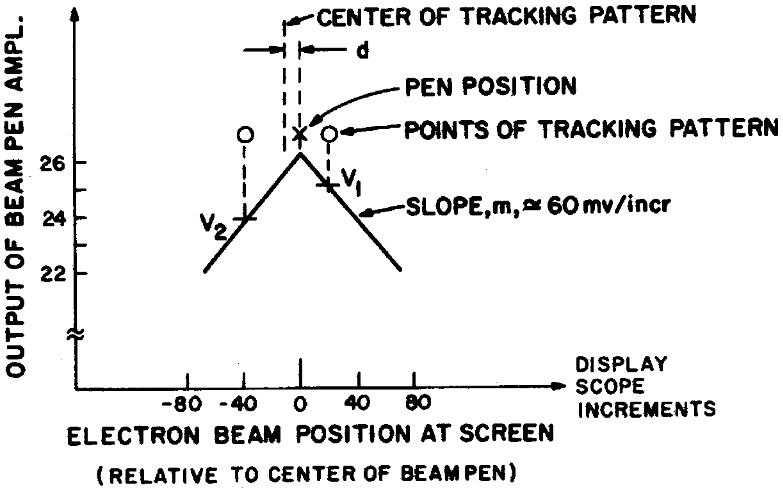


Fig. 7. Linear Approximation to Peak of Beam Pen Response Curve

the binary equivalent of the error distance is loaded into the ΔX register of the line generator of the display console. This, in turn, is added to the horizontal pen register to update present pen position.

Figure 8a is a photograph of the display console and beam pen (foreground). The breadboard model of the experimental analog tracking circuit (horizontal channel) is visible on the table to the right of the console. Figure 8b is a photograph of the existing 32-point digital tracking cross and the 4-point analog tracking pattern developed in this report.

C. INTEGRATING THE ANALOG CONCEPT INTO AN EXISTING DIGITAL DISPLAY CONSOLE

The major effort of this project was the design of the experimental analog and pulse circuitry necessary to implement and test the proposed tracking technique. As the method was to be tested on the ESL Display Console, compatibility with the existing digital hardware was necessary. In addition, two important design constraints were imposed by the present display system:

1) as the display console is an operational facility with fairly heavy usage, experimental tracking circuitry should be capable of being cut into and out of the console hardware with a minimum amount of modification of the existing system, and,

2) a malfunction of the experimental circuitry should not result in interruption of the time-sharing computer system in which the display console operates.

In the existing digital system, the time for one tracking cycle is determined by the display console clock rate and a nine-bit flip-flop

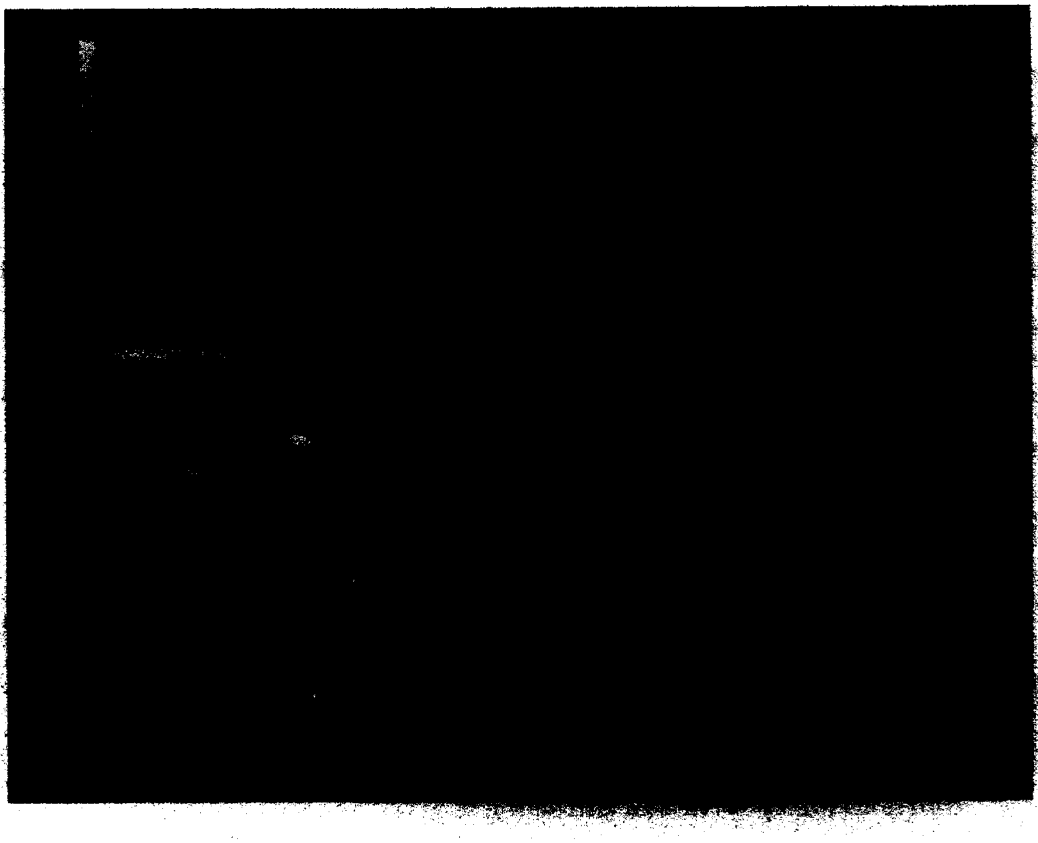


Fig. 8a. Display Console (Left), Beam Pen (Foreground), and Experimental Analog Tracking Circuitry (Right Center)

Fig. 8b. Digital Tracking Pattern (Left) and Analog Tracking Pattern (Right) (Photographed on Display Console, Actual Size)

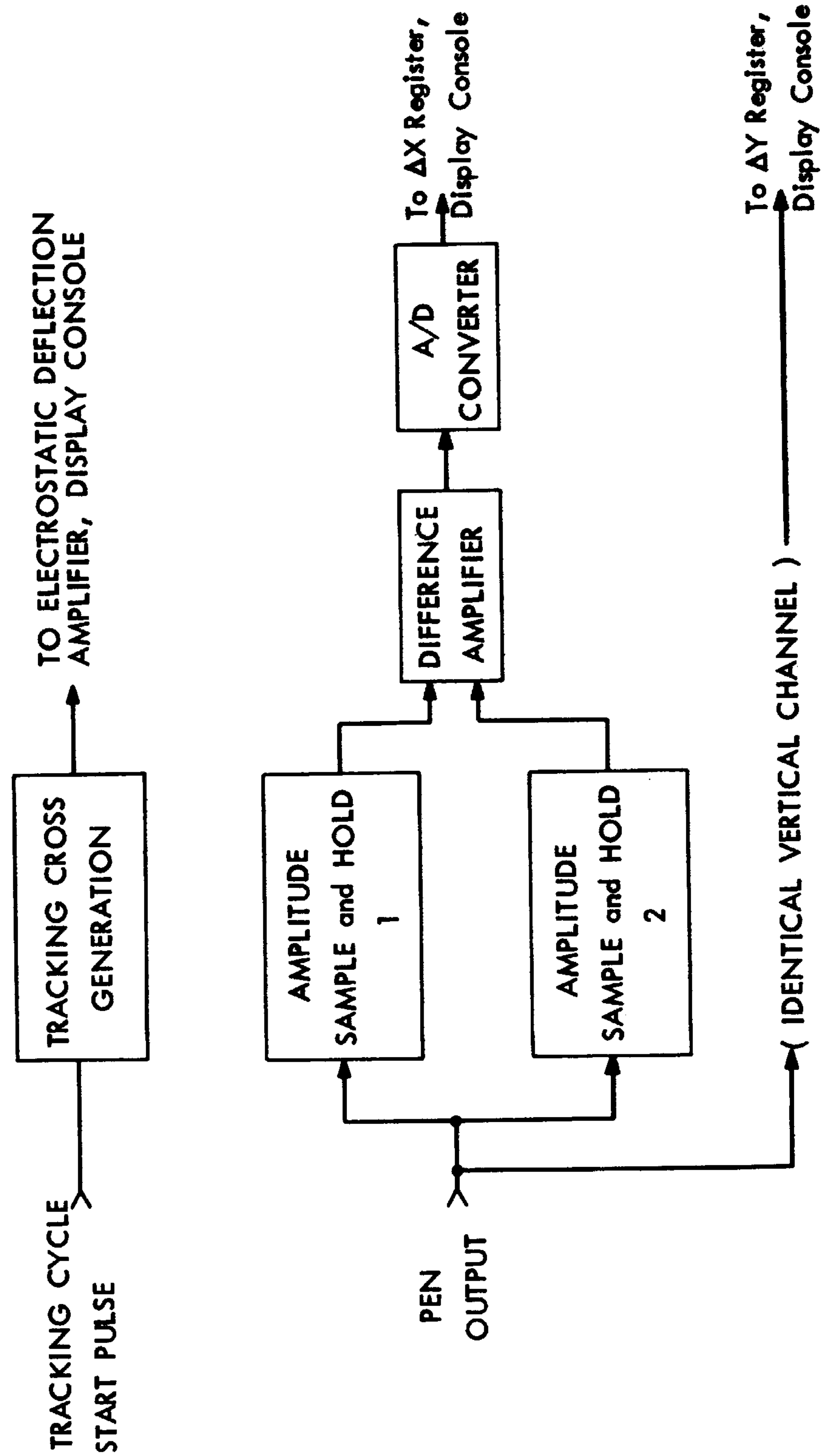
counter. At the beginning of a cycle, clock pulses are fed into the counter. The sequential states of the flip-flops are used to generate the 32-point cross and to control the gating of light-pen responses. During this counting time, the pen output pulses corresponding to points seen on each of the four arms of the cross are counted, processed, and stored in two registers, ΔX and ΔY. At the conclusion of the cycle (overflow of the counter), the contents of these registers are the horizontal and vertical incremental error distances between the center of the cross and the axis of the pen, and they are added to the horizontal and vertical pen-position registers to update the location of the moving pen. The coordinates stored in the pen registers mark the center of the cross to be generated in the next tracking cycle.

The interval between tracking cycles is established by the period of a monostable multivibrator (10 milliseconds in the existing system). The end of a tracking cycle triggers the timing pulse of this multivibrator, and the trailing edge of this pulse is used to start the next tracking cycle.

The analog circuit operates within the above framework as follows: the starting pulse for the digital tracking cycle is also used to initiate the analog cycle. The digital cross is disabled by bypassing the early bits of the counter responsible for incrementing and intensifying the 32-point pattern. The clock pulses are introduced, instead, at a higher bit position. This effectively shortens the length of the counter, and allows the tracking cycle time to be decreased as anticipated in this method of tracking. At the end of the count, the contents of the ΔX and ΔY registers are added, as usual, to the contents of the pen position registers. Thus, if the experimental circuitry can develop, for each axis, a binary number representing the distance separating the tracking cross and pen, and load these into the ΔX and ΔY registers before completion of the cycle, proper tracking will occur.

Figure 9 is a general block diagram of the proposed analog tracking circuit. Basically, a four-point tracking cross is generated and the response of the pen to each point is sampled and stored. The amplitudes of corresponding points are compared and their difference obtained. The magnitude of this difference voltage is converted to a digital representation and added to the display console pen-position registers.

In the existing digital pen tracking system, the quantization of the ΔX and ΔY registers is by increments of two. That is, the binary number 001 corresponds to a distance of $2 \times 1/100$ inch. With this information, and the measured slope of the beam pen field-of-view curve, the required gain of the analog system can be calculated. The A/D converter is quantized into one-volt levels. A change of 1 volt at the output of the difference amplifier causes the least significant bit of the A/D converter to change by 1, and, therefore, corresponds to a change of position of two increments on the display scope. An error distance of two increments existing between pen and tracking cross will result in a difference of $\Delta V = 2\ md = 0.24$ volts between the amplitudes of the two pen output pulses. Thus, the voltage gain of the circuit between the pen output and the A/D converter must be $1/0.24 = 4.2$.


TRACKING CYCLE START PULSE
TRACKING CROSS GENERATION
TO ELECTROSTATIC DEFLECTION AMPLIFIER, DISPLAY CONSOLE
PEN OUTPUT
AMPLITUDE SAMPLE and HOLD 1
AMPLITUDE SAMPLE and HOLD 2
DIFFERENCE AMPLIFIER
A/D CONVERTER
To ΔX Register, Display Console
(IDENTICAL VERTICAL CHANNEL)
To ΔY Register, Display Console

CHAPTER III

IMPLEMENTATION OF THE ANALOG CONCEPT

A. GENERATION OF THE TRACKING CROSS

The initial circuit requirement in the investigation of the analog technique was the development of a four-point tracking cross. At the beginning of each tracking cycle, the information in the pen-position registers is used to magnetically deflect the blanked electron beam to the position of the pen as determined by the previous tracking cycle. The analog cross is developed using electro static deflection to further deflect the beam slightly about this position, first to the right, then left, up, and down. At each position, an unblanking pulse is applied and a point of the cross is formed.

The block and schematic diagrams of the tracking pattern circuitry are shown in Figs. 10a and 11a, respectively. The associated waveforms are shown in the timing diagram of Fig. 12. Initially, the pulse starting the tracking cycle is used to trigger a 35 microsecond delay, necessary to provide settling time for the magnetic deflection yoke. The trailing edge of this delay pulse starts the generation of the cross. Four deflection voltages, symmetrical about zero volts, are generated by four monostable multivibrators (one-shots 1, 2, 3, and 4). These signals are combined, in pairs, to obtain the required horizontal and vertical deflection voltages, and are then coupled to an electrostatic deflection amplifier located inside the display console. After each of the four sequential deflection-plate voltages has achieved its steady state, an unblanking pulse is applied to the CRT and the corresponding point of the cross is illuminated.

