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ABSTRACT

The search for a satisfactory computer graphics input system led to this version of an analog sheet encoder which is transparent and requires no special probes. The goal of the research was to provide high resolution touch input capabilities for an experimental minicomputer based intelligent terminal system. The technique explored is compatible with AC plasma display technology, and the work reported demonstrates an analog realization for graphic input that is both feasible and economically attractive. Use of the encoder can result in large amounts of raw data, but the local terminal processor and storage give the programer a high degree of flexibility for data management. (WBC)

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APPENDIX B

A HIGH RESOLUTION GRAPHIC INPUT SYSTEM FOR INTERACTIVE GRAPHIC DISPLAY TERMINALS

BY

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IR004624

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1. INTRODUCTION

Rapid advances in graphics oriented display technology in the last decade have greatly expanded the capabilities of computer-based information systems to include the human user in a more highly interactive role with the computer than ever before. As a result of this innovative technology several classes of computer-aided applications have risen in importance. Of particular interest are engineering design, supervisory systems and computer assisted instruction (CAI). The graphics terminal and its associated input-output subsystems form the basis for the effective man-machine interface necessary to efficiently present, manipulate and generate the display material for these types of interactive computer applications.

The keyset has always served as the standard tactile input to a computer terminal. However manipulation of graphically formated display material is particularly tedious when the keyset is the only interactive means of data entry available. This is a distinct disadvantage when reaction time is important. For instance, an application may require quick operator response as in a control situation; or it may simply be that limited student attention span is a factor dictating the incorporation of a more natural means of communication. Some type of position encoding apparatus can be employed to provide this additional capability.

Ever since the need for position encoding was recognized, numerous techniques have been advanced which allow the terminal user to input information directly from the display surface to the computer for on-line processing [1,2,3,4,5]. One group of devices has emerged which relies totally on the principle of visual feedback in that a cursor marker is moved in incremental steps through the display presentation. The cursor can be used to address displayed information for various purposes. Unfortunately, operation of cursor generators can be cumbersome and frustrating to the user thus degrading situation response times and reducing the usefulness of the devices. Examples of the device type are the joystick, trackball and mouse.

Another group of encoders is potentially more powerful than the first mentioned in that they are not limited to a cursor mode of operation and are random access. This second group can encode positions relative to the display thus allowing the user to draw directly on the display or to trace from hard copy depending on the encoding technique. Examples in this broader catagory are the light pen, Rand tablet, sonic tablet, Lincoln wand, crossed light beams and analog tablet encoder [1].

Before a suitable encoding technique can be selected for graphic input, specific criteria should be established to define user requirements for the device. For this purpose a review of anticipated tasks can be helpful. Three catagories shall be considered as important applications:

1. Selection of an item from an array or set of possible choices which are displayed for the terminal user's examination. In this context, the encoder can be thought of as a pointer or, with appropriate coding, it can serve as a highly versatile programmable keyset. This application is finding wide acceptance in interactive terminal systems, especially in CAI applications.

2. Input of dimensionally organized information from hard copy. Typically this class of data is generated manually by tracing contours on the encoding surface as it is positioned parallel to an original (e.g., photo or drawing). Data bases for the graphic presentation of maps are often created quickly in this way.
3. Perhaps the most intriging and challenging application is free hand entry. This could include interactive entry of designer's sketches such as schematic diagrams, rapid generation of display graphics as might be desired in CAI service programs, or even digitization of hand written signatures for storage and verification purposes.

The drawing modes described in two and three should be recognized as more demanding than the pointing (touch) mode both on the encoding hardware and on the additional software support needed to process the data for storage and later retrieval. The hardware will need to include more control functions and must be capable of updating coordinate information fast enough to follow hand drawn strokes in real time.

While the encoding of drawings will usually result in large amounts of raw data, editing and compression algorithms can reduce the storage requirements considerably. Availability of inexpensive mass memory and the entrance of intelligent terminal systems will free the central computer from most data manipulation tasks. All things considered, graphics input should become increasingly attractive to potential users of highly interactive systems.

An encoding device intended for both the touch and drawing modes will necessarily be overlayed to the conventional display surface, thus placing the additional requirement of transparency on the encoding surface. Several transmission characteristics become important factors affecting the performance of the composite system. Any attenuation, reflectance and interference in general that may be caused by the inclusion of the encoder must not significantly degrade display contrast and registration. Of the many techniques developed for graphic input, the light pen, sonic tablet, transparent versions of the analog tablet encoder and crossed light beam techniques are either natural or adaptable for display overlayed service.

In any man-machine interface, human factors should affect the hardware design such that routine operation imposes a minimum constraint on the user. In full agreement with this philosophy, a graphics input system is easier and more natural to use if the indicating pointer is not limited to an active probe attached to the encoding hardware by a connecting wire. A passive probe, e.g., the human finger which is always handy, is far better from the psychological standpoint especially in CAI applications involving young children. An equally important consideration is the increased reaction time encountered when an operator must untangle a cord before he can respond to his interactive display. The "efficiency" of the man-machine interface is markedly improved by the elimination of the special probes [2,3,4,5].

This thesis shall examine a version of the analog sheet encoder that is both transparent and requires no special probes (see Figure 1.1). The goal was to provide high resolution touch input capabilities for an experimental minicomputer based intelligent terminal system. The technique explored is compatible with AC plasma display technology (and other display technologies) as well as with the fundamental requirements common to the computer assisted instruction environment existing at the Computer-based Education Research Laboratory (CERL), where the reported research was conducted.

Chapter 2 presents an overview of the thesis project, describing the requirements which led to the chosen encoding technique. Also in this chapter is a description of the principle features and operation of the analog encoder.

Chapter 3 details the actual design and operation of the graphics tablet at the hardware level. The various problems encountered are discussed together with the solutions implemented. The mechanical frame assembly, circuitry realizations and terminal interface notes are presented.

Chapter 4 begins with remarks on the quality of data generated with the device. Various programming tricks are then outlined with the purpose of improving that quality. Finally, some suggested examples illustrate the potential of graphic input.

Chapter 5 summarizes the thesis work and suggests several areas for further research on the analog encoding technique.

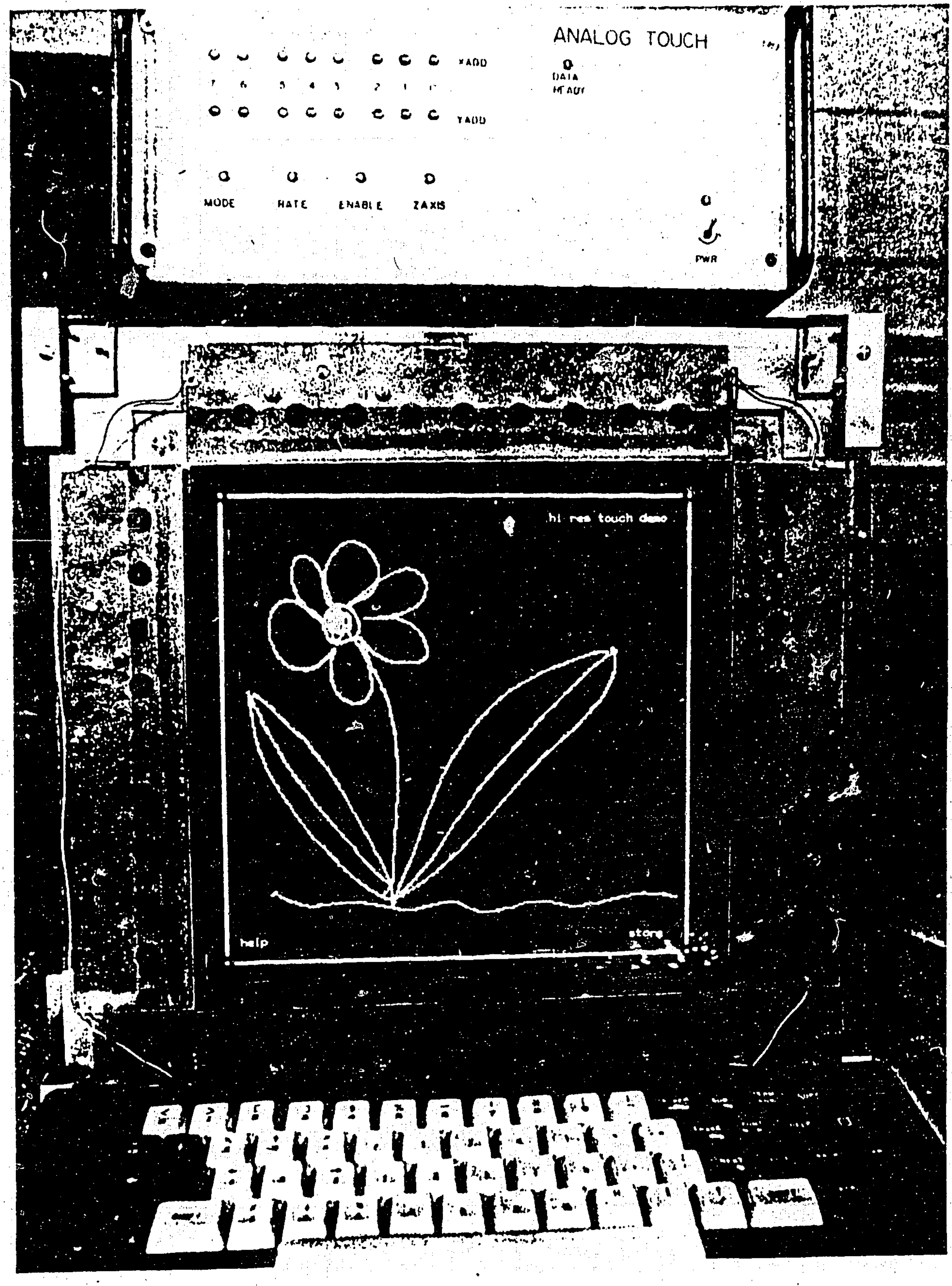


Figure 1.1 Analog Touch Encoder

2. SYSTEM CONCEPTS

2.1 Project Inception

Since CAI is necessarily a highly interactive environment, the PLATO IV system at CERL draws much of its instructional power from the graphics oriented plasma display terminal. Early in the development phase of the graphics terminal, the advantages of direct input other than the keyset were recognized and a research program was initiated to develop a low resolution touch input device. Criteria for its design were established based on the principles outlinted in chapter one.

Many groups of the younger children who were to benefit from PLATO, particularly those in elementary reading programs, found it difficult to adapt to the keyset as the only means of interaction. However, use of the keyset presupposes the ability to read. Pointing at displayed figures then becomes the natural alternative to the problem of indicating a selection from a group of choices for the younger student.

These particular characteristics were emphasized in the subsequent research:

1. The device was required to encode absolute positions as indicated by the lesson user.
2. The touch encoding surface was to be overlaid parallel to the plasma display.
3. Positions were to be indicated with a passive stylus, e.g., the human finger.
4. The resultant device must be relatively maintenance free due to the nature of typical classroom situations.

In response to these needs, an infra-red crossed-light beam position encoder was developed at CERL which successfully met the PLATO IV system requirements of low cost and simple user operation [5]. This device has a resolution of four bits per axis (16 x 16 touch sensitive areas) or approximately one half inch -- roughly the width of the human finger. Operation was restricted to the pointing mode since the data transmission capacity of the system is severely constrained by the low bandwidth return path of the PLATO IV communications network. The infra-red technique is particularly nice because the introduction of the encoding system has no effect on the optical qualities of the display itself. While the crossed beam technique affords absolute resolution (i.e., the light beams are fixed in space and the system digital in nature), the maximum resolution attainable is limited by the physical size of the discrete transducers used to emit and to detect the light beams.

The concurrent development of a minicomputer based intelligent terminal at CERL that has local computing capability and storage stimulated interest in designing a second generation graphics input device that could more fully utilize this increased data handling capacity [6]. Greater resolution more closely approaching the sixty lines per inch of the plasma display itself and position encoding rapid enough to follow hand drawing in real time were major changes in design objectives. It was felt important, however, that the additional touch capability not be gained at the expense of operational simplicity. Although the crossed beam technique had been received with enthusiasm, the mechanical restrictions described above would limit attainable resolution to five or six bits over each axis of the 8-1/2 inch square display surface. Many of the position encoders described in the literature can deliver this increased resolution, but most suffer from high cost and more complicated operation or are incompatible when overlaid with the display surface.