To accomplish the above cross generation, the four deflection one-shots are connected in cascade, the trailing edge of the output of each circuit serving to trigger the following unit. The leading edge of each output pulse is used to initiate a delay slightly greater than the rise-time of the deflection amplifier. At the end of this delay, the unblanking pulse occurs. The above sequence of events is detailed graphically in the timing diagram (Fig. 12).

In addition to generating the required deflection waveforms, the four one-shots also provide four independent circuit states which are used to control the gating of the pen output signals.

B. SAMPLING AND STORING OF PEN SIGNALS

With the beam pen placed over the tracking cross, four output pulses will occur during each cycle, their amplitudes depending on the proximity of the pen to each of the cross dots. The first two pulses are used to determine the horizontal pen position error; the remaining two pulses, the vertical error. The horizontal and vertical channels of this pen-tracking system are identical in design and performance. After the pen output pulses corresponding to the horizontal arm of the cross have been processed, an identical procedure is followed with respect to the vertical arm. The only difference existing between the two channels is the final destination of the binary error signal generated by each circuit. The horizontal channel loads this information into the ΔX register; the vertical channel, into the ΔY register. In view of this duplication, only one channel was constructed and tested. Its output was coupled into the ΔX register, and tracking was effected along a horizontal axis.

The circuitry required for the processing of the pen responses to the horizontal arm of the tracking cross is shown in block form in Fig. 10b, and in schematic form in Figs. 11b and c. The output of the beam pen amplifier is coupled to an emitter follower to provide the required current gain and source impedance for the sampling stages. The output of the emitter follower (the pen response corresponding to each point of the cross) is applied to the inputs of the two channels. The horizontal channel, with which we are concerned here, commences with two parallel analog gates. During each tracking cycle, four pulses are received from the beam pen. The first two are the responses to the horizontal arm of the cross, the initial pulse corresponding to the right dot; the second, to the left dot. While the first point of the cross is being illuminated, and the corresponding beam pen pulse generated, the deflection multivibrator one-shot 1 is in its unstable state, producing a +10-volt, 5-microsecond wide pulse. This pulse, in addition to providing the deflection for the first point of the tracking cross, is used as the control signal at the first analog gate. Gate 1 is opened for this 5-microsecond duration and permits passage of the first pen output pulse. Gating is accomplished with transistors T_{26} and T_{27} (Fig. 11b). Normally, the base of T_{26} is held at +20 volts, reverse-biasing the base-emitter junction. As it is cut off, T_{26} isolates the beam pen pulses from the sampling capacitor C_1. Potentiometer R_3 is initially adjusted to ensure that the maximum amplitude of the pen pulses is less than the +20-volt gate control signal. This gate control signal is derived from the output of one-shot 1 using inverter T_{25}. When one-shot 1 turns on, the gate control signal drops

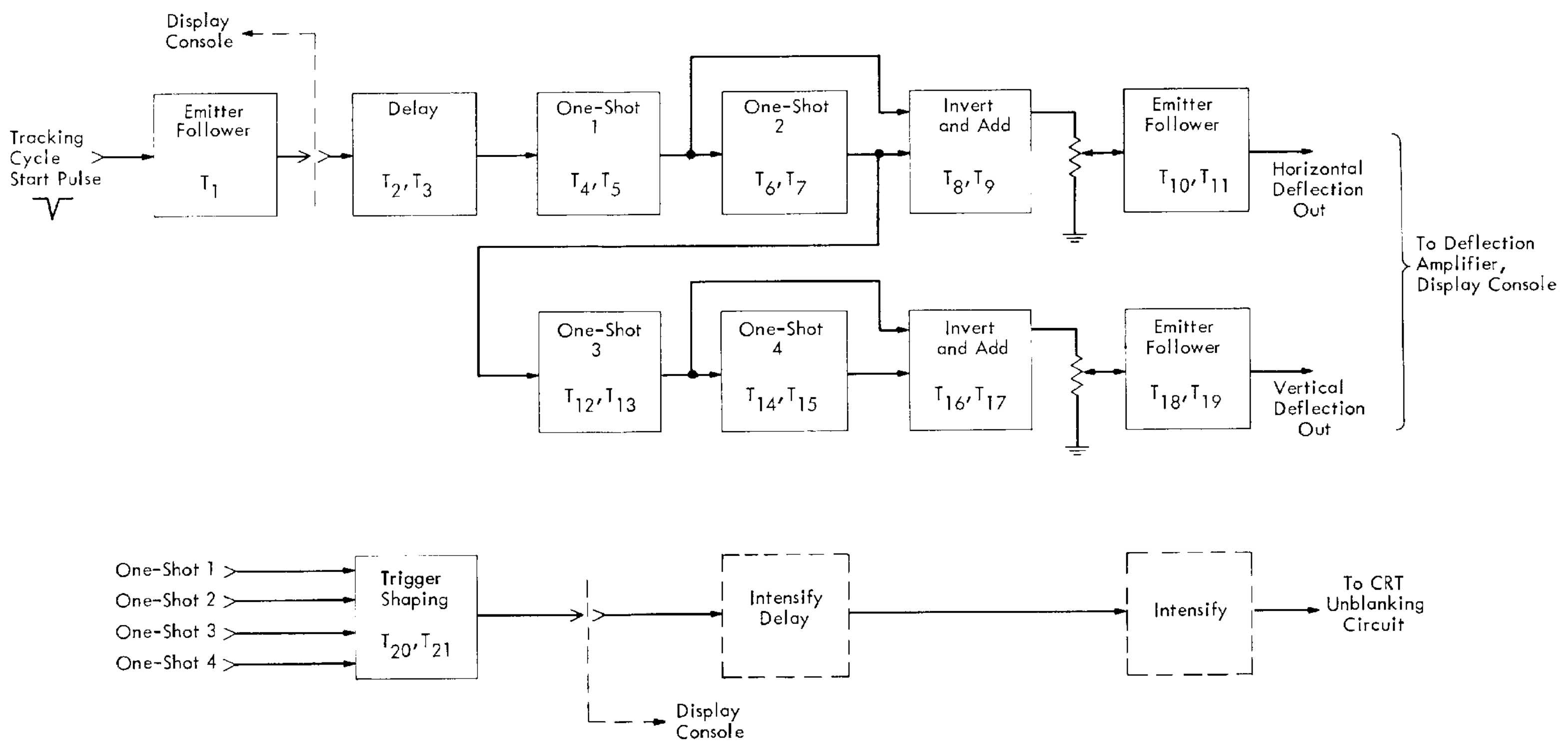


Fig. 10a. Generation of Four-Point Pattern for Analog Tracking

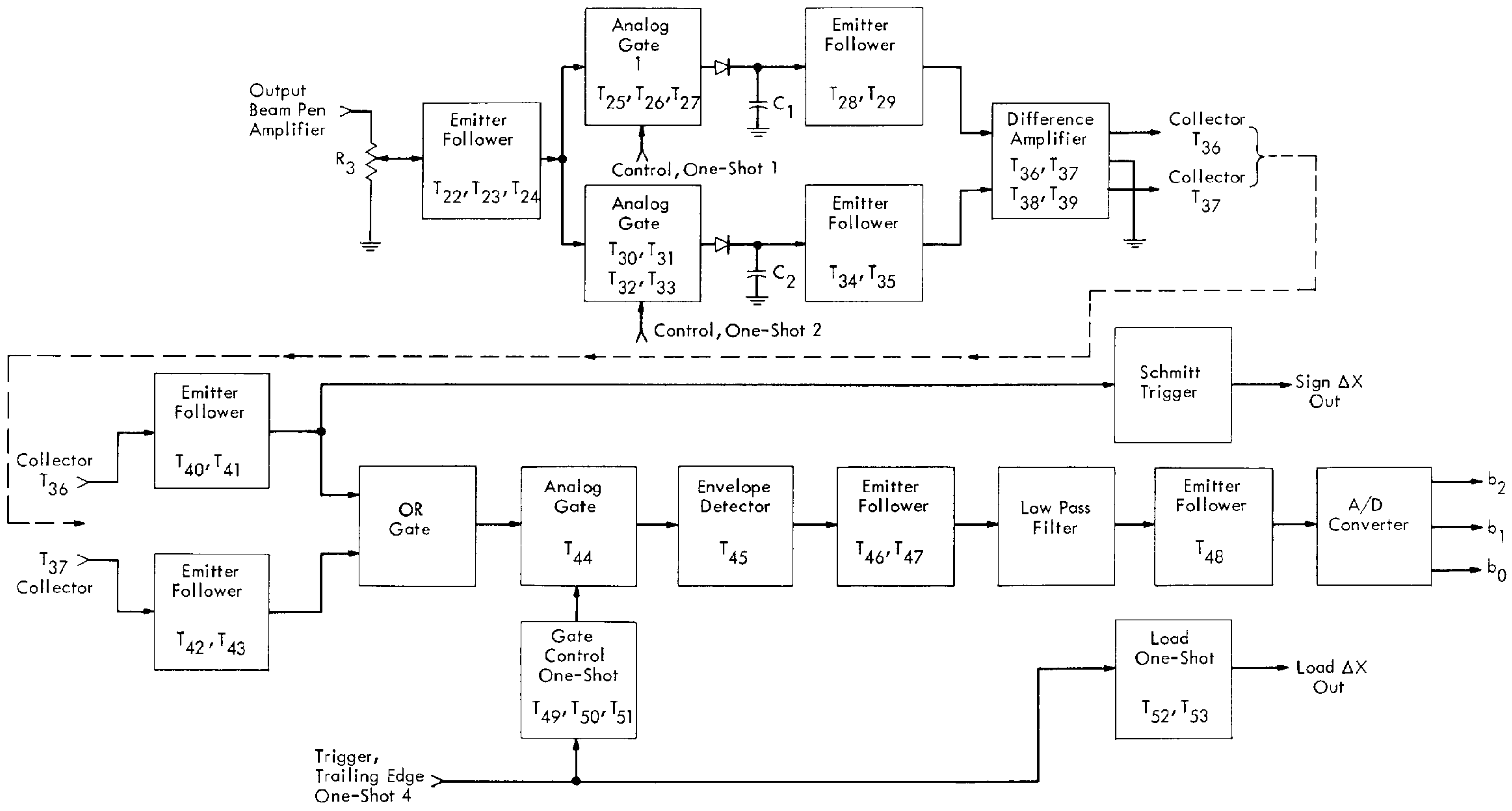


Fig. 10b. Processing of Difference Voltage (Horizontal Channel)

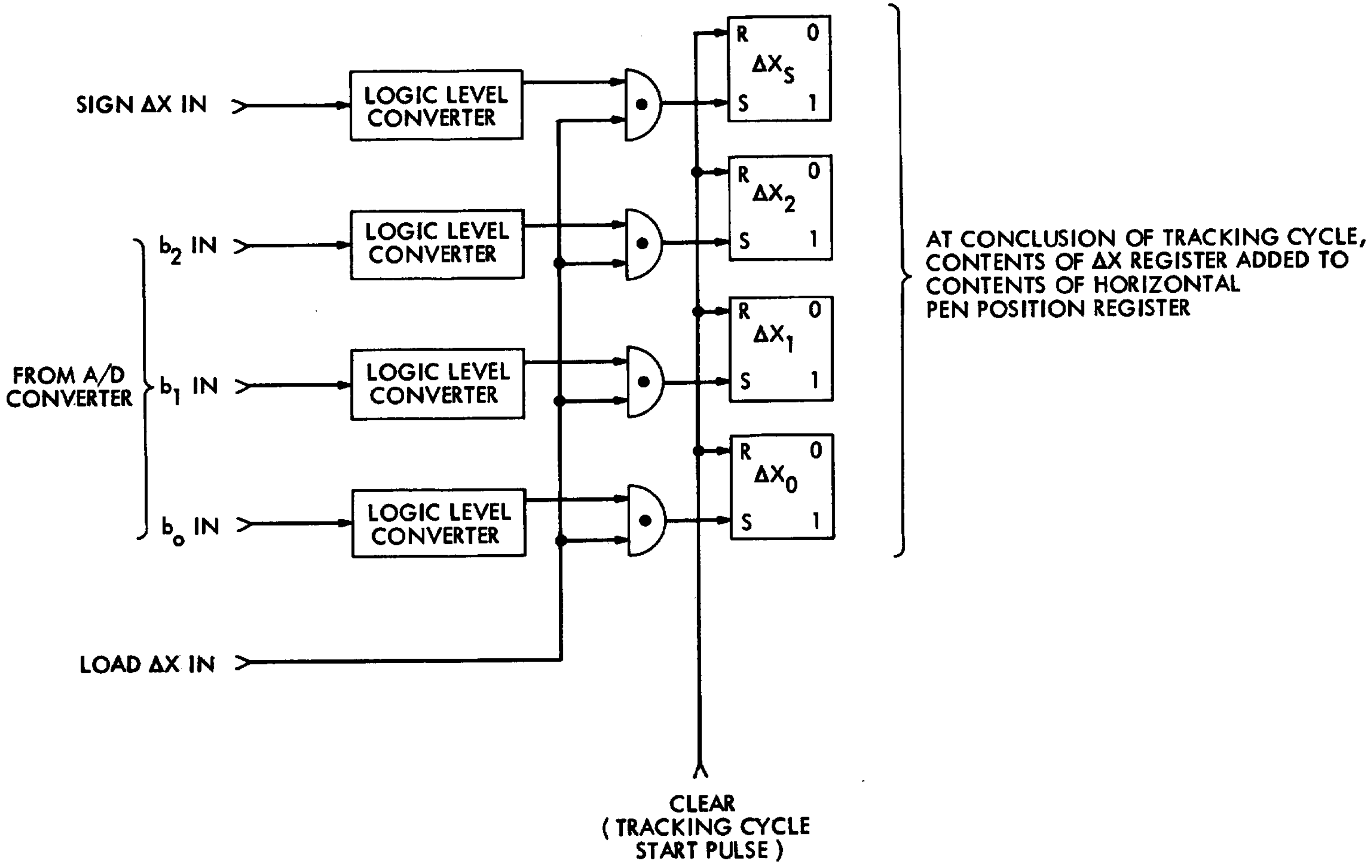
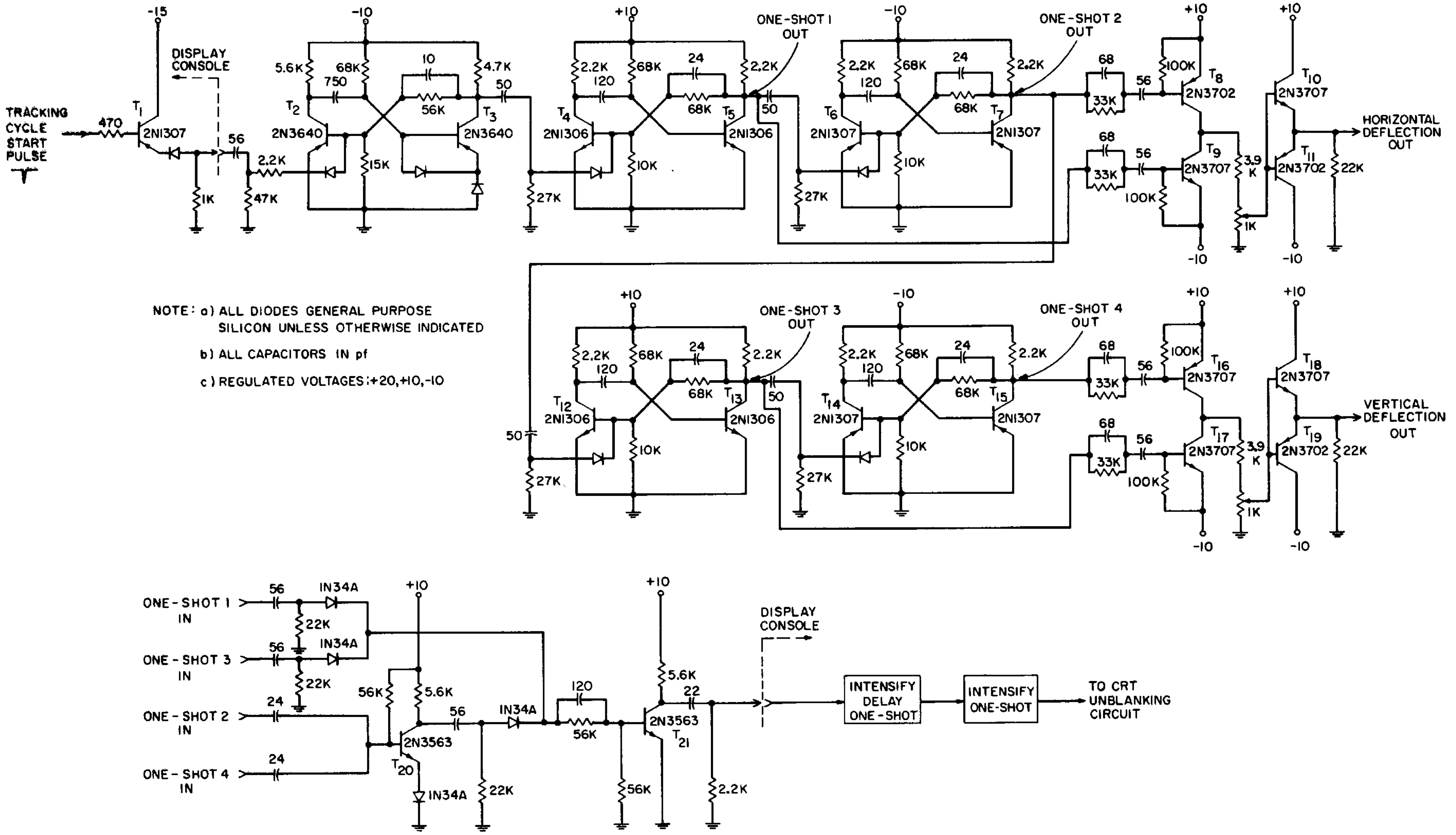


Fig. 10c. Loading of Difference Voltage (Horizontal Channel)



NOTE: a) ALL DIODES GENERAL PURPOSE SILICON UNLESS OTHERWISE INDICATED

b) ALL CAPACITORS IN pf

c) REGULATED VOLTAGES: +20, +10, -10

Fig. 11a. Schematic Diagram of Analog Tracking Pattern Generator

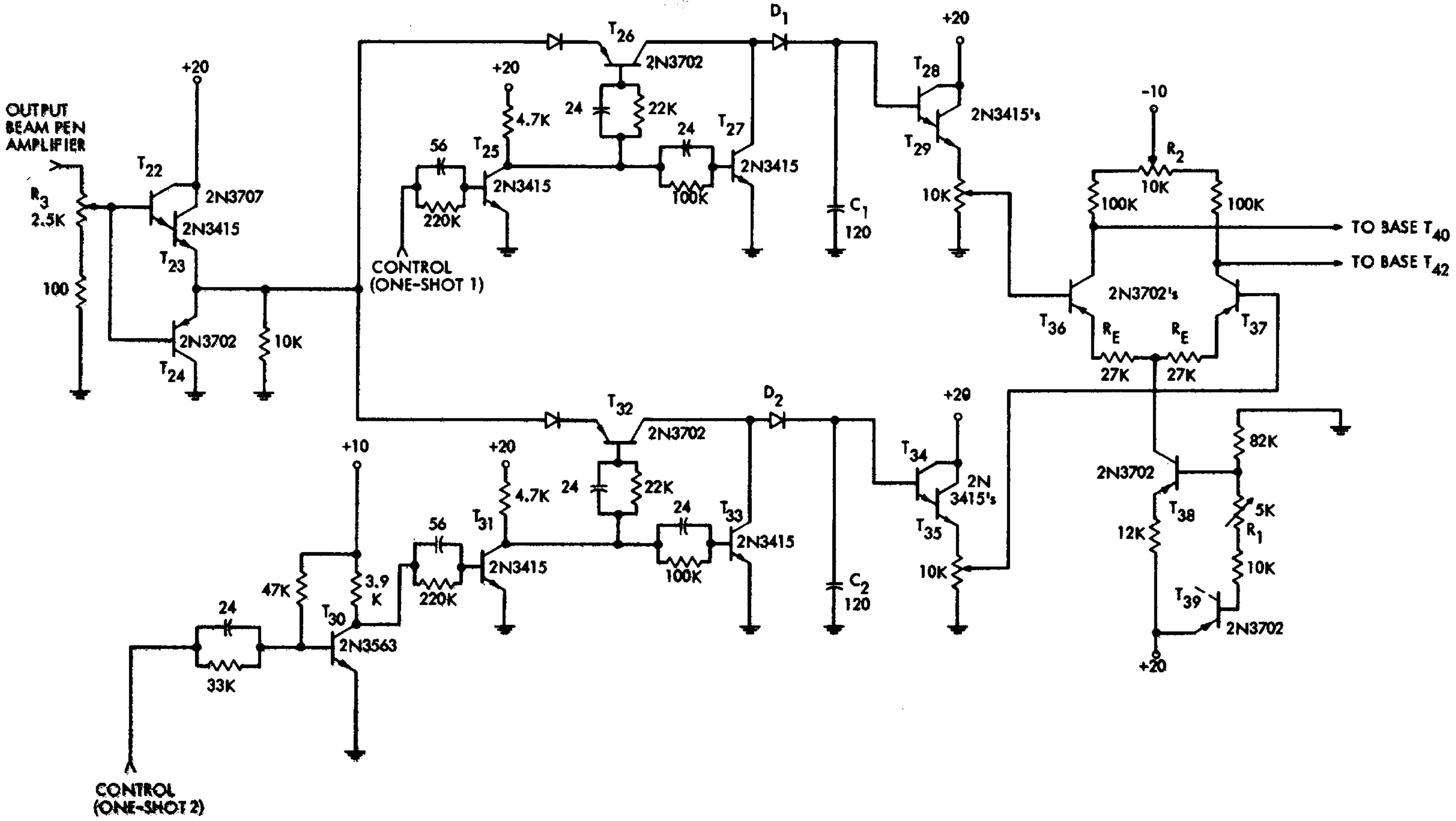


Fig. 11b. Circuitry for Processing the Difference Voltage (Horizontal Channel)

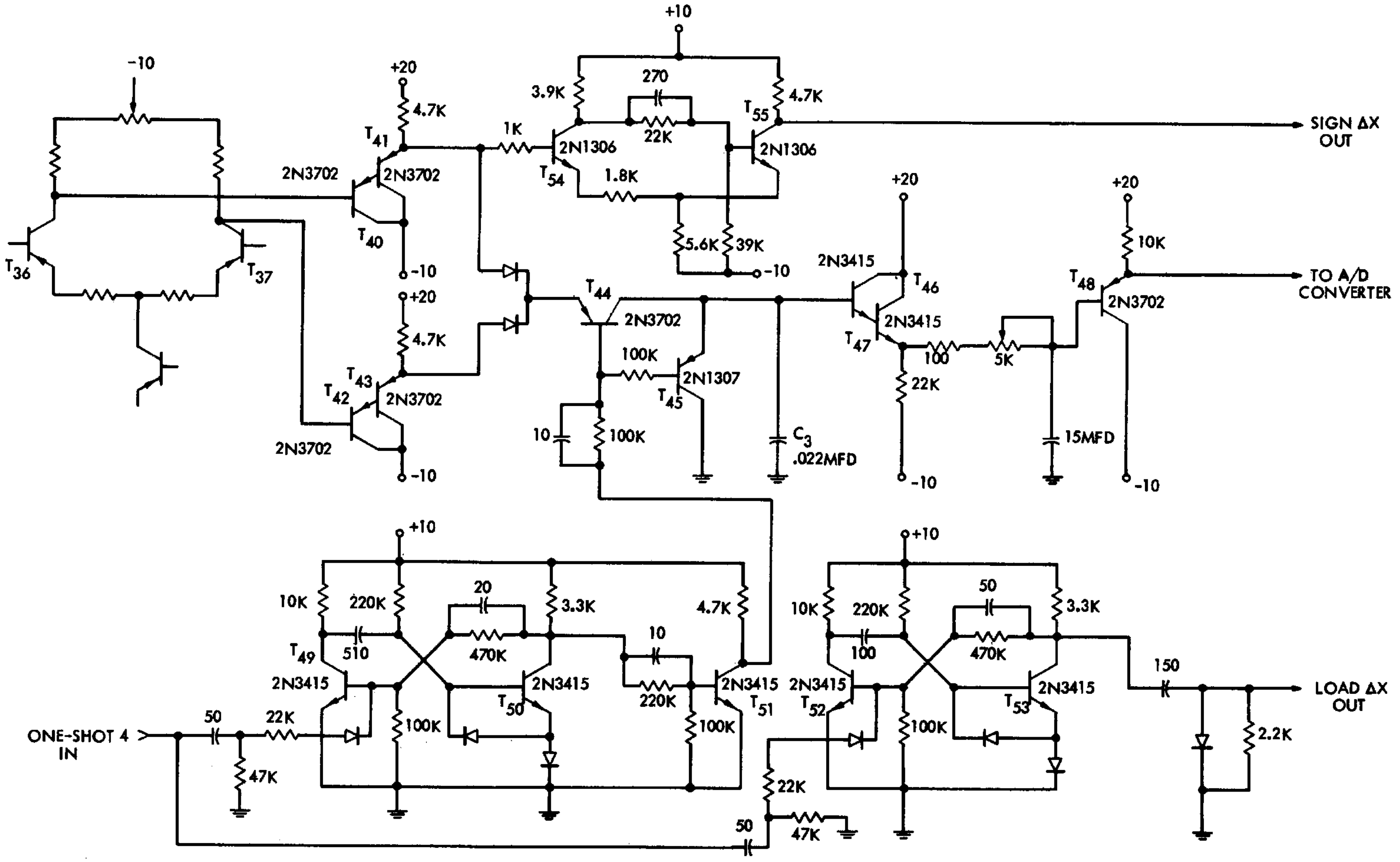


Fig. 11c. Circuitry for Processing the Difference Voltage (Horizontal Channel) (Cont.)