2.2 System Description

The graphics encoder constructed for this research project is built around a glass substrate coated with a conducting thin film that exhibits linear planar resistive properties. The thin film is usually composed of tin oxide or indium oxide depending on the electrical characteristics desired. Tin oxide typically produces films of about 200 ohms per square where as the indium oxide will exhibit sheet resistances a factor of 10 lower. Well established vapor deposition processes are used to form thin films of consistent thickness. A major step in the suggested design evolution is the integration of the thin film with the plasma display itself, the display glass serving as the substrate. This step will provide for a minimum of parallax in the resulting display device.

To visualize how position is determined, consider current flowing through one axis of the thin film coating. This current will create equipotential lines along a linear gradient that are orthogonal to the current flow. A probe touching the conducting surface at some point will assume a voltage that is directly proportional to the position of the probe on the axis parallel to current flow. This voltage is then scaled and digitized to provide a binary representation of the X-Y position. Using diodes connected to discrete contact islands at the periphery of the glass substrate, the nonlinear effects of interfacing a finite area can be minimized. This scheme offers high resolution inherent in the continuous nature of the thin film (see Figure 2.1).

A significant feature of this design is the use of a transparent metalized membrane closely overlayed above the active area of the graphics encoder. The conductive membrane acts as a two-dimensional probe, thus eliminating the need for an active hand-held stylus and connecting wire. Additionally, the overlay presents a barrier against environmental conditions, preventing oil and dirt accumulation on the active surfaces and protecting the more expensive coated glass from scratches. It should be noted that resolution is not limited by the contact area between the membrane and resistive coating. There is the future possibility of back coating the plastic polarizer, already required for plasma displays, thus increasing the transmission efficiency of the composite system. The metalized membrane material is readily available from commercial suppliers. These advantages are particularly suited to the requirements of operating ease and low maintenance (see Figures 2.2 and 2.3).

The control logic accepts mode select and variable length comparator commands from the terminal under program control. The mode may be chosen either to cause the hardware to generate a single coordinate per touch or to generate a stream of coordinates as long as the overlay is in contact with the resistive surface. A digital comparator checks the last converted coordinate with the newest, preventing the issuance of a data ready signal

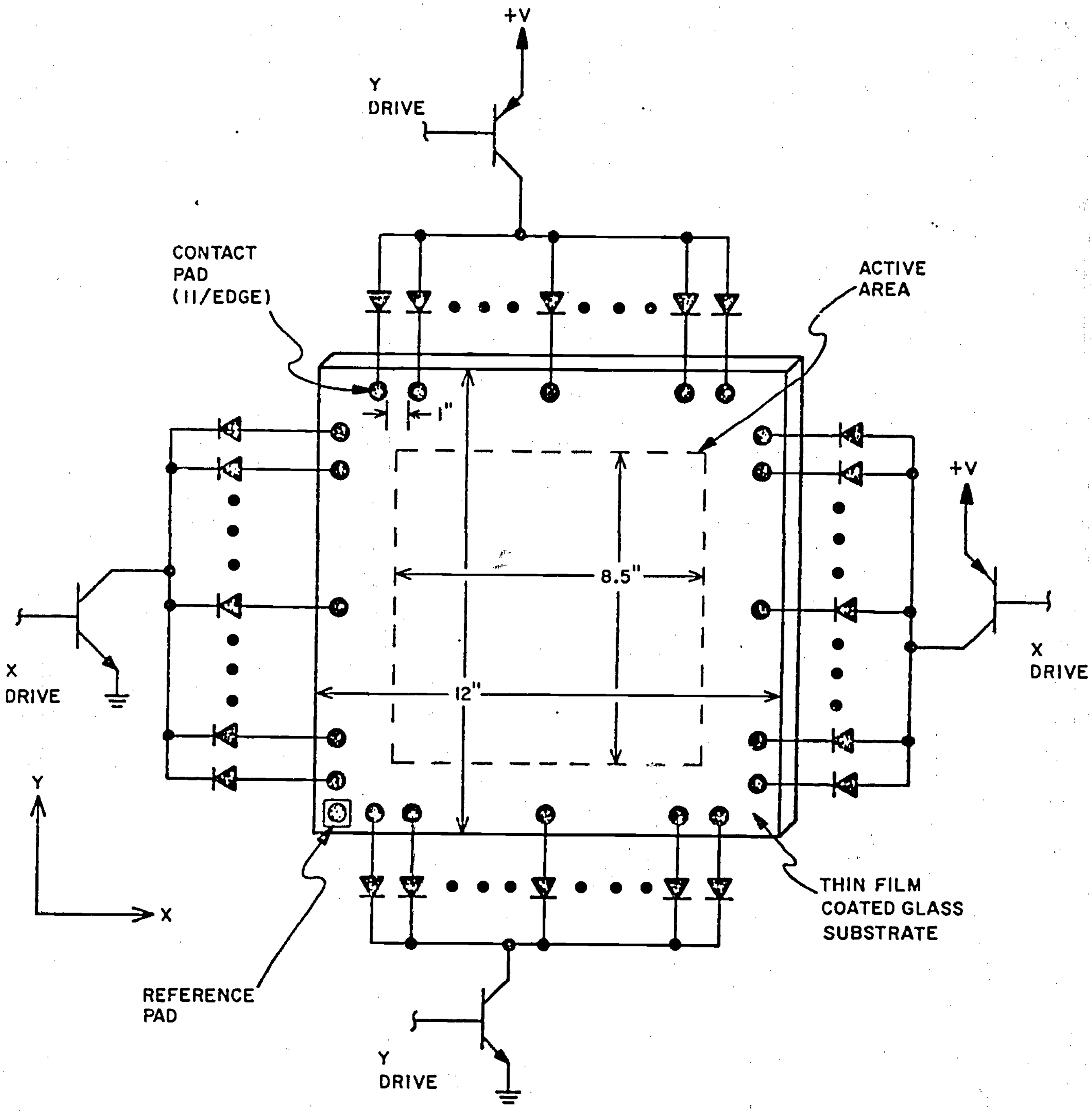
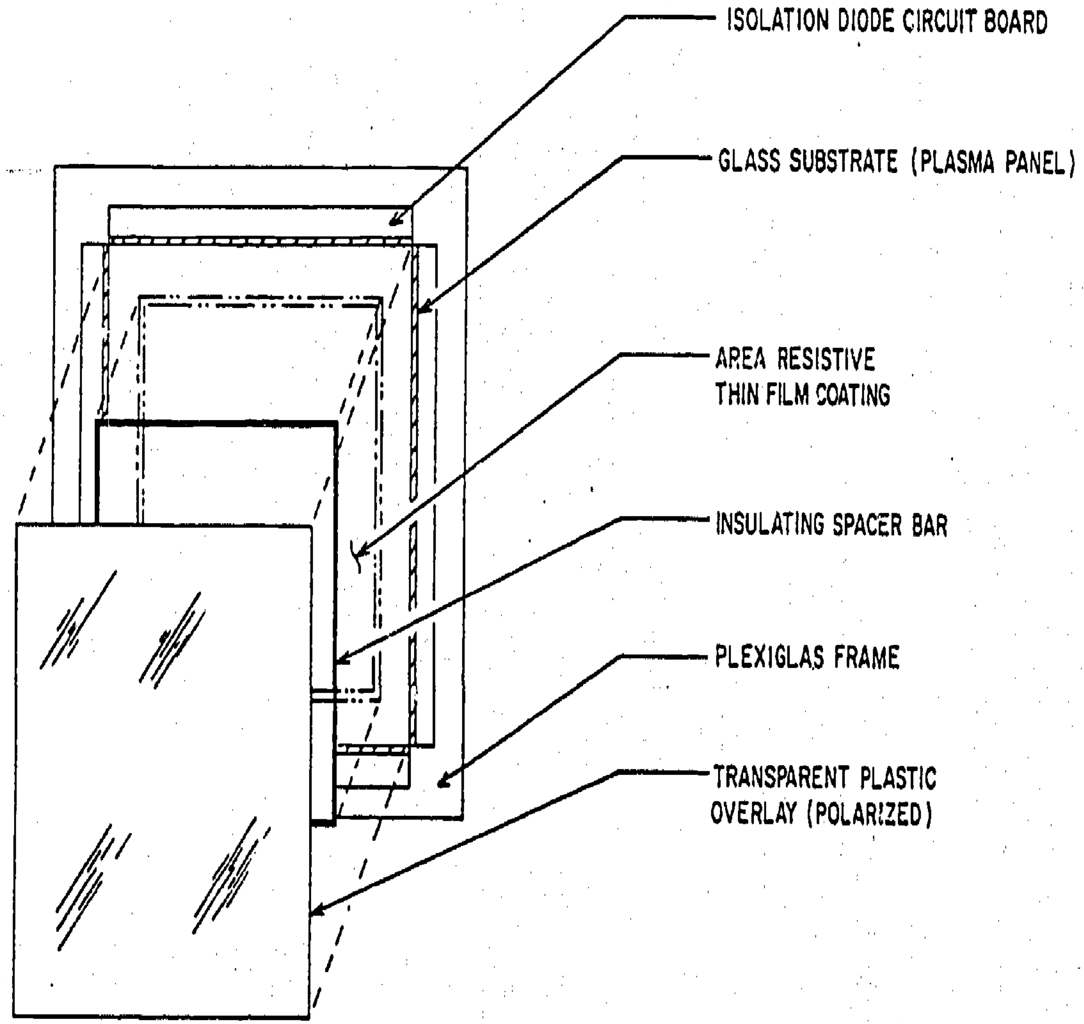


Figure 2.1 Thin Film Interface



TABLET ASSEMBLY

Figure 2.2 Mechanical Assembly: Exploded View

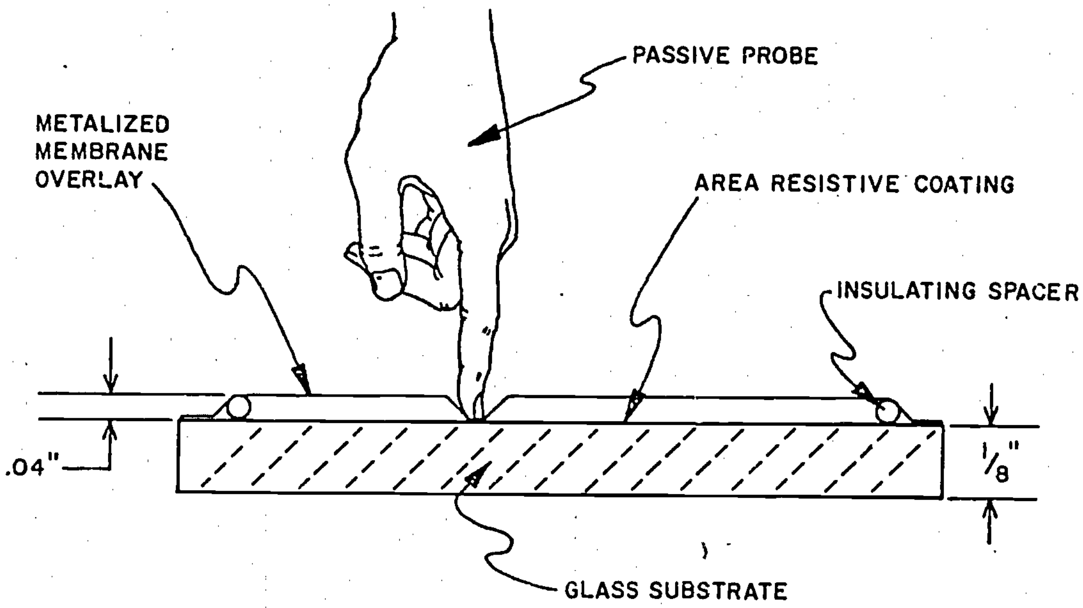


Figure 2.3 Passive Input: Side View

to the terminal in the event that the two data words are equivalent. Comparator precision is program selectable allowing the graphics encoder to operate at reduced resolution while still eliminating the need for the programmer to check for redundant data.