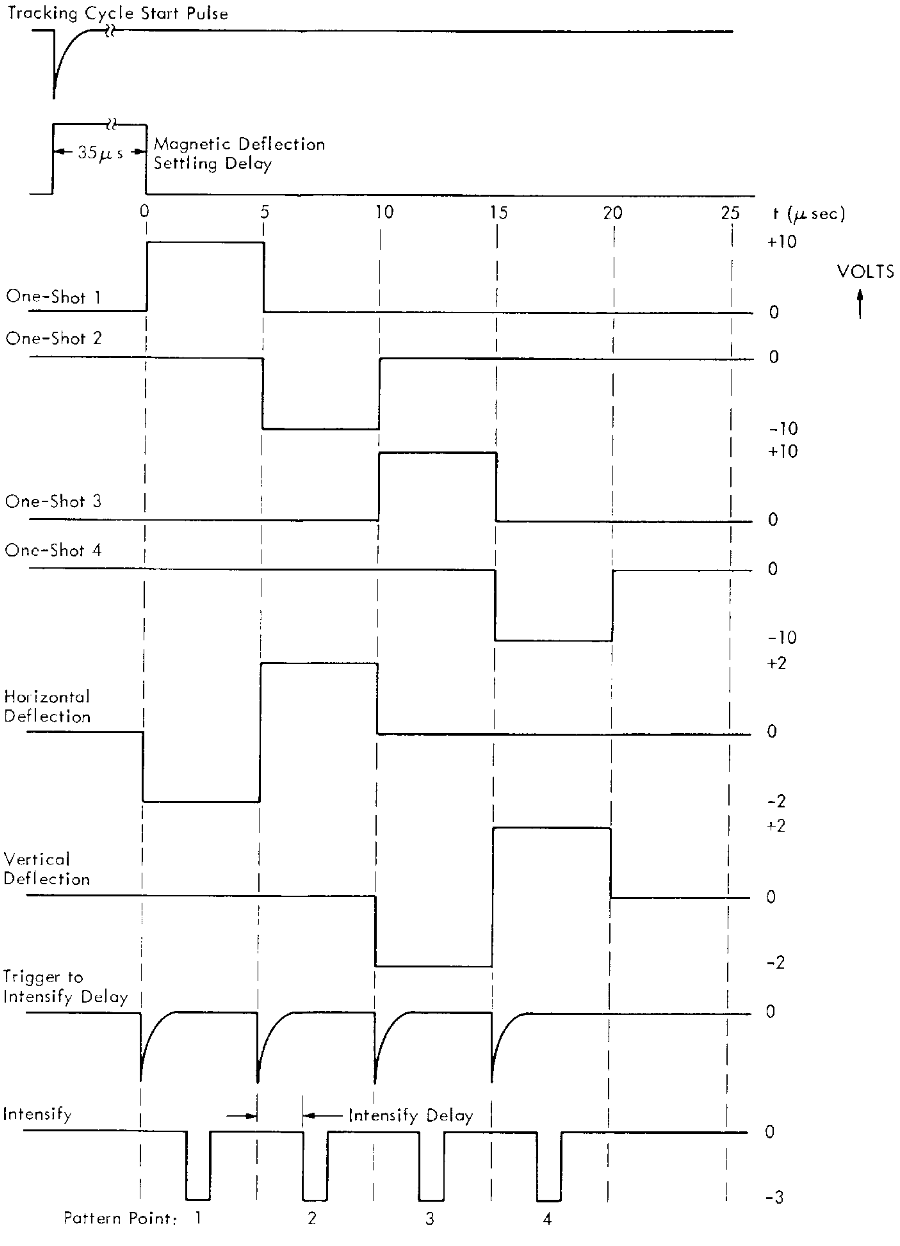


Fig. 12. Timing Diagram (Continued next page)

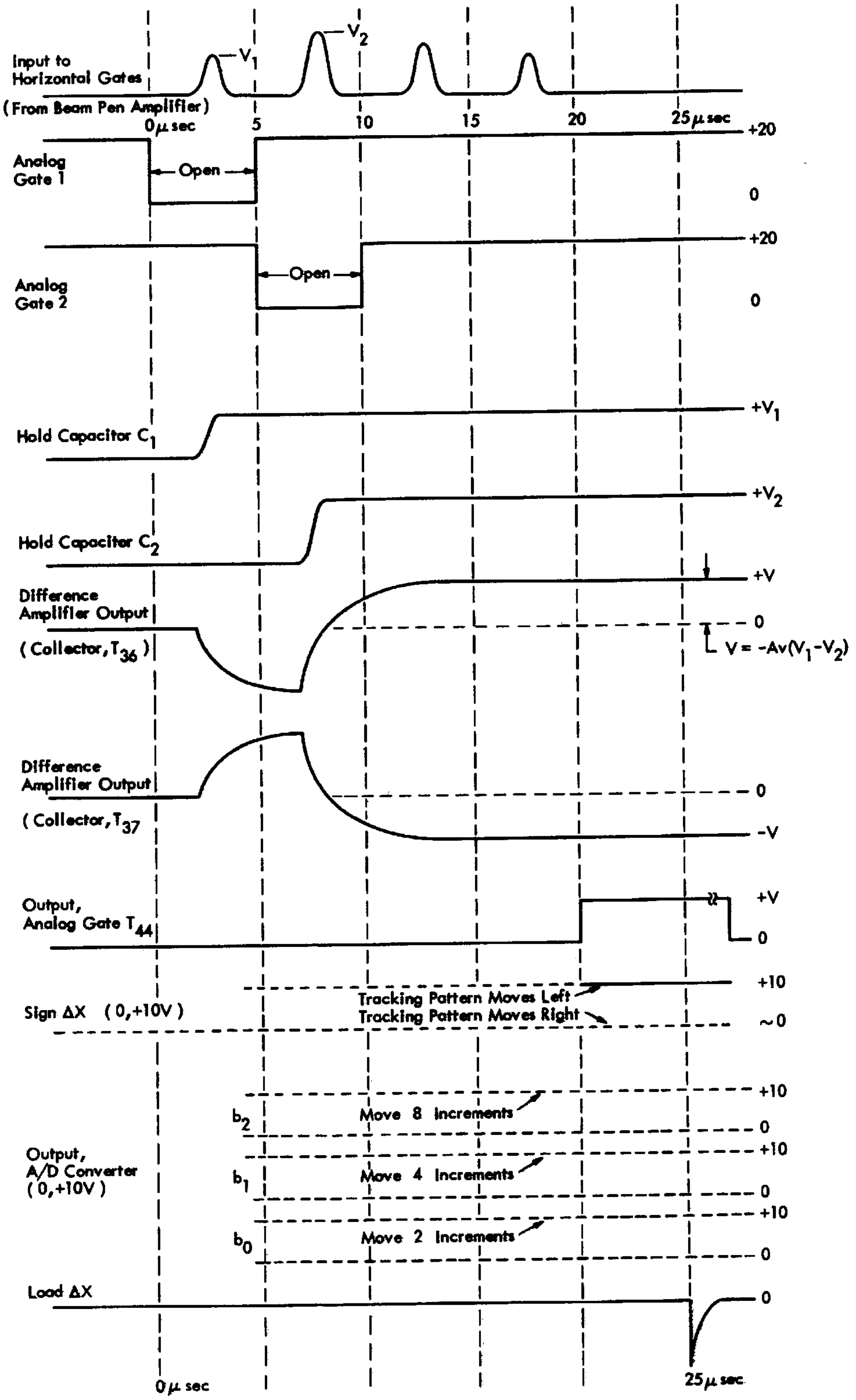


Fig. 12 (Cont.) Timing Diagram

to approximately 0 volts, saturating T_{26} and opening the gate to the hold circuit. Used alone, this series gating element suffers a drawback originating from the base-to-collector capacitance. This intrinsic capacitance, although small, serves to couple part of the leading and trailing edges of the gate control signal to the output. As it is necessary to compare pulse amplitudes differing by fractions of a volt, the errors introduced by these spikes cannot be tolerated.

This difficulty is considerably reduced by the addition of the shunt gate, T_{27}. For most of the voltage excursion of the gate control (i.e., above about 0.6 volt), T_{27} is saturated, clamping the output to ground. This low shunt impedance provides further isolation of the hold circuit and impedes the capacitively-coupled spikes.

Diode D_1 and capacitor C_1 serve as a peak detector. When one-shot 1 turns off, C_1 is charged to the peak amplitude of the first pen output pulse. The shunt transistor is now saturated, resulting in the reverse-biasing of D_1. During the remainder of the tracking cycle, C_1 remains essentially charged at its peak value. Performance of the second analog gate is identical. One-shot 2 generates the control voltage, and hold capacitor C_2 is charged to the peak value of the second pen output pulse. (Similarly, the analog gates of a vertical channel would be controlled by one-shots 3 and 4).

C. DIFFERENCE AMPLIFIER

At this point in the analog tracking cycle, the two sampling capacitors hold the peak amplitudes of the pen responses to the two horizontal points of the cross. The difference between these amplitudes is the error voltage specifying the distance separating the center line of these points and the axis of the pen, and is obtained with the difference amplifier composed of T_{36}, T_{37}, and T_{38}. Each sampling capacitor is coupled to this amplifier through a Darlington-pair emitter follower. This configuration provides sufficient isolation of the holding capacitors to prevent excessive discharge before subtraction occurs. If E_1 and E_2 are the levels applied to the inputs of the difference amplifier, the outputs at the collectors (referenced to ground) are $\pm Av(E_1 - E_2)$, where Av is the d-c gain of the stage.

The operation of the difference amplifier may be seen most clearly by considering the symmetry which the circuit possesses. The basic circuit may be represented as in Fig. 13a. Let the input at the base of Q_1 be E_1, and that at the base of Q_2 be E_2. E_1 and E_2 may be considered to consist of sum and difference components as follows:

let

$$\begin{aligned} E_1 &= Es + Ed \\ E_2 &= Es - Ed \\ \therefore Es &= (E_1 + E_2)/2 \\ Ed &= (E_1 - E_2)/2 \end{aligned}$$

Using superposition, consider first the contribution of Es to the output. From the theory of symmetrical circuits under symmetrical excitations, the amplifier can be divided as in Fig. 13b and analysis of this simple circuit considered. By inspection, the transfer function of this circuit can be written to a good approximation as,

$$Ac = \text{common-mode gain} = Eo/Es \simeq -R_L/(R_E + 2R)$$

Similarly, for anti-symmetrical excitations, point P of Fig. 13a is a virtual ground and the circuit may again be divided as in Fig. 13c and

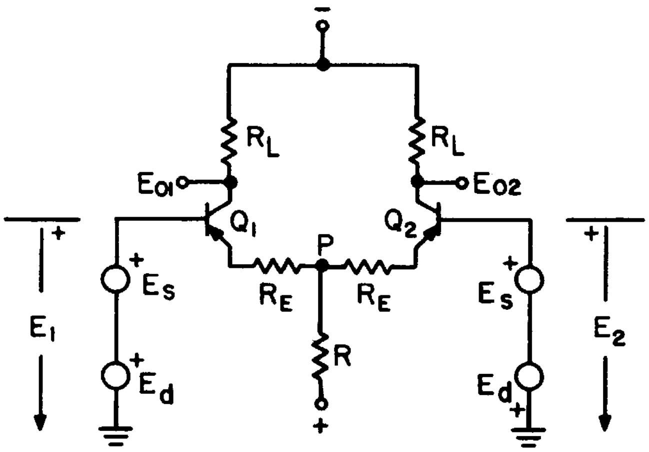


Fig. 13a. Difference Amplifier

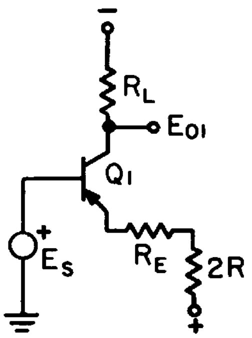


Fig. 13b. Common-Mode Gain, Equivalent Circuit

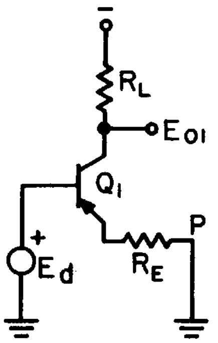


Fig. 13c. Difference-Mode Gain, Equivalent Circuit

analyzed by inspection:

$Ad = \text{difference-mode gain} = Eo1/Ed \simeq -R_L/R_E$

By superposition, the total output is the sum of the above:

$Eo1 = Ed\,Ad + Es\,Ac$

Similarly,

$Eo2 = -Ed\,Ad + Es\,Ac$

For the case under discussion, Es represents the average value of the two levels stored on the sampling capacitors. As we desire that the contribution of this common-mode signal to the output be small, the common-mode gain must be made low. This is accomplished by placing a current source in the emitter circuit of the difference amplifier. The term R in the expression for the common-mode gain is now equal to the very high output impedance seen looking into the collector of current source T_{38}. Thus, as $Ad \gg Ac$, the output of the stage, from collector to ground, is, to a good approximation,

$$Eo \simeq \pm \left|(Ed)(R_L/R_E)\right| = \pm \left|(E_1 - E_2)\, R_L/2R_E\right|$$

The ± sign denoting the anti-symmetrical output swings at the collectors (referenced to ground).

With no input signals, the quiescent voltage at each collector is approximately zero volts. Potentiometer R_6 controls the bias current and establishes the quiescent collector output voltage. Potentiometer R_7 serves as the collector balance control. The emitter-base diode junction of T_{39} provides temperature stabilization of the current source. In addition, the emitter-base voltages of T_{36} and T_{37} are matched at the quiescent operating current of the amplifier. However, as the gain of this stage is low, temperature compensation is not critical.

D. PROCESSING OF THE DIFFERENCE VOLTAGE

Consider the operation of the difference amplifier for the two cases shown in Fig. 14. Two points are excited on the CRT screen, dot 1 first, followed in 5 microseconds by dot 2. In Fig. 14a, the pen is positioned as shown by the symbol X. The resulting pen response amplitudes applied to the bases of the difference amplifier are as shown. At $t = 0$, input E_1 is sensed, reverse-biasing Q_1 and causing the collectors to swing as drawn. At $t = 5$ microseconds, the amplitude of the second response pulse is sampled and applied to the base of Q_2. The collectors reverse direction and move toward a steady-state output voltage of $\pm Av (E_1 - E_2)$. For the case $E_1 > E_2$, the steady-state collector voltage of Q_1 is negative and that of Q_2 is positive. If we define the position error as the signed distance, d, through which the center of the horizontal arm of the cross must be moved in order to coincide with the pen, it is clear that the error for this case is positive. The steady-state collector output voltage must be converted to a positive binary number, equivalent to distance d, and added to the contents of the horizontal pen-position register.

Figure 14b depicts the case for $E_1 < E_2$. Here, the steady-state collector voltages are opposite in sign to those of the previous example. The position error in this second case is negative; the binary number to be added to the pen-position register must be negative in sign.

Thus, the sign of the position error can be determined by sensing the steady-state polarity of either collector. Further, as the collector swings are anti-symmetrical, sensing the magnitude of the voltage at

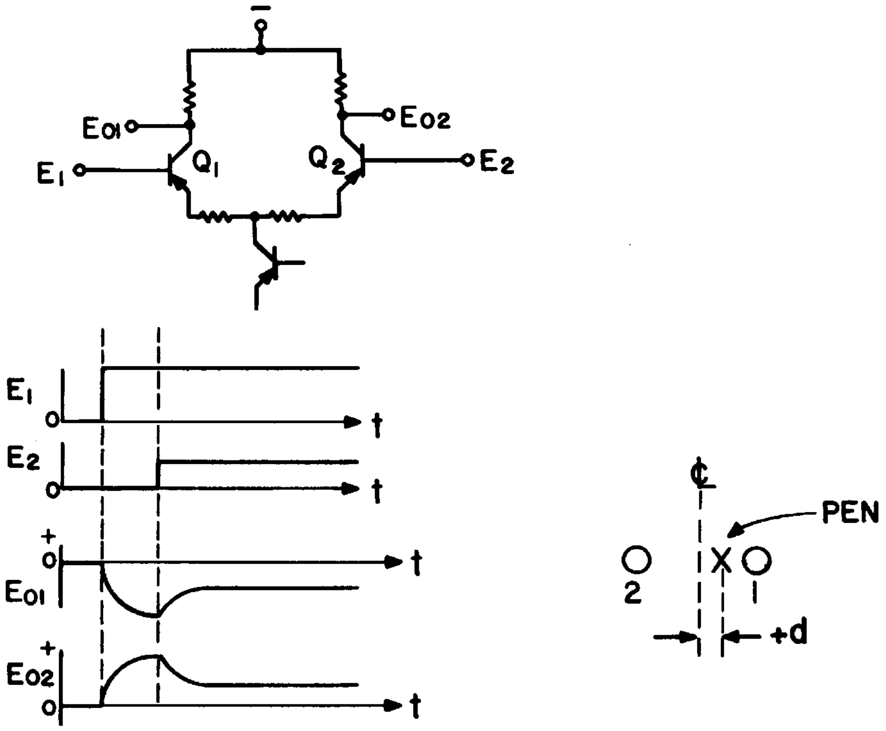


Fig. 14a. Difference Amplifier Output: Positive Position Error

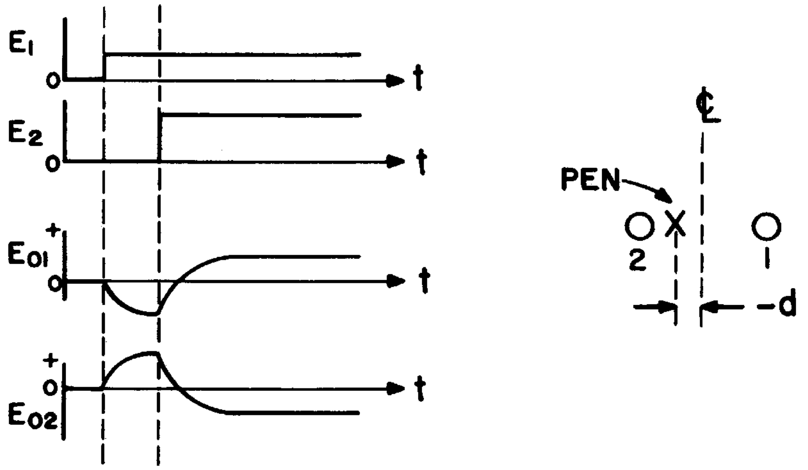


Fig. 14b. Difference Amplifier Output: Negative Position Error

either collector will yield the magnitude of this error. These results are used as described below.

In the existing display console digital hardware, the sign of the positional error information is handled by two flip-flops, ΔXs for the horizontal channel, and ΔYs for the vertical channel. For the horizontal channel under consideration, when ΔXs is in the ONE state, the error is negative, and vice-versa. For a negative error, the collector of difference amplifier Q1 will always be positive in its polarity (see Fig. 14b). Hence, a threshold circuit, designed to trigger when its input is positive, can be used at the collector of Q1 to set ΔXs. As ΔXs is cleared at the beginning of each tracking cycle, no reset circuitry is required.

Conversion of the analog difference voltage is accomplished by a positive-logic analog-to-digital converter. With sign information taken care of, all that remains is to select the collector that is positive-going at the time of sampling and couple it to the A/D converter. This selection is achieved with a diode OR gate.

The circuitry for accomplishing the above is contained in Fig. 11c. Emitter followers couple the collectors of the difference amplifier to the diode gate; the collector of T_{36} is also coupled to a Schmitt trigger which serves as a threshold detector to load the horizontal sign flip-flop in the display console. The circuit is designed for an upper trip point of 1.5 volts, which, subtracting the emitter-to-base voltages of the emitter follower, corresponds to a difference-amplifier collector voltage of approximately + 0.3 volts. (The least significant bit of the A/D converter is set when its input rises to + 0.5 volts; the correct error sign must be established before this level is reached.) When the collector of T_{36} rises to this voltage, the trigger circuit fires and sets the sign flip-flop to the ONE state, indicating a negative position error. The constraint on the hysteresis of the Schmitt trigger is that the lower trip point occur before the collector of T_{36} drops to - 0.5 volts. With the component values shown, the circuit exhibits a hysteresis of 0.6 volt.

The diode gate couples the positive-going collector of the difference amplifier to an analog gate. The gate remains closed until the output transient (see timing diagram, Fig. 12) has decayed to zero. At this time, the gate is opened and the steady-state output voltage is coupled to the following stages. If it were not for the problem of noise, the output of this gate could go directly to the A/D converter. The noise difficulty is treated in the following section.

E. NOISE CONSIDERATIONS

The noise associated with the beam pen manifests itself in the following manner. If two points of the cross are displayed and the pen is placed in the exact center, the steady-state output of the difference amplifier fluctuates slightly about zero volts from tracking cycle to tracking cycle. Considering only the horizontal arm of the cross, each tracking cycle derives the difference between the amplitudes of the pen responses to two points. In a static experimental test (feedback loop open; tracking cross and pen both stationary), small variations in beam-pen pulse amplitudes occur from cycle to cycle and result in variations in the difference voltage. Part of the noise exhibited by the beam pen is believed due to the electron beam and CRT phosphor.[5] Also, since the extremely small signal detected by the pen undergoes considerable amplification prior to insertion into the tracking circuitry, stray signals picked up in an early stage can contribute significantly to the output.

The specific effect of variations in the difference voltage due to noise is to lower pen-tracking resolution. Assume that in a static test situation (tracking loop open, and pen held in a fixed position between two points of the cross), the output of a unity gain difference amplifier exhibits a maximum change of N volts over a large number of comparison cycles. This value of N is the peak-to-peak noise. Now, assume that in a completely noise-free system, the pen is placed between two stationary dots and moved along the line joining them until the output voltage of the difference amplifier changes by N volts. The distance moved will be,

$$d = N/2m$$

where m = slope of the pen amplitude-position response curve

Thus, the noise output voltage of the first case is equivalent to a pen motion of d increments. Hence, in a noisy system, an output difference voltage corresponding to a pen motion of d increments or less will be indistinguishable from the random noise output voltage.

The expression,

$$d = N/2m$$

N: peak-to-peak noise at output of unity-gain difference amplifier

m: slope of pen amplitude-position response curve

can be considered as a figure-of-merit for a pen used in the tracking circuit. A decrease in d (increase in resolution) can be achieved by either decreasing the peak-to-peak noise, or by increasing the slope of the pen response curve. In the experimental circuit of this thesis, since the pen field-of-view could not easily be altered, this noise difficulty was circumvented by decreasing N through filtering.

As described earlier, the analog gate following the difference amplifier serves to pass a segment of the steady-state difference voltage to the next circuit stage. Before applying this signal to the A/D converter, some additional processing occurs in order to reduce the amplitude of the undesired noise riding on the d-c difference voltage. The character of the noise was studied by gating a portion of the steady-state output of the difference amplifier (with the circuit in the stationary open-loop state) into a resistive load. The predominant components of the observed cycle-to-cycle variations were found to be 10 and 60 Hz. The 10-Hz noise, initially difficult to explain, was found to be the difference beat frequency between the tracking cross deflection rate (one tracking cycle every 7.7 milliseconds, or 130 Hz) and the 120-Hz power supply ripple in the deflection amplifier. This component was altered by decreasing the period between tracking cycles to 5 milliseconds, hence pushing the beat frequency into a more-easily filtered range. The 60-Hz component is due to hum pickup.

To reduce this noise before entering the A/D converter, the discrete output pulses of the gate are passed through an envelope detector and converted to an analog waveform. This signal is then coupled to a simple low-pass filter.

The circuitry, and timing, employed after the difference amplifier are shown in Fig. 11c and the timing diagram (Fig. 12). Transistor T_{44}

serves as a series gate. Its control signal is generated with a monostable multivibrator (T_{49} and T_{50}) and an inverter (T_{51}). Normally, T_{51} is cut off, maintaining the base of the gating element at +10 volts. This base voltage is sufficient to back-bias the base-emitter junction of the gate, holding it closed. The two pulses being handled are those corresponding to the tracking pattern points generated by one-shots 1 and 2. To ensure the complete decay of the transient in the output of the difference amplifier, the trailing edge of the output pulse of one-shot 4 is used to initiate the control pulse for gate T_{44}. At this time, the gate control multivibrator is turned on (viz. triggered into its unstable state), saturating inverter T_{51} and pulling the base of T_{44} to ground, thus opening the gate. The gate remains open for the duration of the monostable multivibrator output pulse.

The addition of transistor T_{45} and capacitor C_3 allows the gate circuit to additionally perform as a boxcar detector. Consider the series gate, T_{44}, with a resistive load only (Fig. 15). Assume that the tracking loop is opened and that the pen and tracking pattern are held stationary as in Fig. 3. The gated output of the difference amplifier appears across R_L as illustrated in Fig. 15. The amplitude of each pulse is the difference voltage generated in the tracking cycle. The average amplitude of the pulses is the difference voltage resulting from the misalignment of pen and tracking pattern, and is the signal of interest. The variations from pulse to pulse constitute the noise discussed in the previous section. Removing the load resistor and adding T_{45} and C_3 converts the pulsed output of Fig. 15 to the analog signal of Fig. 16. Briefly, the circuit

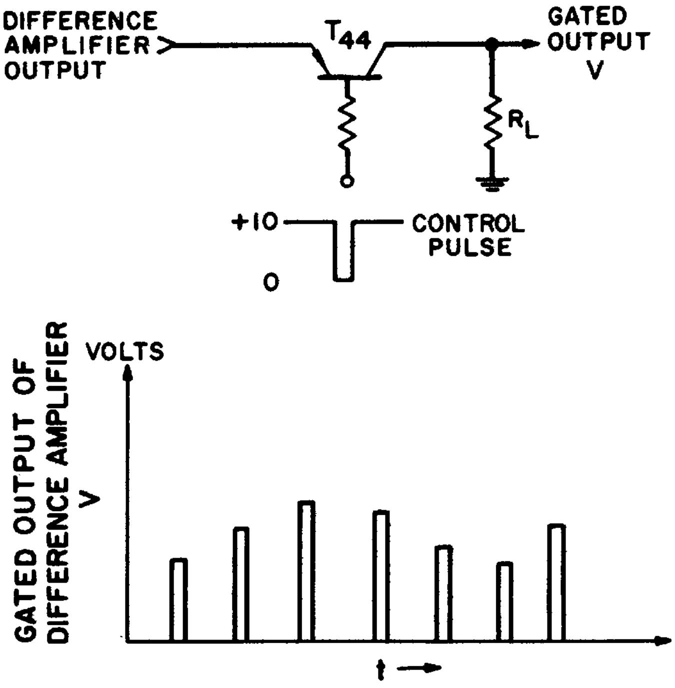


Fig. 15. Gating of Difference Amplifier Output

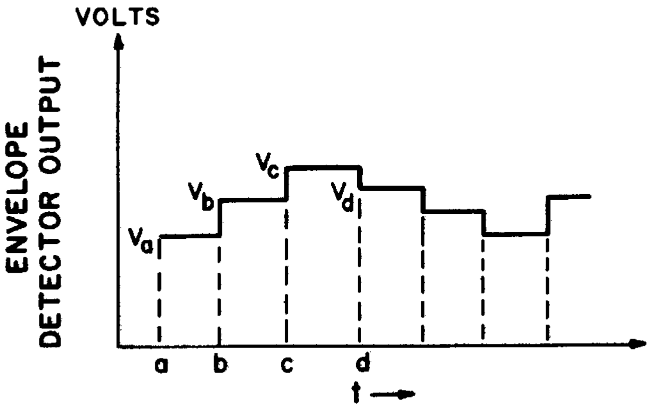


Fig. 16. Output of Envelope Detector

functions as follows: If the level at the emitter of T_{44} is greater than the voltage stored on capacitor C_3 when the gate is opened, charging current flows into C_3. When the gate control pulse rises to +10 volts, T_{44} and T_{45} become cut off; capacitor C_3 remains charged at the level of the input to the gate (less the small saturation voltage of T_{44}). This situation occurs in Fig. 16 at time b. Should the input to the gate be less than the voltage on C_3 when the gate is opened, the collector-base junction of silicon transistor T_{44} becomes forward-biased, turning on germanium transistor T_{45} and allowing C_3 to discharge through it. C_3 continues to discharge until it reaches the level of the gate input (again, less the saturation voltage of T_{44}). This situation occurs at time d in Fig. 16. The "boxcar" envelope results. Emitter follower T_{46}-T_{47} couples the envelope to a simple RC low-pass filter. The output of the filter is applied to the final stage of the analog tracking circuit, the A/D converter.