Accuracy and thus usable resolution of the graphics encoder deteriorate due to the effects of noise. Since the resistive coating and overlay are parallel to the active elements of the plasma panel, substantial coupling of sustainer noise to the circuit can be expected. A reference pad, included in the lower left corner of the resistive coating, is brought to one side of a differential amplifier stage, the overlay to the other. Thus the differential amplifier attenuates the sustainer noise through common mode rejection and also reduces the effects of variation in the drive circuitry power supply. Following the differential amplifier are sample and hold circuits that have low pass characteristics. These low pass filters attenuate any other high frequency noise that may have been introduced into the system. It is because of these low pass filters that a short delay is necessary for the sample and hold circuits to acquire the initial analog position. Only the initial delay is needed, for subsequent positional changes are incremental to the previously held analog value.

Internal operation of the system is synchronous beginning with the depression of the overlay to the coated glass surface. The control logic generates timing levels that drive the area resistance in each axis successively. Concurrently, the X channel acquires the positional X analog while the X axis is being driven. Then, as the Y axis is driven and Y analog sampled, the X channel is multiplexed to the ADC, converted and held in the

X storage register. Alternately, the Y analog is converted. Providing the initial acquisition delay has passed, the terminal is notified that a coordinate pair is ready for transmission. If the coordinate pair is not the first in a sequence and the programmer has specified stream mode, the hardware will check the data word for redundancy as previously described, before raising the data ready level. Had the hardware been in the single mode, the control logic would wait until contact with the overlay was removed and remade before generating new coordinate data.

2.3 Intelligent Terminal Notes

The intelligent terminal hardware consists of several subsystems configured to perform as a highly versatile graphics display terminal. A DEC PDP 11/10 minicomputer serves as the display processor, driving a 512 x 512 line Owens-Illinois AC plasma panel. The PDP 11 is a good choice because of its agile instruction set and architecture. A principle advantage of this machine is its bus oriented communication structure which allows peripheral device registers to be treated as if they were physically part of the computer. Vital to the flexibility of this bus structure is a multilevel interrupt system which makes possible the handling of the many tasks required for interactive operation. Data acquisition can either be handled through the terminal external data hardware or through a standard module such as the DEC DR11-C general interface if more flexibility and speed is necessary. Since several interface modules can be attached to the bus, the intelligent terminal can easily serve as a local processor and memory for various auxiliary devices ranging from graphic input to automated experiments [6,7].

2.4 Audio Cue

In typical CAI touch applications it has been reported in the literature [5,8] that the lack of immediate feedback indicating input acceptance from the touch sensitive surface can cause confusion on the part of the student. This problem can become quite serious when several sequential touch inputs are desired before display material is updated. A terminal device such as the Teletype does not suffer from this drawback since the depression of a key is followed by the printing of the character, returning both visible and audible cues. The analog tough panel is silent giving no indication that the system has recognized an input.

In the crossed light beam touch entry system developed at CERL a small audio oscillator was included in the feedback path from the terminal. Upon acceptance of a touch input the oscillator was activated for 100 ms emitting a soft high pitched tone. The addition of this audio cue has eliminated any question as to whether or not the touch input was transferred to the terminal. Since a touch input is accepted when a pair of orthogonal beams are broken and does not necessarily involve physical contact with the encoding surface, the emission of an audio tone was considered essential.

The analog touch surface must actually be physically depressed to generate a coordinate pair. Although the natural feel is advantageous as a cue, it was felt best to include an audio beeper for the tablet when operated in the pointing mode. The intelligent terminal has an audio oscillator built in to its terminal hardware. The beeper is activated simply by addressing its location as a peripheral on the PDP 11 bus. In the drawing mode, of course, the activation of the beeper would serve only as a nuisance; visual feedback must be relied on here.

3. SYSTEM DESIGN

Since the principle by which the graphics tablet operates is analog in nature and the resultant data is for computer consumption, the circuitry required to encode the (X,Y) position is best described as a hybrid mixture of analog and digital circuit techniques.

It will be helpful to refer to Figure 3.1 during the subsequent discussion since the drawing presents the organization of the tablet electronics in block diagram form. On this figure one can find the functional subunits and, more importantly, identify major signal paths within the unit. Later, when referencing one of the detailed schematic drawings to follow, this composite diagram should be used to clarify the source, destination, and function of the interconnections indicated. For example, the CMP (compare) signal can easily be identified as originating on the digital comparator card (Figure 3.8) and entering as a status line to the control logic card (Figure 3.7).

The analog circuitry basically consists of a signal processor with input signals coming from the encoder assembly and with output finally feeding the analog to digital converter, at which point a binary representation of the position is determined. Standard TTL chips form the control logic section and data handling circuits. The controller must generate sequencing signals based on the internal clock, internal status and external commands. The data circuits handle the buffering and interface to the DR11-C module as well as provide a redundancy check during stream coordinate generation.

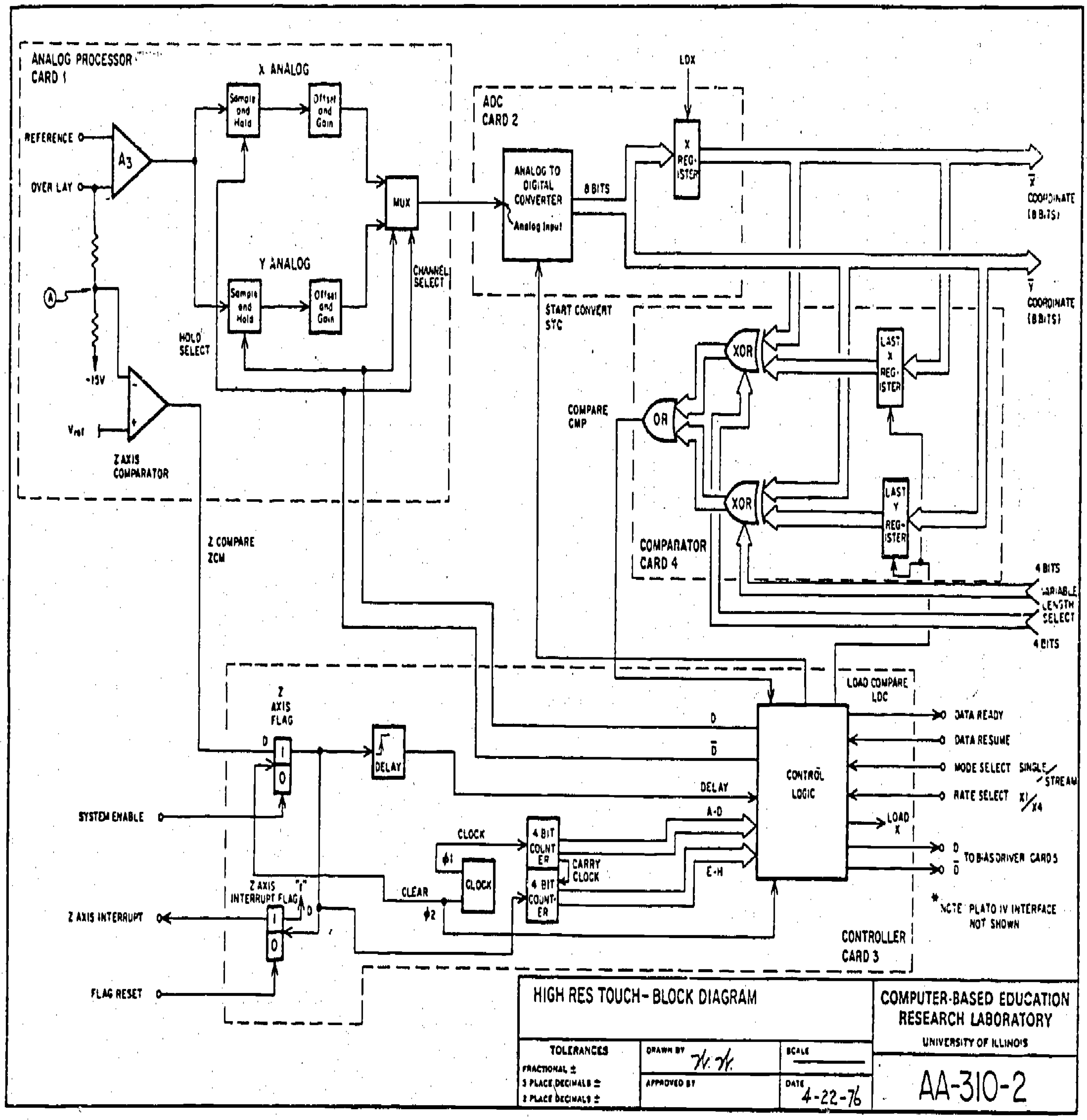


Figure 3.1 System Block Diagram

The remaining circuitry is comprised of discrete realizations necessary to permit digital control of the analog processor and to drive the encoder sheet resistance.

The control section continuously generates the signals necessary for operation of the analog section. For this, the thin film oxide coating must be biased alternately for each axis. Concurrently the sample and hold circuits and analog multiplexer switch channels to match the proper axis. Other signals are produced only when the overlay is depressed onto the active encoder surface.

Good overlay contact is interpreted as a valid Z axis condition and initiates the sequence that will encode stylus position. The Z axis condition (ZCM), determined on the analog board, is synchronized to the system clock with the Z AXIS FLAG. The setting of this flag enables an event counter, which determines the frequency of coordinate conversion, and also fires a one-shot delay to disable the data ready flag until the analog circuits can acquire the correct position. After the delay has passed, the hardware will convert a single coordinate or a rapid stream, depending upon the control status from the terminal.

3.1 Mechanical Assembly

The mechanical assembly consists of a frame for supporting the thin film coated glass substrate, the overlay subassembly and circuit boards for the isolation diodes (see Figures 2.1, 2.2, and 2.3). Since the prototype touch surface includes an extra glass substrate, the frame was fashioned to permit mounting the tablet as close to the display panel as possible to reduce the effects of parallax. The 12 inch square glass plate is surrounded by a 1/8 inch thick plexiglas frame 15-1/2 inches square. Underneath, a thin stainless steel sheet provides support for the circuit boards and overlay. A cutout in the plexiglas along each edge of the glass plate holds circuit boards carrying the isolation diodes. Silver-loaded epoxy resin is used to form the contact islands. In production, aluminum pads would likely be evaporated onto the thin film through a mask. The contact pads are attached to the circuit boards by flexible loops of #30 wire to lend some strain relief to the connection.

The conductive overlay is silver epoxied at each of the four edges to 1/32 inch single-clad glass-epoxy circuit boards. These boards provide the necessary overlay clearance by acting as insulating spacers. The copper foil serves as the bus material for electrically attaching the gold coated mylar overlay. The overlay boards can be pulled in all four directions, helping stretch the membrane above the encoder surface. They also act as a clamp with the steel sheet, holding the entire assembly together. The assembly easily mounts on a standard Owens-Illinois 512 x 512 plasma panel.