F. THE A/D CONVERTER

The final step in the processing of the difference voltage is the conversion of the filtered analog signal to its binary equivalent. As described earlier, binary representation of the position error allows it to be loaded directly into the ΔX register of the display console.

Let us assume that the maximum speed at which an operator will move the pen is of the order of 28 inches per second. This requires that the tracking cross be capable of moving at this same rate. Since the period between adjacent tracking cycles is to be set at 5 milliseconds, the maximum distance that the pen can move between cycles is,

$$d = 28 \text{ inches} \times 5 \text{ msec}/1000 \text{ msec} = 14/100 \text{ inch}$$

$$= 14 \text{ scope increments}$$

To move the tracking pattern this distance in one tracking cycle, the binary number 111 (7_{10}) must be loaded into the ΔX register (since the contents of the ΔX register are added to the pen position register at a double-increment scale). Therefore, a 3-bit A/D converter is required to ensure a tracking capability at the above maximum speed.

A threshold logic approach is employed in the design of the converter.[6] The main advantage offered by this approach is circuit simplicity. Identical threshold stages are employed for each bit, with the performance of the circuit depending on the proper choice of a set of weighting resistors interconnecting these three stages. In addition, the circuit provides simultaneous binary conversion of the analog input. By way of quick review, consider the threshold element shown in Fig. 17. The set $[e_i]$ represents the input signals to the device. Associated with each input is a weight, w_i. If the sum of the signals present at the inputs, multiplied by their respective weights, exceeds the threshold T of the device, the circuit fires and the output F is a logical ONE. If the excitation (sum of the weighted inputs) is less than T, the output is a logical ZERO.

The analog difference voltage to be converted can vary between zero and approximately +10 volts. The quantization of the A/D converter was chosen to be in steps of one volt and the desired binary approximation to the input voltage is as shown in Fig. 18a. The required binary output of

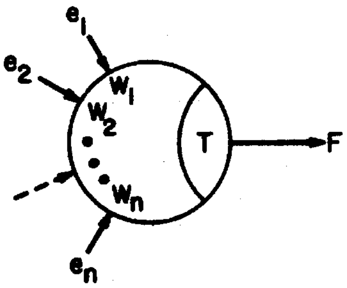


Fig. 17. Threshold Element

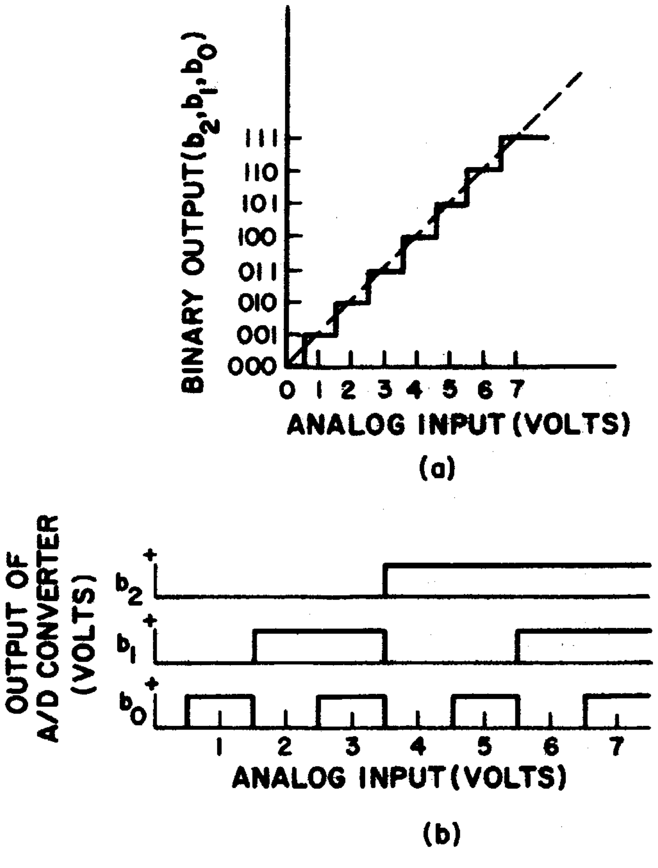


Fig. 18. Analog-To-Digital Conversion

the converter, as a function of the analog input, is shown in Fig. 18b. The least significant bit is to fire initially at an input of 0.5 volts; bit 1, initially, at 1.5 volts, and bit 2 at 3.5 volts. Consider the threshold configuration of Fig. 19. This circuit generates the desired function, as can be easily verified by calculating the excitation at the inputs to the three elements over the input voltage range. If the excitation exceeds the threshold, the element fires; if not, the output remains ZERO.

The circuit development of the above threshold configuration must contend with the physical realization of three negative weights. To handle this, an appeal to a theorem of threshold logic must be made. Briefly stated, the sign of a weight can be reversed by complementing its corresponding input. In addition, to ensure the continued realizability of the function, the original threshold must take on a new value, T_{new}, where,

$$T_{new} = T_{old} - \text{(sum of the original weights whose inputs are to be complemented)}$$

Thus, if the inputs to all negative weights are complemented, the new thresholds must be:

$$\begin{aligned} T_{o\ new} &= 0.5 - (-4-2) = 6.5 \\ T_{1\ new} &= 1.5 - (-4) = 5.5 \\ T_{2\ new} &= 3.5 - (0) = 3.5 \text{ (unchanged)} \end{aligned}$$

The modified configuration is shown in Fig. 20. Again, verification of the output can be handled by examining the excitations to the elements over the given range of e_{in}. Realization of the positive weights can now be handled with real conductances.

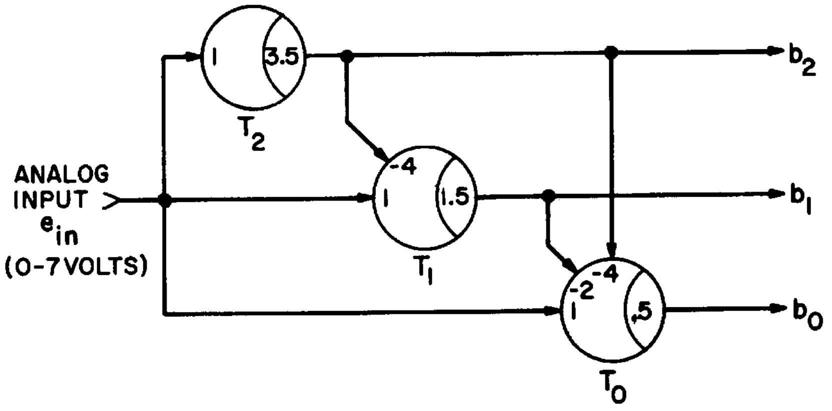


Fig. 19. Threshold Logic A/D Converter

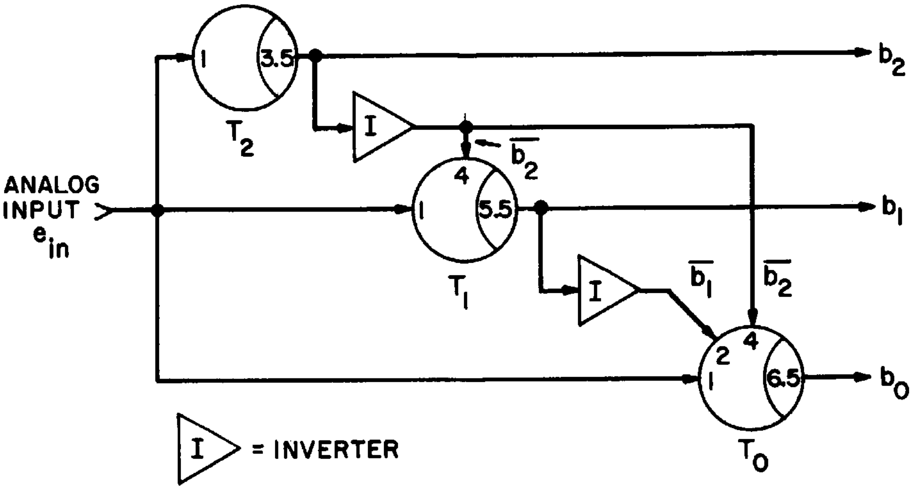


Fig. 20. Modified Threshold Logic A/D Converter
(All Input Weights Positive)

In making the transition from the theoretical configuration of Fig. 20 to an actual circuit, one further modification was made. The circuit of Fig. 20 was arrived at by considering all level changes to be of one-volt magnitude. In the practical A/D converter, it was desirable to have the binary outputs change by 10 volts rather than one volt. This ensured adequate drive to the following stage and allowed neglect of the small saturation voltages of the output transistors. Thus, while quantization of the analog input remains at 1 volt, that of the binary outputs (and their complements) is set at 10 volts. However, if those weights (whose inputs are now quantized by 10) are decreased in magnitude by a factor of 10, no change in the weighted input results (i.e., the product input x weight remains the same), and the threshold behavior is unaltered. Finally, in the practical threshold circuit designed, the inputs are not isolated but are loaded by the weights (conductances) of the other inputs to the threshold element. The effect of this is to require that the actual threshold voltage for each circuit element be equal to the corresponding threshold level of Fig. 20 divided by the sum of the weights (conductances) of that element. This can best be illustrated by considering the threshold element corresponding to bit 1 of Fig. 20. The actual circuit configuration used for this element is as shown in Fig. 21. When the voltage v is equal to or greater than V_{T1}, the circuit fires and the output rises to 10 volts. (The conductance $G_4 = 0.4$ reflects the 10-volt quantization of $\overline{b_2}$). From Fig. 18, it is seen that one condition on this circuit is that it trigger when e_{in} rises to 1.5 volts. Thus, by superposition,

$$\begin{aligned} v &= e_{in}\,[G_1/(G_1+G_4)] + \overline{b_2}\,[G_4/(G_1+G_4)] \\ &= 1/(G_1+G_4)\,(e_{in}G_1+\overline{b_2}G_4) \end{aligned}$$

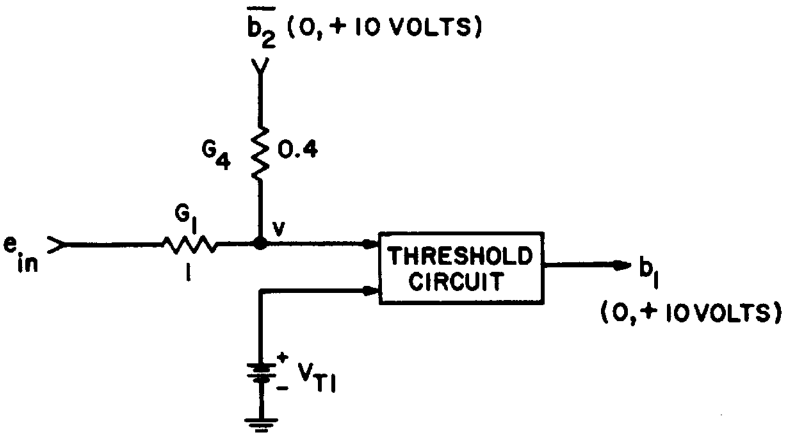


Fig. 21. Bit 1: Calculation of Threshold Voltage

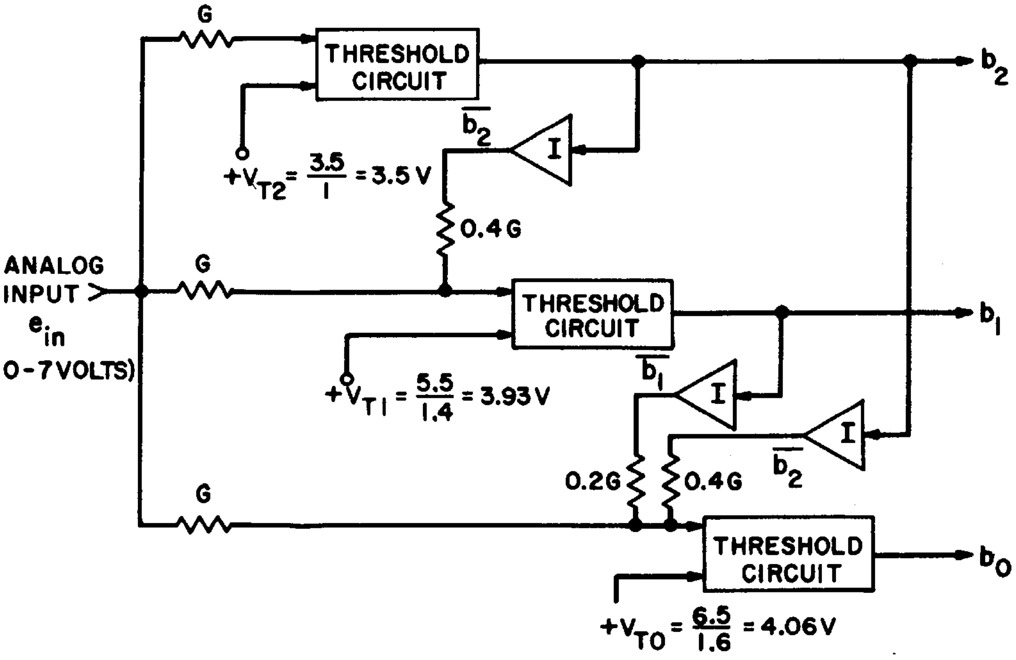


Fig. 22. Block Diagram of the Three-Bit A/D Converter

At the threshold point,

$$v = v_{T1} = 1/(G_1 + G_4)\ [1.5(1) + 10(.4)]$$
$$= 5.5/(G_1+G_4) = 5.5/(1+0.4)$$

Thus, the required threshold voltage for this circuit is observed to be equal to the threshold level of the element divided by the sum of its weights.

Figure 22 is the block diagram of the A/D converter, showing the weights and threshold settings. The circuit realization of the threshold configuration is shown in Fig. 23.

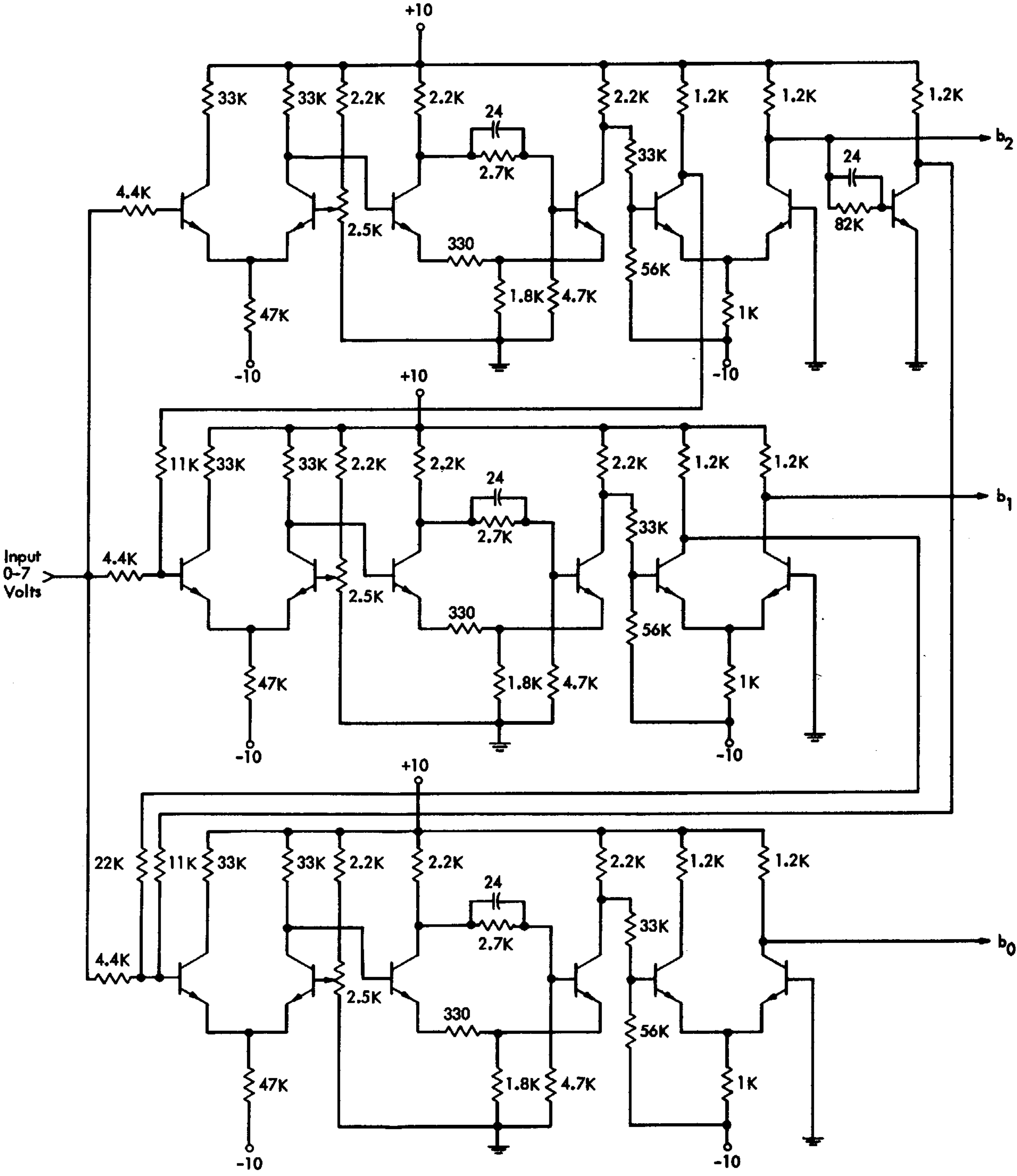
The threshold circuit consists of a Schmitt trigger and a high-gain differential amplifier. The amplifier reduces the hysteresis of the Schmitt circuit by the factor $1/A_V$, where A_V is the amplifier voltage gain. Following the threshold circuit is a second high-gain symmetrical amplifier. Driven by the output of the Schmitt trigger, this circuit provides the required binary output as well as its complement. (Bit 2 uses a second inverter at its output for isolation of the two 11K resistors.) Weighting of the inputs is handled with conductances. As developed in this section, the magnitudes of these weighting conductances are in the ratio,

$$G: 0.4G: 0.2G.$$

The threshold voltages are established in the circuit through the use of potentiometers in the base circuits of the input amplifiers.

G. LOADING OF SIGN AND POSITION INFORMATION

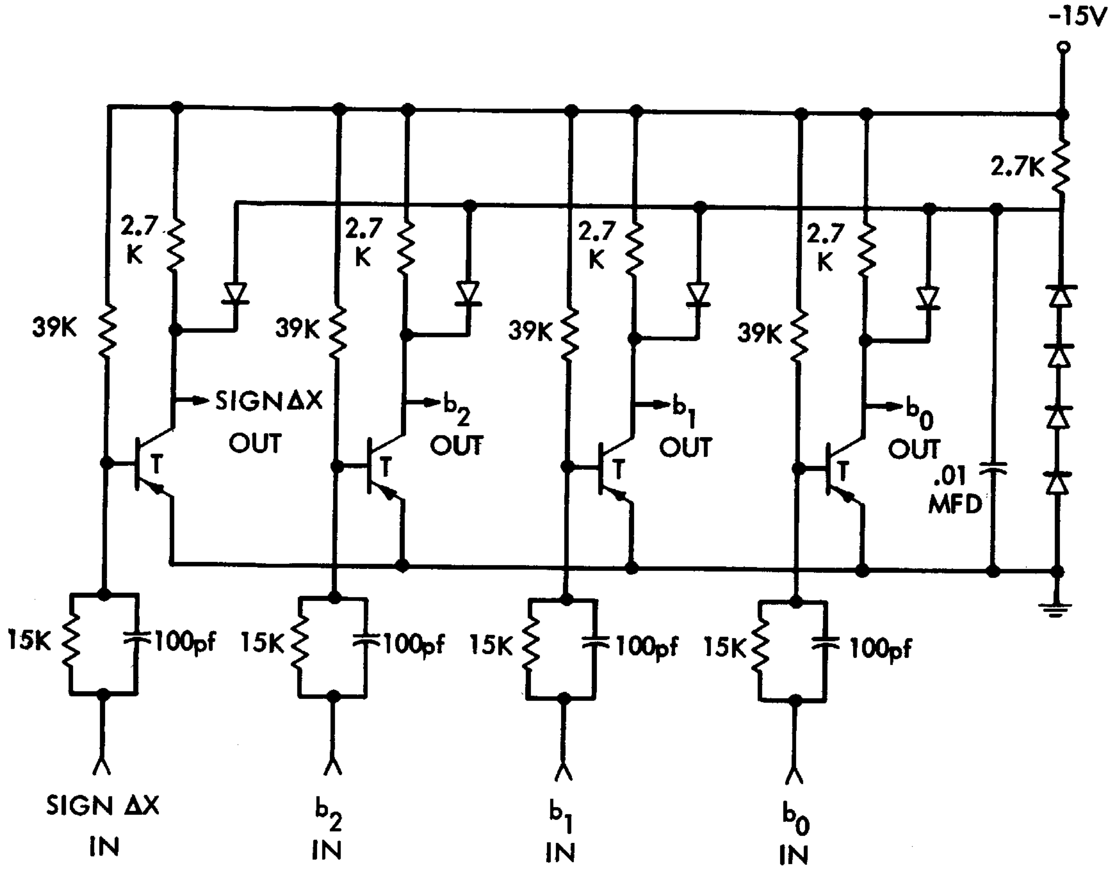
The final circuit requirement is to load the sign and binary magnitude of the position error into the ΔX register of the display console. This is accomplished as shown in the block diagram of Fig. 10c. The



NOTE: All Transistors 2N3415

Fig. 23. Schematic Diagram of the Three-Bit Threshold Logic A/D Converter

logic level converters, Fig. 24, convert the +10-volt positive logic of the analog channel to the -3-volt negative logic of the display console. The output of the logic converters are applied to AND gates. When the position error word is available from the analog channel, a "load ΔX" pulse is applied to the gates and the ΔX register is loaded. From this point on, the tracking cycle is identical with that of the existing digital tracking system of the ESL Console; i.e., the signed contents of the ΔX register are added to the contents of the horizontal pen-position register to establish the new pen position and provide the starting point for the next tracking cycle. The contents of the pen position register are available to the computer should this information be needed.



NOTE: T = 2N1307

Fig. 24. Logic Level Converters

CHAPTER IV

RESULTS OF TRACKING TESTS

The horizontal channel of the analog tracking circuit was connected to the display console and tracking along this axis was accomplished with the beam pen. The first feature observed was that the motion of the tracking pattern was always toward the pen, regardless of whether the pen was positioned inside or outside the cross. This is a consequence of the existence of signal outside the immediate vicinity of the illuminated points of the cross. Consider, for example, the two cases of Fig. 25. In both, the positive difference voltage developed causes the tracking pattern to move to the right, positioning it over the pen. This desirable tracking feature arises from the wide field-of-view exhibited by the present beam pen. (However, as discussed in Chapter III, this wide, gently sloping response curve is not an optimum shape for high resolution.)

When tracking with the beam pen, two difficulties were encountered. The action of the analog tracking circuit is to position the two-point pattern about the pen such that the two pen output pulses are of equal amplitude. It was observed that only in the vicinity of the center of the CRT did equal pulse amplitudes correspond to the mid-point of the cross. As the pen moved closer to the edge of the display scope, the position of equal signal amplitude shifted progressively closer to the inner tracking point. Fortunately, in an application such as tracking, this anomalous behavior of the beam pen signal is not critical. In drawing on the display console, the pen is used to maneuver the tracking pattern to the desired position. As long as the pattern movement is

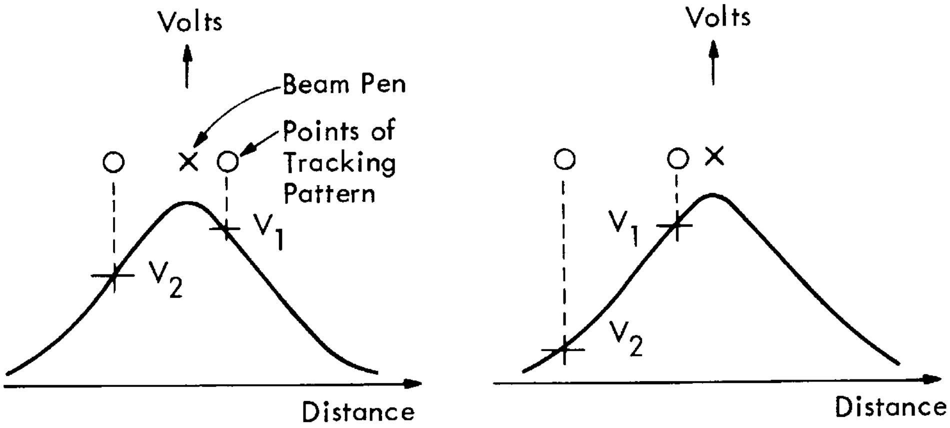


Fig. 25. Positive Difference Voltage

smooth and predictable, coincidence of pattern center and pen axis is not essential. It is essential for successful analog tracking, however, that the pen output decrease with increasing separation between pen and CRT beam position. The major difficulty experienced was that, in certain areas of the display scope, the pen response to the two horizontal points of the pattern was relatively insensitive to pen position. The amplitudes of the two output pulses remained approximately equal throughout the area occupied by the tracking pattern. As no difference voltage was developed, tracking was interrupted and pattern movement ceased. The above difficulties were most pronounced after the display console had just been turned on. An exceedingly long waiting period (on the order of a half hour or longer) was required before the amplitude of the output signals of the beam pen system achieved equilibrium.