3.2 Thin Film Bias

Driving one axis of the resistive thin film coating is straightforward. A bias voltage can be applied to opposite bus strips along the edge of the glass plate. Referring to Figure 3.2, if the bus strips are vertically aligned, the sheet resistance will appear as an infinite plane in the vertical directions. That is, a system with this type of edge termination will work well for one axis, since no current will flow through the

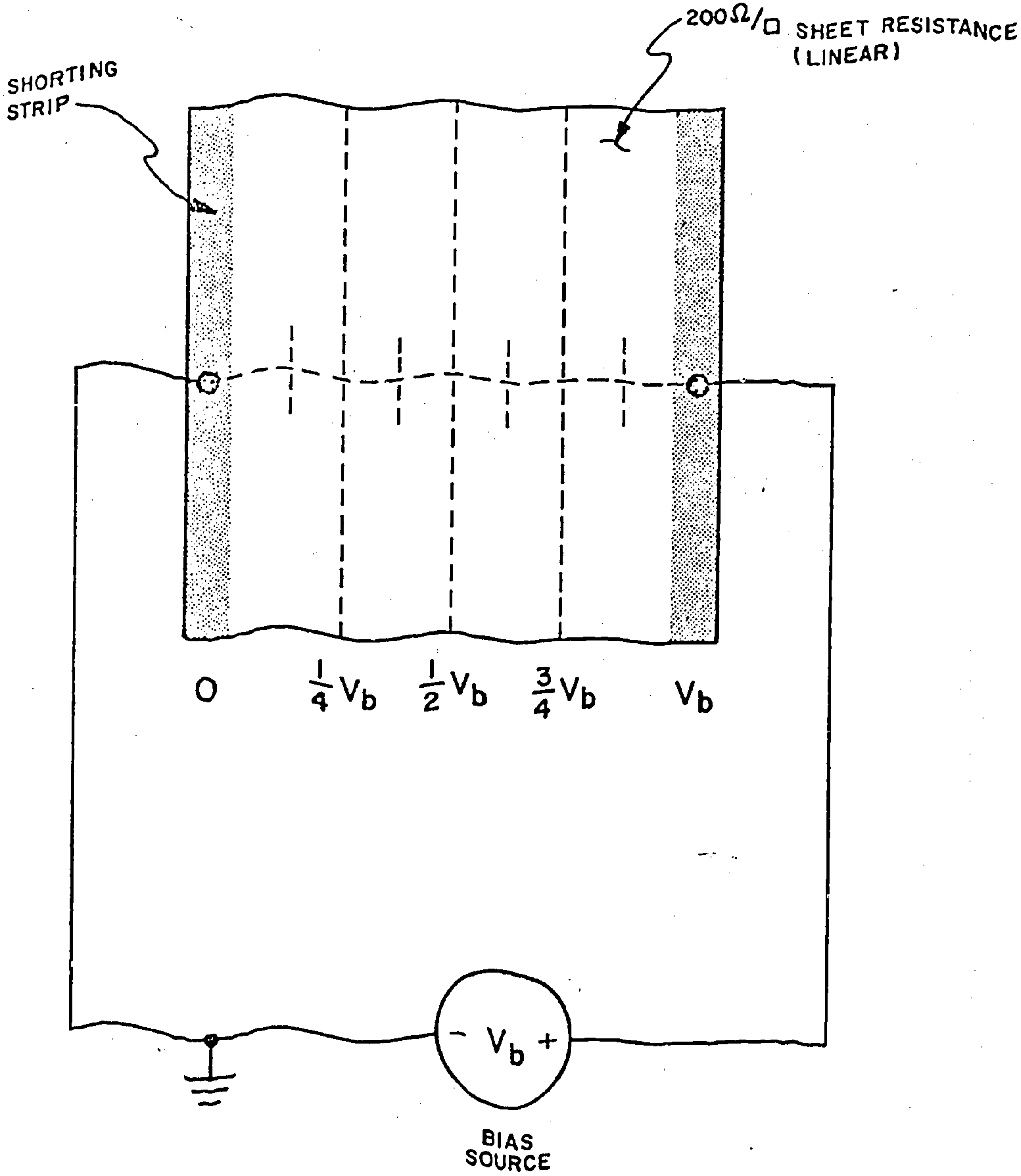


Figure 3.2 Sheet Potentiometer

upper and lower edge. The linearity of the equipotential lines that form the analog "graticule" will rely on the uniformity of the thin film coating. If however, the upper and lower edges were similarly interfaced, the unbiased edge strips will form a shunt redistributing more current along the edge of the encoder and badly distorting the desired graticule.

The shunting effect of the edge termination can be effectively overcome by replacing the bus strips with a row of small contact pads (see Figure 2.1). The pads average about an eighth inch in diameter and number eleven per edge. The total area of the pads is small compared to the total area at the edge, thus the shunting effect due to the high conductivity of the pads is reduced. Each pad on a given edge is connected to a silicon diode. The junctions opposite the pads are tied together leaving all diodes on an edge reverse biased with respect to one another so that the individual pads remain effectively isolated from the connection to the drive circuitry. These diodes insure that current can only flow into or out of an edge.

The glass driver circuit applies a fixed bias voltage alternately across each axis of the thin film coating under command of TTL logic levels from the controller (see Figure 3.3). NPN transistors T1 and T2 act as level shifters to provide the proper base drives to the axis edge switching transistors. These transistor circuits have been designed to operate either in cutoff or in saturation. Complementary inputs (D and $\overline{D}$) cause the configuration to switch between two stable states; discussion of the operation of the upper circuit in Figure 3.3 is the mirror image of the lower circuit.

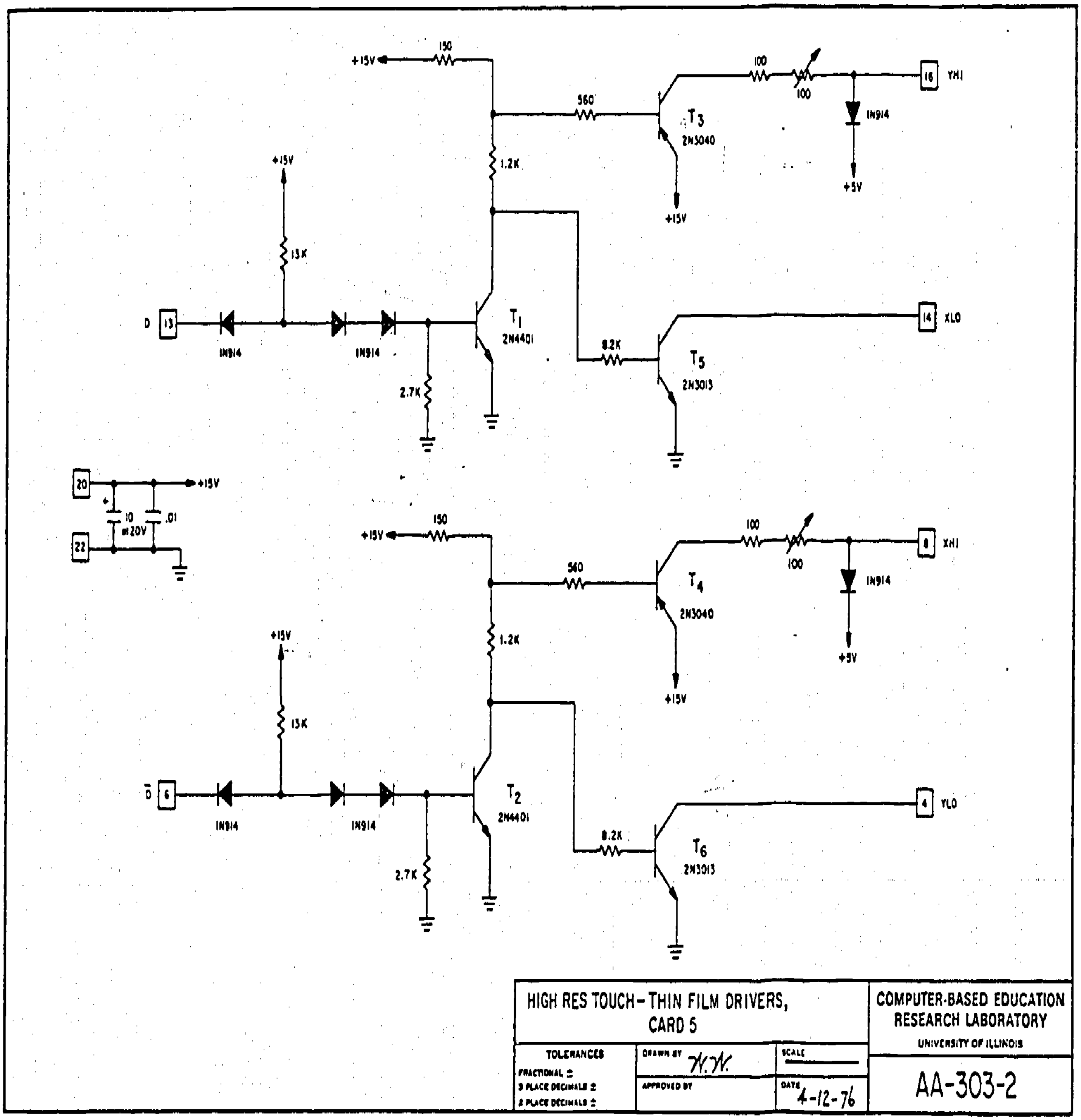


Figure 3.3 Bias Driver

As the input at D rises to a logic one (see the upper circuit), T1 moves into saturation, its base drive supplied by a standard DTL input circuit. The collector voltage at T1 falls within a few tenths of a volt above ground, removing base drive from NPN transistor T5 thus leaving it in cutoff. Simultaneously T1 sinks base drive for PNP transistor T3 through the collector circuit resistor divider, pulling that transistor into saturation. T3, T6 and T4, T5 are the transistor pairs switching bias for the Y- and X-axis respectively. Thus when T3 is saturated in the upper circuit, the complemented logic input to the lower circuit will source base drive for T6, also turning it on. As the input D resets to a logic zero, T1 will turn off -- its collector rising towards Vcc = +15 volts. T3 will no longer have base drive and will move into the cutoff region as its stored charge is removed through T5 and T6. T1's load resistor sources about 1 mA of drive for T5, enough to saturate the transistor.

The oxide film and isolation diodes comprise the loads for the edge switching transistors. In lumped form, this load appears as two diode drops in series with about a 200 ohm resistor. It is important for long term stability that a fairly constant current be driven through the thin film. For this reason, the high axis edge transistors T3 and T4 are PNP devices. The emitters are tied to the relatively stable +15 volt power supply, thus allowing these transistors to also be operated in the saturation region. The collector to emitter voltage of any transistor operating in the active region would tend to drift with ambient temperature variations. This is due primarily to the temperature dependence of a transistor's common emitter forward transfer ratio h_{FE}. Fortunately, the V_{CE} (sat) of good switching transistors is much more independent of temperature and base drive than V_{CE} (act).

The collector leads of T3 and T4 have a series resistance introduced to limit the current through the thin film to approximately 20 mA. This current produces a potential difference of about 3.4 volts across the 8-1/2 inch active area of the encoder. Diodes in the circuit act to clamp the upper edge of each axis at 5.6 volts. Clamping was necessary because unwanted spikes occur during switching transitions.

Using this drive scheme, the oxide has a positive potential along its entire surface at all times. The value depends upon which axis is being driven and the physical displacement with respect to that axis. An oscilloscope connected to the overlay would display a square wave if the overlay were depressed off the X = Y diagonal. On the diagonal, since the X and Y coordinates are equal, one would observe a DC level proportionate to the contact distance from the origin. The signal appearing on the overlay when in contact with the thin film coating is a time multiplexed voltage representing the analog (X,Y) position.

3.3 Analog Processor

The analog processor functions to separate and hold the X and Y channels, to provide offset and gain adjustment for each channel, and to multiplex these scaled analog voltages to the ADC module (see Figure 3.4). Since this particular design is required to operate overlaid to an AC plasma panel, the encoding surface (i.e., thin film coatings) can be expected to pick up considerable high frequency noise through coupling to the high voltage 50 KHz sustainer in the plasma panel. For this reason the front end of the processor has been designed to eliminate all effects of this noise. Additionally, the condition of overlay contact must be measured to determine the