A possible factor contributing to the difficulties described above may be brought out by considering the construction of the display CRT used with the beam pen system. Signal pickup by the beam pen is contingent on the existence of localized charge variations in the vicinity of the incident CRT electron beam.[5] For this reason, the usual aluminized low-resistance layer covering the phosphor must be omitted in the construction of the tube. Only the high-resistance phosphor remains on the face of the CRT. When the tube is turned on and the high accelerating voltage applied, the potential of the phosphor screen begins to rise toward an equilibrium value. Without the aluminized layer, equilibrium is achieved slowly. Further, without this layer, foreign objects placed on or near the display screen can influence charge distribution on the phosphor surface.[5] The existence of static charge, on the bulb face or on the surfaces of the plastic protective faceplate, will also affect charge equilibrium within the tube. An improvement in performance might be possible through the use of a transparent conductive coating to replace the aluminized layer. The resistance of this coating should be high enough to allow charge variations to occur in the immediate vicinity of the incident electron beam, yet low enough to improve the screen time constant and establish more uniform electrical characteristics over the phosphor face.

Noise injected into the tracking system appears as "jitter" in the position of the tracking cross when the pen is held stationary over this pattern. With the pen over the center of the cross, only the noise signal is present at the input to the A/D converter. If this signal is of sufficient magnitude to exceed the threshold of the least significant bit (b_o), an error distance will be loaded into the pen position register and the position of the tracking pattern will shift. The low-pass filter improves the problem; however, as its break frequency is moved lower, tracking becomes noticably sluggish. The resulting long filter time constant decreases the dynamic response of the tracking circuit. A reduction in tracking pattern jitter can also be achieved by decreasing the gain of the difference amplifier until the noise amplitude is less than the threshold voltage of the low-order bit of the converter. When tracking, the effect of this tradeoff is to cause the pattern to continually lag the position of the moving pen. However, gain reduction does offer a compromise solution of the noise problem. For example, with the difference amplifier gain reduced to two (R_E = 47K), jitter of the tracking cross was eliminated and the change in tracking performance could not be visually detected.

The time required to develop the horizontal position error using the analog approach is 25 microseconds. At the end of this period, the ΔX register is loaded. Loading of the ΔX register into the horizontal pen position register is accomplished using the existing digital hardware and requires an additional 14 microseconds. This timing is shown graphically in Fig. 26.

With an identical vertical channel in use, and assuming the same processing times, the duration of the complete tracking cycle can be extrapolated as in Fig. 27. (Tracking cycle time is not doubled since the horizontal error voltage can be loaded into the ΔX register during processing of the vertical arm of the cross.)

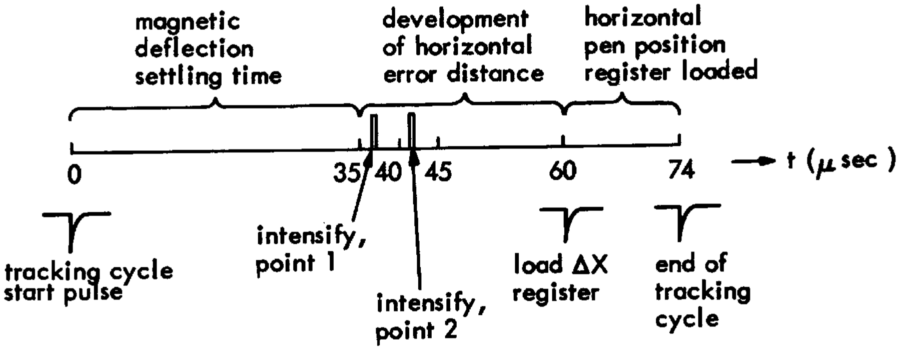


Fig. 26. Timing: Horizontal Channel Tracking Cycle

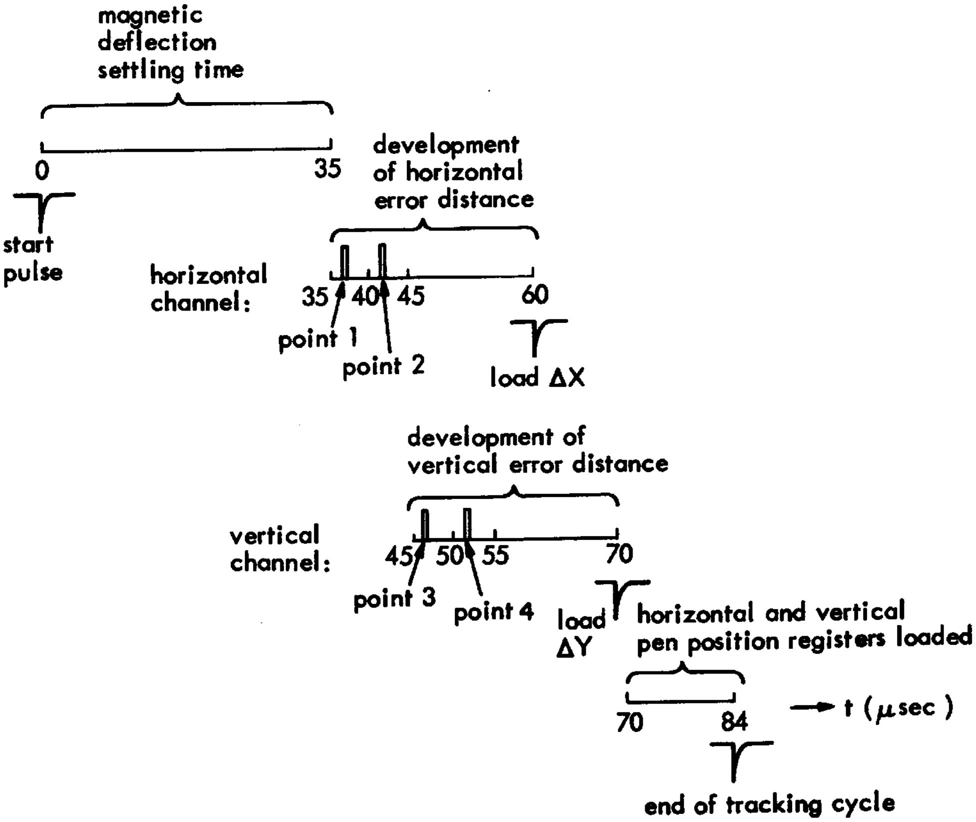


Fig. 27. Extrapolated Timing: Two-Channel Tracking Cycle

CHAPTER V

CONCLUSION

A. SUMMARY

The feasibility of employing the analog concept for pen tracking has been demonstrated in this study, although, as described in the previous chapter, some anomalous behavior was experienced in tracking with the experimental beam pen. The merit of the analog technique lies in the small processing time required to determine the position of the moving pen. Decreasing the tracking interval allows more time to be utilized for display — a particularly important consideration when many consoles share the same display channel. Further, when the tracking function consumes but a small part of the total display time, it becomes reasonable to sample the position of the pen more frequently, thereby improving tracking reliability at high writing speeds.

The time required to develop the horizontal position error (the horizontal distance between tracking pattern center and pen) with the analog technique is 25 microseconds. With an identical channel available to process the vertical arm of the pattern, the extrapolated time necessary to develop both the horizontal and vertical position errors is 35 microseconds (Fig. 27). In the existing digital tracking system, employing a light pen, the updating period is approximately 1 millisecond. However, comparison of these periods is not really justified since most of the time required by the present digital tracking cycle is due to the phosphor-decay difficulty described earlier in the report. A fair comparison might be to assume that a pen sensor, such as the beam pen, having an output pulse-width of the same order of magnitude as that of the intensify-pulse, provides the input to the digital system. In this case, assuming that the tracking pattern is drawn at its maximum speed, the time required to develop the horizontal and vertical error vectors would be,

$$t = 1.8 \text{ usec/point} \times 64 \text{ points}$$
$$= 115 \text{ microseconds.}$$

Because positional information is derived from the small voltage difference existing between two d-c pulses, the performance of the analog system exhibits high noise sensitivity. Good resolution and low tracking pattern jitter, in the presence of noise, require an input sensor having a sharply-sloping response curve. The beam pen, still in the experimental stage, is potentially well suited for use in an analog system because of its extremely fast response time. The limitations of this present pen system, specifically the wide field-of-view and the noise variations of the output signals, are currently under study and modifications to the existing system are being developed in an effort to reduce these difficulties.[5]

In view of the anomalous behavior experienced over certain areas of the display surface in tracking with the beam pen - namely, the interruption of tracking - further study of the analog technique is warranted. The specific difficulty faced is that, as both systems, beam pen and analog tracking, are in their early stages of development, insufficient performance detail is available to allow a clear delineation of the limitations which each circuit imposes on the tracking operation. In short, more evidence must be gathered. It is recommended, therefore, that, as the next stage in the development of this tracking method, the light pen be used as the input sensor to the analog channel. This would allow a more comprehensive determination of the performance limitations inherent in the analog tracking circuit.

B. RECOMMENDATIONS FOR FURTHER STUDY

Several possibilities for improving tracking performance, brought out in working with the experimental analog circuit developed in this report, might be considered in the development of future tracking systems.

First, since the beam pen continues to supply signals to the sampling circuits as it is lifted from the display face, care must be exercised in retraction if the pattern is not to be shifted. Further, extraneous signal pickup by the pen after it has been removed from the display surface can also cause movement of the tracking pattern. A spring-return switch mounted on the pen case would solve this problem. Actuated by thumb pressure or, if mounted on the end of the pen, by pressure against the display surface, a normally-closed switch could be used to ground the pen input whenever tracking was not taking place.

Secondly, a fifth point, added to the center of the present tracking pattern, might serve as a convenient visual guide for more accurate positioning of the pattern. In the existing analog deflection circuitry, this could be accomplished by adding an additional monostable multivibrator between the yoke settling delay and one-shot 1.

As emphasized in this report, the processing of the horizontal and vertical error voltages is identical. Because of this redundancy, the possibility of time-sharing a single processing circuit between the horizontal and vertical channels might be considered in the design of a complete analog system. The resulting slight increase in tracking cycle duration may well be overshadowed by the reduction in required circuitry.

Further, the use of more sophisticated low-pass or bandpass filters to reduce the noise difficulty should be examined.

Finally, the use of analog predictive circuitry should be explored as a possible means of improving tracking performance. The simple noise filter in the present experimental circuit serves to provide velocity prediction in the sense that the voltage on the filter capacitor is the average of past error voltages. If an error signal should fail to be developed over several cycles, the voltage on this capacitor would provide tracking continuity. However, as pointed out in Chapter IV, if the time constant of this circuit is made too large, sudden changes in pen motion will not be detected. The inclusion of circuitry for predicting pen acceleration should be considered in future work with analog tracking.

It should be pointed out at this time that the analog concept, as applied in this study, is equally applicable to the light pen. The field-of-view of the light pen described in Chapter II is shown in Fig. 28. As the metal pen-cylinder surrounding the fiber-optic cord serves as a light-shield, the width of the response curve depends on the diameter of this cylinder. The present contour appears adequate for use in analog tracking — however, to improve it for the application of interest, it may be possible to generate a more triangular shape by altering the optical geometry of the pen cylinder.

The width of the pen output pulse is determined by the speed of the phosphor which excites it. The light pen presently used with the display

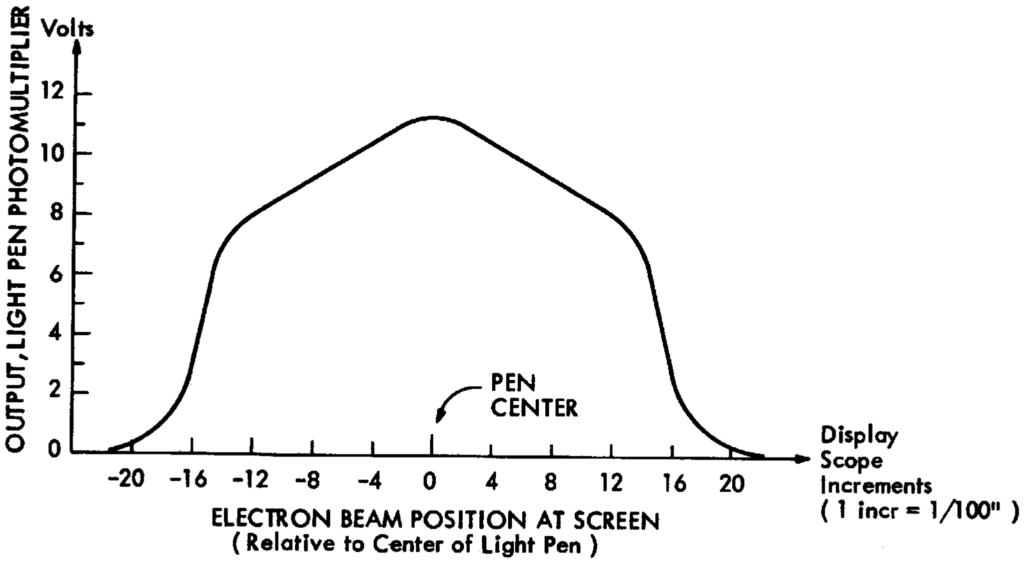


Fig. 28. Light Pen Amplitude-Position Response Curve

console responds to the high-persistence screen phosphor and generates the wide output pulse shown earlier in Fig. 5. If the present display CRT and light pen were employed in an analog tracking circuit, nearly all of the time consumed by the tracking cycle would be spent waiting for the decay of each of the four output pulse. Full use would not be made of the opportunity for high-speed processing offered by the analog concept. Recent work with dual-phosphor display tubes may offer a possibility for avoiding this limitation. The use of such a display tube, containing both a non-visable (ultraviolet or infrared) fast-decay phosphor and a high-persistence visible phosphor, is a promising area for future investigation. A light pen sensitive only to the fast phosphor could be used to advantage in an analog pen tracking system.

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