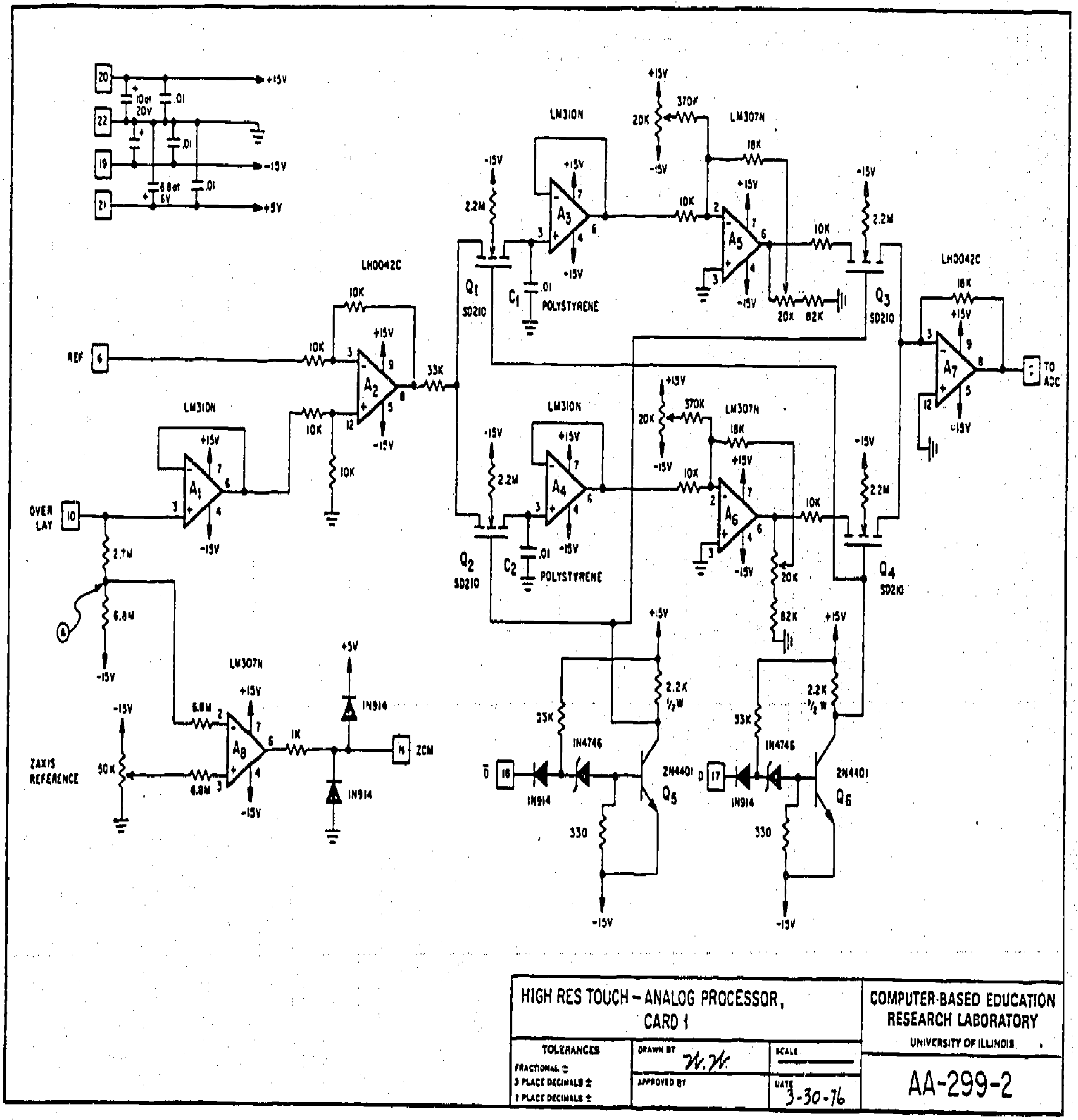


Figure 3.4 Analog Processor

status of the Z axis signal. These tasks must be reliably performed without the introduction of instability or channel crosstalk and also without slowing the response of encoder down such that quick touches will not register.

As one might expect, since the analog touch encoder is basically a special purpose measurement system, instrumentation techniques are employed in the analog circuitry. The front end is a differential amplifier (A2) possessing a high common mode rejection ratio. Differential input has two advantages, both made possible by the inclusion of a reference pad located at the origin on the oxide coating (see Figure 2.1). The voltage on this pad is very near the proper offset voltage for setting X = 0 and Y = 0. The differential configuration subtracts the inverting input from the non-inverting input, thus automatically readjusting the X and Y analog signals for the $V_d + V_{CE}$ (sat) of the lower thin film driver electronics. More importantly, the reference pad signal also has superimposed on it the coupled sustainer noise. The noise signal present on the overlay and on the reference pad are nearly equal. Thus, common mode rejection in the differential amplifier attenuates this noise to a level that can be handled by subsequent circuitry.

The overlay signal is buffered by a high input impedance voltage follower (A1). If this were not done, the resistor divider input of the differential stage would load the overlay, adversely affecting the common mode rejection performance. Worse than this, the input resistors would draw current from the oxide circuit, more or less depending on the physical location of contact with the overlay. This current would contribute a non constant error to the desired analog (X,Y) value that would be difficult to correct.

The output of operational amplifier A2 is cleaner than the raw overlay signal but still time multiplexed. The demultiplexing and hold functions are accomplished by series bi-directional switches Q1 and Q2 with their polystyrene holding capacitors C1 and C2. These capacitors and resistors R1 and R2 form low pass filters when the switches are closed. The upper corner of the first order filter has been placed at 500 Hz and provides 40 dB of additional attenuation for the 50 KHz sustainer noise. The corner cannot be placed too low because of the longer initial acquisition time then required. Actual tracking of typical drawing strokes is quite slow and does not restrict the choice of the corner frequency.

Operation of these circuits can be described in two periods. During the sample period the analog switch Q1 (or Q2) is closed and capacitor C1 (or C2) tracks the input as affected by the transfer function of the filter. The switch is turned off during the hold event such that the high input impedance (10^{12} ohms) of voltage follower A3 (or A4) and the high channel resistance of the transistor switch isolate C1 (or C2) preventing its discharge. it is important that the holding capacitors have polystyrene or polycarbonate dielectrics since other materials (e.g., ceramic, paper) cannot hold a stored charge for any length of time without decaying.

The analog switching transistors chosen are N-channel enhancement MOSFETS characterized by a low on resistance (30 ohms) and a low off leakage current (10 nA). These transistors are turned on completely with a gate to source voltage greater than about 8 volts and off with a V_{GS} of about 0.5 volts or less. The MOSFET is ideal for analog switch configurations both because of the bi-directional nature of the induced channel from drain to source and because the high input impedance at the gate prevents the introduction of error from the switching control signal. The substrate is tied to the most negative potential for N-channel devices to minimize leakage to the substrate.

The sample and hold buffers each feed the summing terminal of amplifiers A5 and A6 which invert the X and Y channel signals and provide a means to calibrate the full scale response of the encoder for each axis. Offset adjustment is made by summing a variable DC reference with the analog position. This alignment sets the origin for the encoder. Gain adjustment permits the full scale span of the encoder to be set as desired. The gain of the amplifier is varied by tapping a percentage of the output from a resistive divider and feeding it back to the inverting input. Center gain is about 1.8 and can be finely adjusted over a small range with this scheme.

The outputs of amplifiers A5 and A6 appear as clean levels after processing. The value of each is directly proportional to the position of overlay contact on each axis. At this point the X and Y channels must be time remultiplexed for input to the ADC. Similar analog switches (Q3 - Q4) to those in the sample and hold circuits are used to select the input to the summing node of amplifier A7. Amplifier A7 also provides the additional gain and inversion necessary for proper input to the converter.

For good switching of the MOSFET devices used in the processor, a high speed level translator was designed. The FET gates are switched between ±15 volts with a single transistor (Q5 or Q6 -- 2 devices are needed for complementary outputs). It was discovered that slow switching of the gate circuit caused both channels to be partially on during transitions, creating crosstalk problems with the sample and hold circuits. Using passive pullup and an NPN switching transistor, the 30 volt transition is made in approximately 200 nanoseconds.

The actual design of the translater resembles DTL logic circuitry in that the use of an input diode keeps the base drive to the switching transistor independent of the TTL input. This is important because it is desired not to drive the transistor too deeply into saturation. The use of a 16 volt zener diode in the base lead enables standard TTL levels to switch the 30 volt bipolar signal with one transistor. The presence of a logic zero at the input causes the input diode to be forward biased, leaving the potential at the cathode of the zener diode insufficient for avalanch conduction. The TTL output driving this input must be able to sink about 4 mA in addition to other loads. With no base drive available the transistor Q5 (or Q6) is cutoff and the MOSFET gates are pulled up to +15 volts through the collector resistor. Since the gates draw negligible current there is no voltage drop across the collector resistor.

A logic one on the input diode will reverse bias the silicon diode and satisfy the zener drop, driving the base of transistor Q5 (or Q6). Base current has been selected to drive Q5 (or Q6) quickly into saturation yielding a good fall time at the collector. The small base to emitter resistor drains stored charge out of the base lead during the transition to cutoff, reducing saturation storage time. The rather small valued collector pullup resistor is necessary for passive pullup to yield fast rise times. Active pullup would require less average power dissipation but would unnecessarily increase circuit complexity.

By isolating the overlay with a buffer, the condition of overlay contact can be determined easily without affecting the measurement of position. The status of the overlay can be assessed by attempting to force current through the overlay into the oxide coating. A resistor divider connected to the -15 volt supply limits the maximum injected current to about 2 micro amps, about 1,000 times much smaller than the current used to drive the oxide coating. If the overlay is not in contact, no current will flow and the 6.8 M ohm resistor will pull the divider center node (point A) to -15 volts. If on the other hand, the two thin films are touching one another, current will flow through this resistor causing a voltage drop to occur across it. The voltage at point A can range from -15 volts indicating no contact, to a less negative value indicating overlay contact.

The node A is connected to the inverting input of amplifier A8 which is configured as a comparator. When the node voltage falls below the fixed reference voltage at the non-inverting input the comparator output switches from -12 volts to +12 volts. Clearly these voltage levels would be disasterous for TTL inputs so a diode clamping circuit fixes the logic zero at -0.6 volt and the logic one at 5.6 volts. The TTL compatible output is labeled ZCM (Z compare).

3.4 ADC and Data Buffering

The task of the analog to digital converter (ADC) is to provide a binary representation of the analog position (see Figure 3.5). Eight bits of resolution are used giving 256 quantizing levels from 0 to 10 volts. The ADC begins conversion on command (STC) from the controller, which has already selected the proper axis. Conversion always occurs on the channel currently being held in the analog processor. The particular converter chosen operates with the successive approximation algorithm yielding the binary output in less than 50 microseconds. Ramp converters would be too slow (if competatively priced) for eight bits and tracking converters are not useful in a multiplexed system for the same reason since the algorithm must track small perturbations to be efficient.

The X channel is first to be converted; the binary result being strobed into data latches 4 and 5 by the controller to free the converter to handle the Y signal. At the end of the Y channel conversion,the full 16 bit coordinate pair is available for transmission to the terminal. The request for data transmission is made in the controller based on status and timing information.

The data is placed on twisted pair lines through hex inverters with 47 ohm series resistance. This is done for two reasons: The twisted pair and series resistor form a balanced transmission line, giving better noise rejection for longer line runs. The second reason is born from experience. It is poor practice to attempt to drive long lines with standard TTL flip flop outputs. Line reflections can cause the circuitry to change state because of internal feedback connections. The hex inverter solves this problem by actually being a one way device; no feedback is possible.

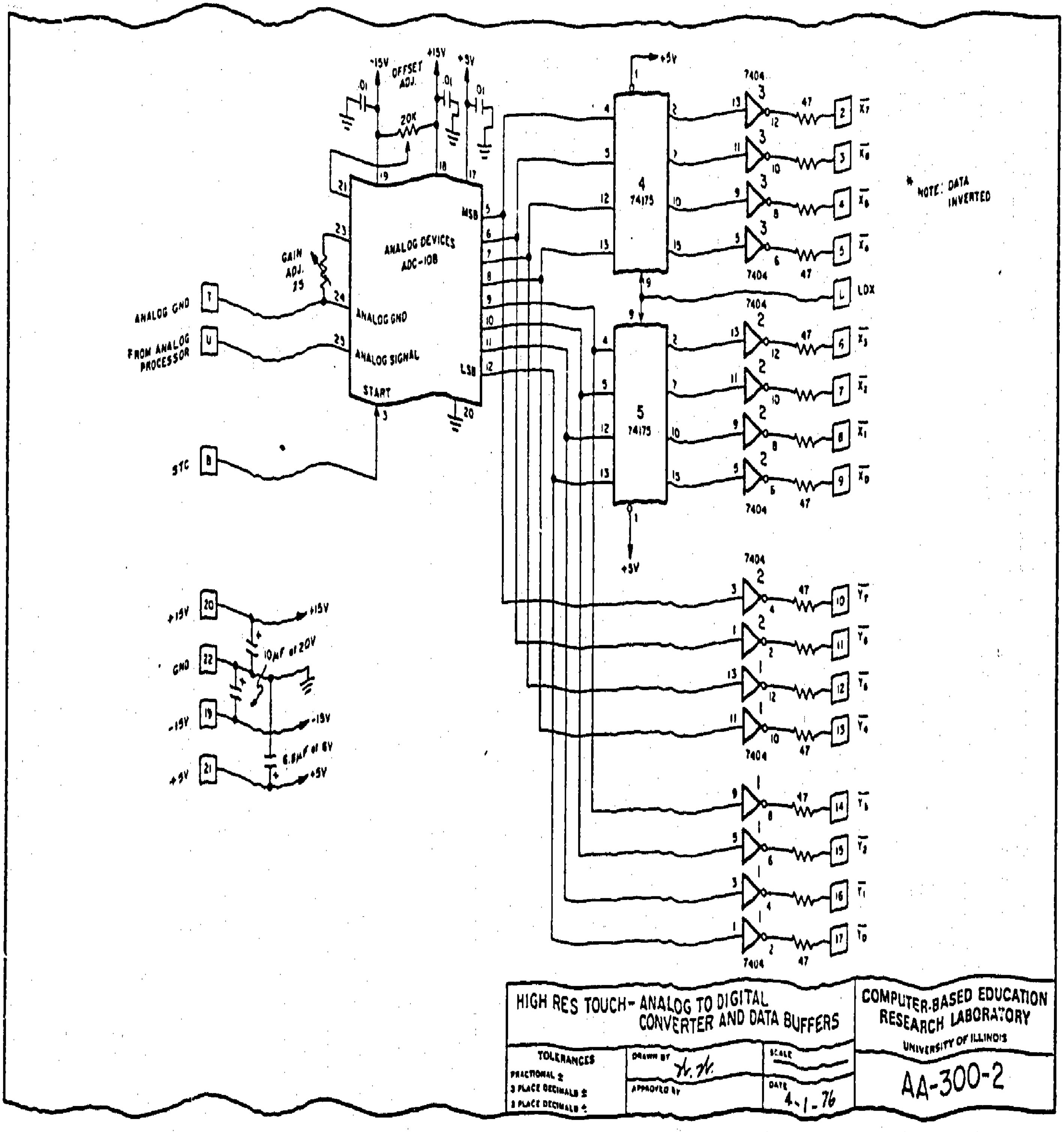


Figure 3.5 ADC and Data Buffers

3.5 Digital Comparator

The digital comparator card is responsible for reducing the quantity of redundant data sent to the terminal during encoder operation when in the drawing mode (see Figure 3.6). Buffer registers (8 and 10) store the least significant four bits of each coordinate. As each new coordinate pair is generated, quad exclusive OR gates (15 and 13) compare the four least significant bits of the new values with the old valued stored in the buffer register. The outputs of the XOR gates are OR-ed together with wired logic using open collector gate outputs. A logic one value for $\overline{\text{CMP}}$ indicates that the last two data words are equivalent.

Comparator precision is program selectable by disabling the XOR outputs with NAND gates (18 and 20). For example, to operate at full resolution the select inputs to the NAND gates (DRO 0-3, 8-11) must be a logic one. All digits are then compared. To operate with 6 bits resolution for the X axis and 7 bits for Y, DRO 0, 8 and 9 must be toggled to logic zero. The comparator will then ignore the least significant 2 bits for X and LSB for Y. Five bits is the coarsest resolution that can be checked for redundancy.

Without the comparator, a relatively stationary or slow moving stylus will generate quantities of useless data at up to 400 coordinates per second. To completely eliminate redundant data it is necessary to look farther in the past than one event. Quantizing boundaries are so close (0.03") and steadiness of the free hand so poor that slow stylus movement will invariably toggle on quantizing boundaries, creating a seesaw of data

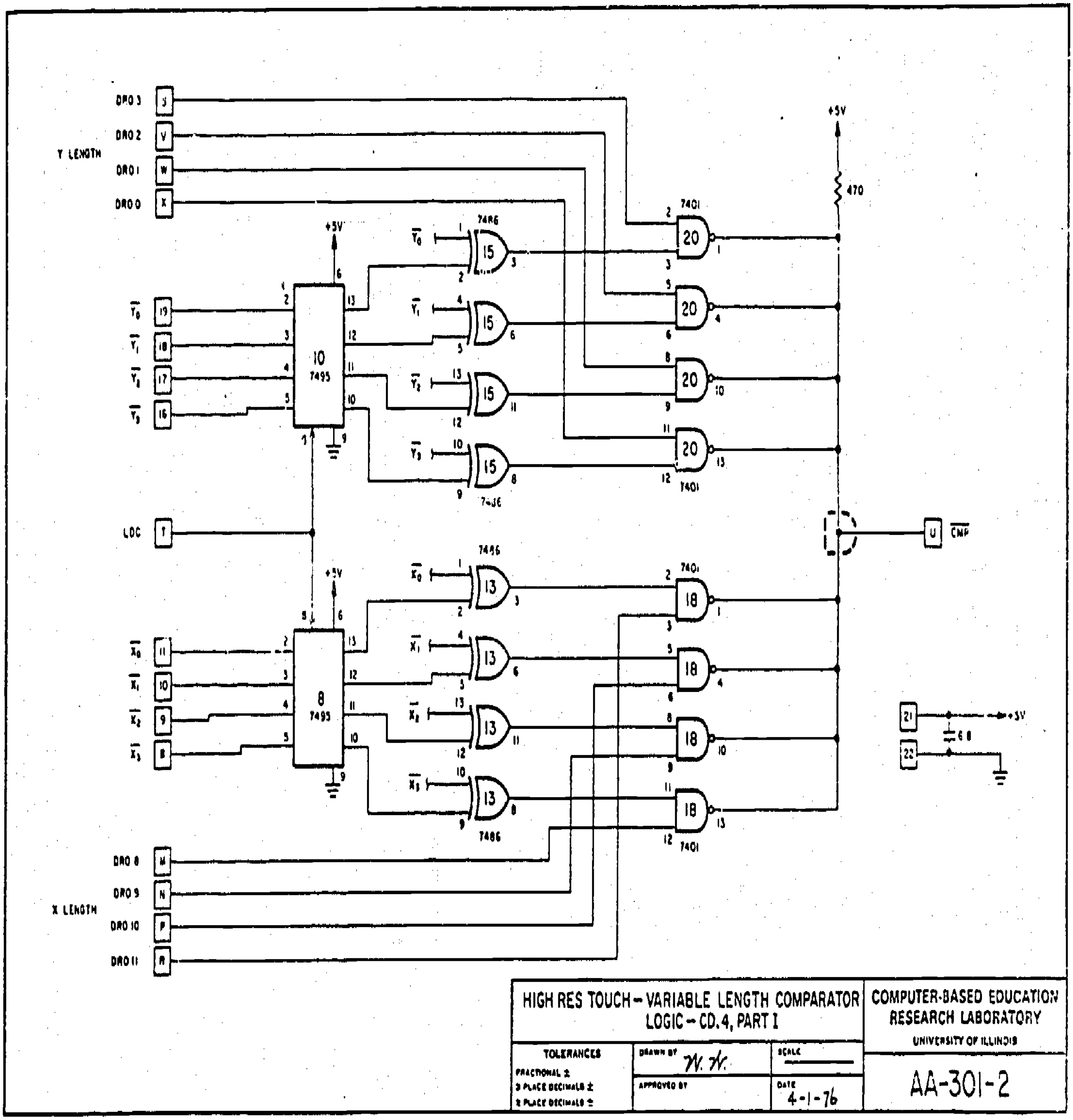


Figure 3.6 Digital Comparator

at high generation rates. Terminal software can be used to accomplish this check or more hardware can be included to perform the comparisons. A study of typical data streams indicates a check two or three events in the past will catch most of the redundant data normally caused by this effect.

3.6 Controller

The controller, shown in Figures 3.7 and 3.8, functions to generate timing and control signals for other circuits in the touch panel hardware. In addition, status information is received and originates on this board which coordinates interaction with the computer based intelligent terminal. Internal operation is synchronous with asynchronous external communication established with the terminal.

A two phase clock has been implemented to simplify the overall logic design of the controller. Three TTL inverter gates are cascaded in an astable network running at about 51.2 KHz. A J-K flip flop (15) and two NAND gates produce a two phase clock with a frequency one half that of the multivibrator. Although this configuration has complemented outputs because of the NAND gates, the use of NOR gates for true outputs fails to work as logically predicted because hazards introduce false clock spikes. Phase 1 (Ø1) drives counter circuits for sequencing control levels and pulses while phase 2 (Ø2) synchronizes changes in the Z-axis condition.

A pair of cascade connected 4-bit binary counters divides the Ø1 clock pulses into larger time segments. The upper counter (13) counts to 16, generating basic timing pulses. The lower counter (12) controls the occurrence of a valid coordinate conversion; call this an event. The status of the event affects the signals which activate the ADC and latch its results

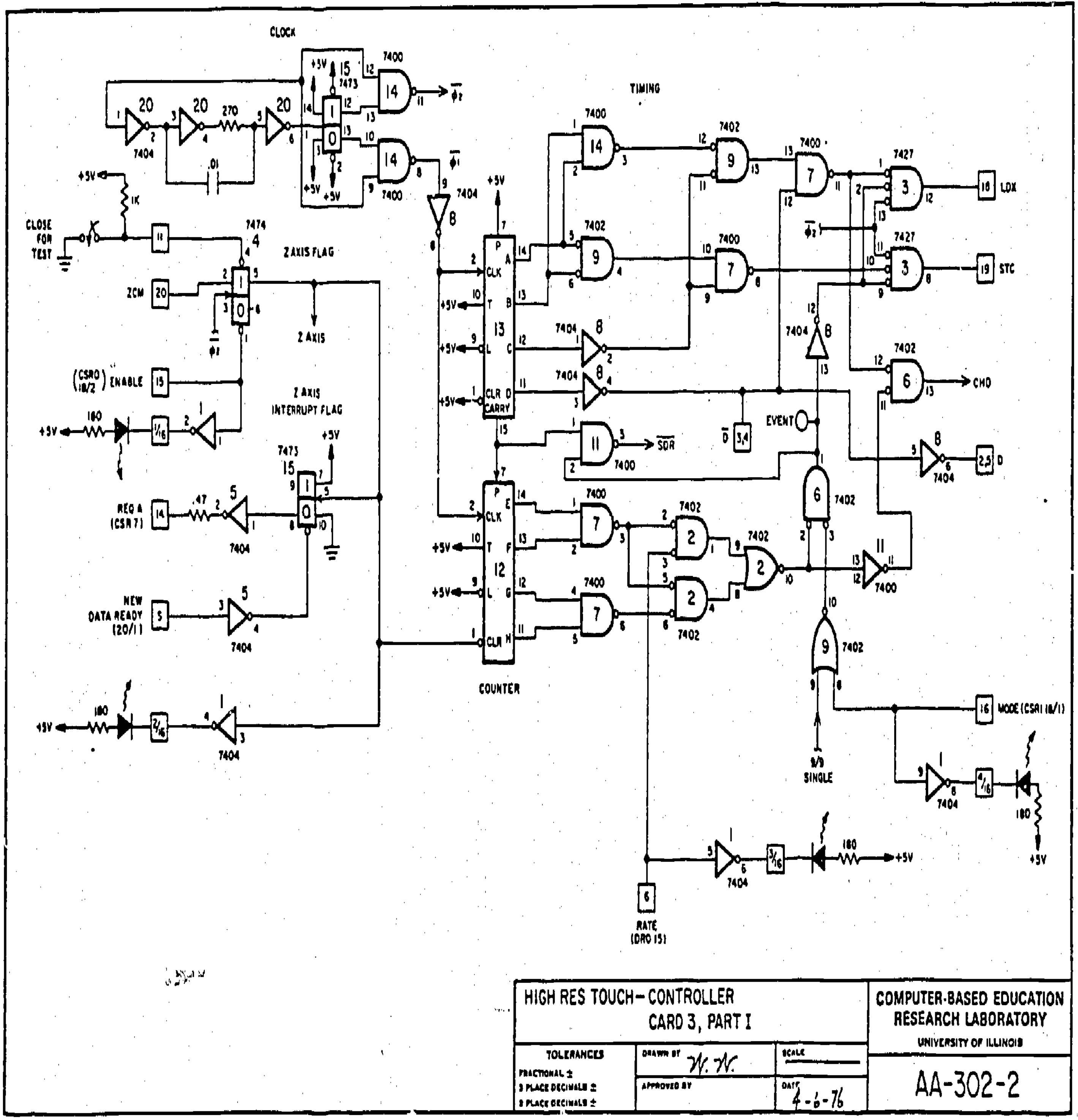


Figure 3.7 Controller: Timing

as well as affecting the notification to the terminal of new data for transmission. Events can occur at 1/64 or 1/256 the 2 phase clock frequency depending on the status of the RATE input (DRO 15 -- see section 3.8). This allows maximum data rates of 400 and 100 coordinates per second respectively in stream mode.

During a valid event period (which is 16 clock pulses long) the gating circuitry to the right of the upper counter produces the STC (start convert) pulse on the first and ninth count and the LDX (load X) pulse on the eighth. The SDR (strobe data ready) pulse is issued on the sixteenth count, marking the end of an event. When in the cleared state, the event counter is producing the no-event output. The D and $\overline{D}$ outputs of the upper counter (each true for 8 counts) control the multiplex circuits and the glass driver as described above. These signals are generated regardless of the state of the event since they are needed to assess overlay contact. Event occurrence can be restricted to one data transfer per touch by placing a logic zero on the MODE input.

The setting of the Z-AXIS FLAG begins the sequence that will encode stylus position. A ZCM true signal from the analog processor is latched into the Z-AXIS FLAG by 02, removing the clear input to the event counter and firing one-shot (18). At this point the timing circuitry is running but the one-shot delay inhibits the SDR pulse. The output of the one-shot is synchronized by the DELAY SYNC flip flop with the CHD (check delay) pulse. Since CHD is only produced during a non event, this insures that the beginning and the end of the delay do not fall within a conversion period.

The fall of the DELAY SYNC flag permits SDR to pass normally to strobe the DATA READY FLAG and also sets the SINGLE FLAG. The SINGLE FLAG will remain set until it is reset by the terminal after having received transmitted data. This will happen on the first data word sent per touch. The output of the SINGLE FLAG is ORed with the status CMP from the digital comparator, bypassing the comparator status for the first in any stream of coordinates (since the first coordinate is never redundant). The CMP status line is normally connected to the data input of the DATA READY FLAG; thus the flag can only be set when the last two coordinates differ. This sequence ends when ZCM falls, causing the Z-AXIS FLAG to reset. In turn, the event counter is cleared and and the Z-AXIS INTERRUPT FLAG is set. The interrupt flag can be used to implement the various data editing algorithms discussed later in Chapter 4.

3.7 DR11-C Interface and Programming Notes

The touch encoder is interfaced to the PDP 11 computer via a DEC DR11-C general purpose interface. The DR11-C provides the logic and buffer register necessary for program controlled parallel transfers of 16-bit data between the PDP-11 system and a peripheral device. The interface also includes status and control bits that may be controlled by either the program or the peripheral device for command, monitoring and interrupt functions. This section is included to give the programmer the information necessary to use the touch panel in an interactive mode [9].

Interface logic consists of three registers: control and status, input buffer and output buffer. These registers are addressed by the PDP-11 using its standard instruction set. The registers along with their addresses are shown in Figure 3.9.

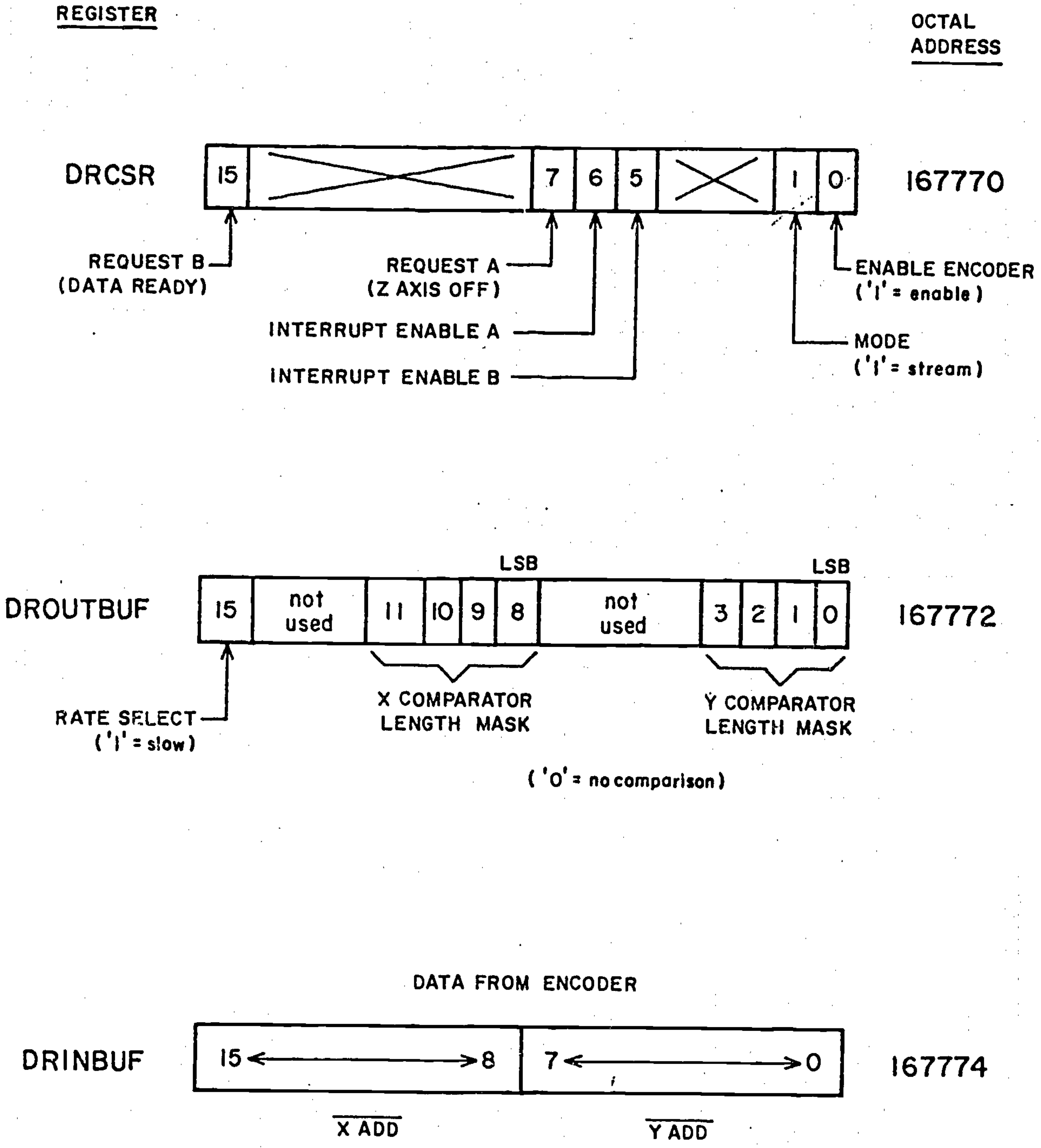


Figure 3.9 DR11-C Registers

Coordinate data from touch is read from DRINBUF. Data is inverted with the Y address in the lower byte. Note that for the 512 x 512 plasma panel, each byte must be separated and shifted left one bit to restore the 9th bit of the (X,Y) address (note the 9th bit is always zero for 8 bits of touch panel resolution).

Register DRCSR serves command and status functions. Request B (REQ B) is tied to the output of the data ready flag in the touch hardware and is used to signal each new coordinate pair generated. On the lower byte boundary, Request A (REQ A) is raised each time contact is removed from the encoding surface. These status lines can either be used in a busy-wait loop or in an interrupt mode by setting the interrupt enable bits for the proper request line. The bottom two bits of DRCSR are allocated for control: bit 0 must be set to enable the touch panel and bit 1 controls the Mode ('1' = STREAM).

The DROUTBUF is used exclusively for control of touch. The MSB selects the RATE of touch in stream mode. A logical one here will set the maximum data rate at 100 words/sec. The lower four bits in both bytes of this register contain the masks for the digital comparator (see section 3.6). These bits can be changed easily by using the bit set (BIS) and bit clear (BIC) instructions or with the move byte instruction (MOVB) [7].

3.8 PLATO IV Interface

To facilitate study of high resolution touch applications for the standard PLATO IV student terminal, a full resolution interface was designed and included in the encoder hardware (see Figure 3.10). The same size plasma display device is used in both the student and intelligent terminal, so the encoder tablet can be mounted on either one without modification.

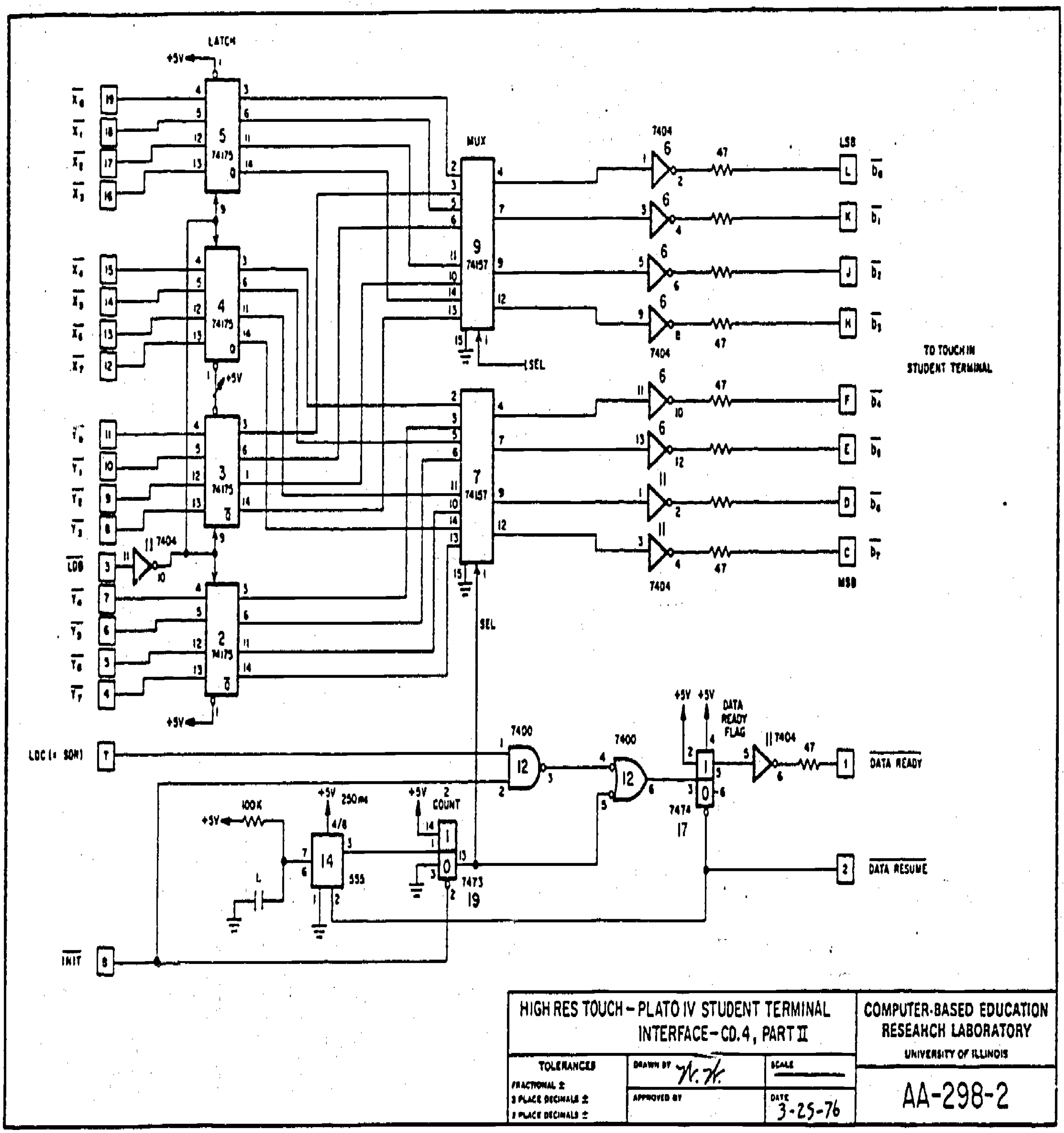


Figure 3.10 PLATO IV Interface

The student terminal can accept 8 bit wide data words at a rate not to exceed 10 words (or keys) per second [10]. For full resolution, two data words must be transmitted; the first word sent is the X coordinate. Upon completion of coordinate conversion the resultant data is strobed into quad latches by pulse LDB. This additional buffering is included because of the much longer response time required by the student terminal (and the wish to keep the two interfaces independent).

At first touch, the synchronized delay signal from the controller, INIT, initializes this interface by resetting the 2-count flip flop (19) and also inhibits the SDR pulse until the first valid coordinate is generated. The LDC pulse is conveniently used to latch the data ready flag (17). This output level notifies the terminal that new data is available. The output of the 2-count flip flop selects which coordinate is gated onto the data lines through dual channel MUX chips 7 and 9. After the data has been transferred, the terminal issues a data resume pulse which resets the data ready flag and triggers a 250 ms delay with one shot (14). The delay insures that data is not transmitted too quickly. The falling edge of the delay sets J-K flip flop (19) which causes the MUX to gate the Y coordinate on the data lines and latches the data ready flag for the second time. After the Y coordinate has been received by the terminal, no more data can be sent until touch contact is broken and remade since the 2 count flag holds the clock input of the data ready flag high.

The distinction between X and Y coordinates can be made in the users program by timing the delay between keys sent and discarding the keys if the delay is much longer than 250 ms. This method has been programmed on PLATO and has performed quite satisfactorily. A completely foolproof hardware scheme can be had by running the MUX select line to the MSB of the data word and shifting all other bit inputs right one position. The bit can then be read as a tag for which coordinate is on the terminal input line. Of course, this technique reduces the resolution by one bit but will give satisfaction to anxious hardware-suspicious programmers.

4. EVALUATION AND APPLICATIONS

4.1 Quality of Data

The quality of data generated by the encoder is fairly good subject to a few problems outlined below. Eight bit resolution on each axis has been realized although the combined effects of resistive coating and circuit nonlinearities cause absolute accuracy to fall short of this goal. Parallax and imperfect physical mounting of the encoding surface make it difficult to assess system accuracy. Since the finger is the typical choice for the passive stylus, absolute accuracy is not as important as achievable resolution. For this reason the reduced full scale accuracy is not considered a serious shortcoming of the overlay technique.

For proper encoding, the overlay must be in good contact with the resistive coating. In the pointing mode this is not a problem. The drawing mode, however, gave initial problems because the user would lightly depress the overlay yielding poor contact and response. Perhaps this was due to the user's past encounters at CERL with the crossed light beam touch panel which requires no contact with the display surface at all. Once aware of the purpose of the overlay, the user has little difficulty operating the encoder. This experience indicates that some minimal training of new users would be beneficial.

Electrical noise is not problem in this system due to appropriate design methods in the analog processor circuitry. However, spurious data sometimes caused by undesirable characteristics of the overlay is another type of noise that can be a problem. False data is generated when overlay contact resistance rises so high that the input amplifiers load the analog signal. This is because contact resistance is too great during periods of light stylus pressure. Voltage drop across the contact is not negligible under this condition and will introduce measurement errors. This particular problem usually manifests itself as the overlay rises from the resistive surface. The mechanical suspension for the overlay exhibits a finite risetime during which contact still exists, though of quickly increasing resistance. This effect can be seen as a "tail" of data points leaving the last valid contact moving toward the origin of the encoder (which is the equilibrium point for no overlay contact).

The above phenomenon has been verified by removing the overlay and replacing it with an active probe. The contact resistance as a function of stylus pressure in this case results in excellent response characteristics. The input circuitry has been designed to minimize the effects of contact resistance and stylus pressure, but clearly additional research into the materials involved would be beneficial. In spite of the many precautions taken to insure quality data, some editing of the input data may be desirable before processing it.

Quantization of the analog coordinates exhibits two more effects worth noting in any discussion of data quality. Diagonally drawn strokes are encoded in a staircase fashion rather than shortest distance; e.g., consider the hypotenuse of a right triangle the shortest distance and the perimeter through the vertex of the right angle the staircase path. The resulting encoded stroke appears this way because the coordinate pairs are actually measured at different points in time due to the multiplexed nature of this technique. This effect does not seem to be a problem since the displayed data is actually easier to see, although the extra data may not be desirable for some applications (e.g., character recognition) [11].

Unwanted coordinates can also occur as the analog signal momentarily rides one of the ADC quantization boundaries. As the signal balances on one of these boundaries, the LSB of the converter will toggle, yielding more data than is necessary to characterize the stylus motion. Strokes parallel to either axis will sometimes show this effect since the resolution and speed of the encoder is great enough to capture the unsteadiness of the human hand. Corrective measures such as a form of hysteresis programmed into the editing software will probably have the most success in eliminating this problem although, again, the effect is not necessarily deterimental to all applications using the drawing mode.

4.2 Programming Techniques

One method for eliminating the spurious tail has been programmed on the PDP 11 and works well in most instances. As mentioned in Chapter 3, a Z axis interrupt flag in the controller is set each time contact is removed from the encoder. At this instant, the DR11-C is made to interrupt the normal graphics input routine. Interrupt service then erases the last several data points (typically 4 points when fast, 2 when slow) and decrements the data pointer to the last valid coordinate. The tail data is ignored in each data stream by the interrupt service routine in this way. Knowledge of past coordinate history is required as far back as needed for erasure of dots already written on the display screen. This is one useful algorithm made possible by the local processor and memory in the intelligent terminal.

Storage of the data generated from hand sketching can quickly deplete the scarce resource memory if the data is stored in its raw form. The analog tablet operates on a 256 x 256 resolution, thus each coordinate would require a full sixteen bit word in the PDP 11 core or disc memory. At a maximum generation rate of 400 words per second (i.e., the position is slewing as fast as the update rate -- meaning no internal compare (CMP) true signals) even a simple digitized drawing will soon occupy a large amount of memory. For example the word "Hello" handwritten in two inch high letters typically produces an average of 500 data points. Fortunately there are several techniques that can afford a savings in the quantity of memory needed to store a given drawing. Basically these techniques can be classed as either coding, in which all information is kept, or reduction, with which only enough information is retained to approximate the original drawing.

A simple coding technique can be employed to reduce storage requirements by about one fourth. Within a given continuous curve segment each coordinate has exactly eight neighbors. By examining the list of coordinates with the computer, each adjacent coordinate can be recoded as one of the eight possible neighbors. Thus, given a full length initial coordinate, all subsequent data in that stream can be recoded as 4- bit patterns. Three of the bits will encode all eight possible increments. To provide for interruptions in the data stream as would normally be expected from removing contact from the tablet surface, the fourth bit can be used as a flag to signal interruption of the stream. The next full word following the word containing a set flag bit will contain the new base coordinate address. Considering the write time of the plasma panel, there is plenty of time to decode this information. Resetting of the Z axis flag in the touch panel can initiate an interrupt in the intelligent terminal thus giving a clear indication for reloading a new base address. Small skips farther than the nearest neighbor must be dealt with in the coding program. In this manner, since most coordinate streams are fairly long, one sixteen bit coordinate can now store four data points in place of one.

One group of researchers has found that sampling the analog position at 50 coordinates per second instead of 400 per second yields enough information for many recognition applications [2]. Quite often, enough of the original character of a drawing can be retained by decreasing the sampling rate. Then, depending on whether the resultant data is for machine or human consumption, the points can be connected by straight line segments using the graphics terminal line generator. Connecting the points can be done during display generation and serves both to increase visibility and to emphasize the serial history of the original drawing. For machine use such as character recognition, this need not be done.

4.3 Application Examples

At this point it may be helpful for the uninitiated reader to review several possible applications for high resolution touch. Programs utilizing touch in a pointing mode are already well received in many types of applications since the need for on-line processing is minimal. Stream encoding may require more sophisticated algorithms and more of the host system's resources, resulting in enthusiasm tempered by the economics imposed by a given user. One example will be given using the touch mode due to its simplicity, while two are given for the stream mode. Each example here emphasizes the different resources needed by the system.

Supervisory control. In this example the touch panel and underlying display are operated as a programmable keyset, allowing rapid man-machine interaction. Consider a typical power plant dispatching station through which a large power distribution network is monitored and controlled.

The graphic terminal can be programmed to display a regional map indicating major substations. If trouble occurs at a substation, the host computer can flash an appropriate symbol near the substation on the display. The human operator, reacting quickly, can touch the indicated symbol whose positional address will cause a more detailed diagram of the desired substation to be written on the display. In turn, the operator can locate the specific trouble and actuate appropriate rerouting changes by touching the overlay above the proper switches and commands on his terminal screen. A wide variety of industrial supervisory control applications could benefit from this type of improved man-machine interface when automatic control must be overridden by operator intervention.

Conference. With storage display devices, particularly the AC plasma panel, two or more touch-equipped interactive terminals connected via data link can be used as electronic blackboards or notepads. Terminal users would have the added benefit of instant graphics to make their conference discussions between remote sites more efficient.

As an illustration, perhaps a remote user requests repair service from a central facility. Possibly defective components could be quickly pinpointed for discussion by circling the suspected part on a display presentation of the schematic and transmitting the modified diagram over normal communication channels with electronic speed. This type of application will require little if any processing or storage of touch encoded data due to its transient nature.

Character recognition. Programs have been written by which hand-printed characters can be recognized [2,12]. Basically, information on position and serial history from the encoded characters is used to determine the character identity from a stored dictionary of coded character images. The character recognition algorithm can work well in an interactive system, since errors can be corrected through visual feedback.

Character recognition could be considered useful for many purposes. In CAI applications, children could learn to print with the aid of an overlaid graphics tablet and character recognition software. Many commercial applications also exist, e.g., signature verification for remote banking terminals. On-line processing and storage are necessary for implementing algorithms for which this degree of detail is required.

The applications for direct graphics input are bounded only by one's imagination and the economics of the situation. Several other pointing applications developed for the PLATO system are discussed within reference [5] and are not recreated here. A reader further interested in low resolution touch applications should consult this paper.

5. CONCLUSION

5.1 Summary of Results

The work reported in this thesis demonstrates an analog realization for graphic input that is both feasible and economically attractive. The introduction of a metalized overlay has eliminated the active stylus typically required by high resolution encoders. In particular, finger operation of the touch panel becomes possible by its addition. The prototype graphics entry system has shown that this encoding scheme is compatible with existing AC plasma display technology and that it also permits close quantization of stylus position. Use of the encoder can result in large amounts of raw data, but the local terminal processor and storage give the programmer a high degree of flexibility for data management.

5.2 Suggestions for Further Research

Possibilities for further research for this type of device exist both at the hardware and software level. At present, the encoder is only useful with immediate visual feedback in the drawing mode due to the unreliability of overlay contact. Occasional skips, sprays and noisy data can then be detected and corrected by the interactive system. Higher inherent reliability will lead to greater user confidence and a wider acceptance of this device. Extensive software development can increase this reliability as well as realize potential user applications.

Basic to improved reliability is fundamental research into overlay materials particularly suited visually and mechanically to the encoding task. A polarizer film is considered mandatory to reduce reflected glare from the thin film coatings and thus enhance display contrast. The polarizing film must be laminated with a carrier film whose expansion coefficient is carefully matched with the conductive film to avoid later breaks. Contact properties existing between the overlay film and resistive film could be optimized by increasing contact resistance.non-linearity such that there is a more rapid increase in resistance as the overlay contact area decreases.

The mechanical assembly could be improved by evaporating the resistive thin film directly on the display glass. Parallax and attenuation would then be reduced to a minimum. The overlay also acts to protect this expensive coating from deterioration. Better overlay suspension could also decrease overlay rise time, resulting in a faster Z axis response.

Long term stability and improved absolute accuracy should be the focus of any research directed toward a commercial product. Since the technique described in this thesis is analog in nature, it is subject to analog drift caused by temperature variations. For this reason, a feedback network designed to track these variations could be incorporated in the analog processor to maintain proper full scale calibration regardless of operating temperature. Non-linearities in the thin film resistive coating could be corrected by using a read only memory (ROM) to store corrections mapped over the resistive surface. The ROM could then be used as a look up table for the correct address or as a displacement table to calculate the correct address using fewer ROM bits but requiring an adder. Schemes such as the ROM table must, of course, be rationalized by high accuracy needs because each coating must be mapped in production and the ROM tables individually programmed.

A more sensitive means of assessing overlay contact resistance would effectively solve much of the spurious response problems. A possible method that would automatically compensate for this variation and also eliminate the staircase effect described in Chapter 4 relies on a technique involving constant current injection from the overlay into the resistive coating. Each axis would divide current linearly, yielding an offset from center screen. Both axes could be measured concurrently and stored in analog form for multiplexing to the ADC, eliminating the time difference between coordinate measurements observed using the technique described in this thesis. One such technique using current injection with a passive stylus is described in reference [3] but the approach is incompatible with the noisy environment imposed by the AC plasma panel. This author had difficulty realizing a constant current source stable enough for high resolution encoding, but feels that the technique is a promising one for future development.

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