DESIGN AND CONSTRUCTION OF AN OPAQUE OPTICAL CONTOUR TRACER FOR CHARACTER RECOGNITION RESEARCH

by

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ABSTRACT

This thesis describes the design and instrumentation of an opaque contour-tracing scanner for studies in optical character recognition (OCR).

Most previous OCR machines have attempted to recognize characters by mask matching, a technique which requires a large and expensive computer, and which is sensitive to small changes in type font. Contour tracing is a promising new approach to OCR. In contour tracing, the outside of the character is followed, and the resulting horizontal and vertical co-ordinates, X(t) and Y(t), of the scanning spot are processed for recognition. Although much additional research is required on both scanner design and processing algorithms, it is expected that an OCR device which uses a contour-tracing scanner will be significantly less expensive than existing multifont recognition machines.

In this thesis, four possible contour-tracing scanners are proposed and evaluated on the basis of cost, complexity and availability of components. The design that was chosen for construction used an X-Y oscilloscope and a photomultiplier as a flying-spot scanner. In instrumenting this design, a digital-to-analogue converter, an up-down counter and many other special purpose logic circuits were designed and constructed.

The scanner successfully contour traced Letraset characters, typewritten characters and handprinted characters. At the machines maximum speed, a character is completely traced in approximately 10 msec. Photographs of contour traces and the X(t) and Y(t) waveforms are included in the thesis.

Although the present system will only trace two adjacent characters, proposed modifications to the system would enable an entire line of characters to be contour-traced.

Included in the thesis are recommendations for further research on scanner design.

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I. INTRODUCTION

1.1 Purpose of Research

This thesis describes the design and construction of an optical scanner for research in machine recognition of typewritten, handprinted, and handwritten characters. An OCR system is often considered to be a concatenation of the three subsystems shown in Fig. 1-1. [1]

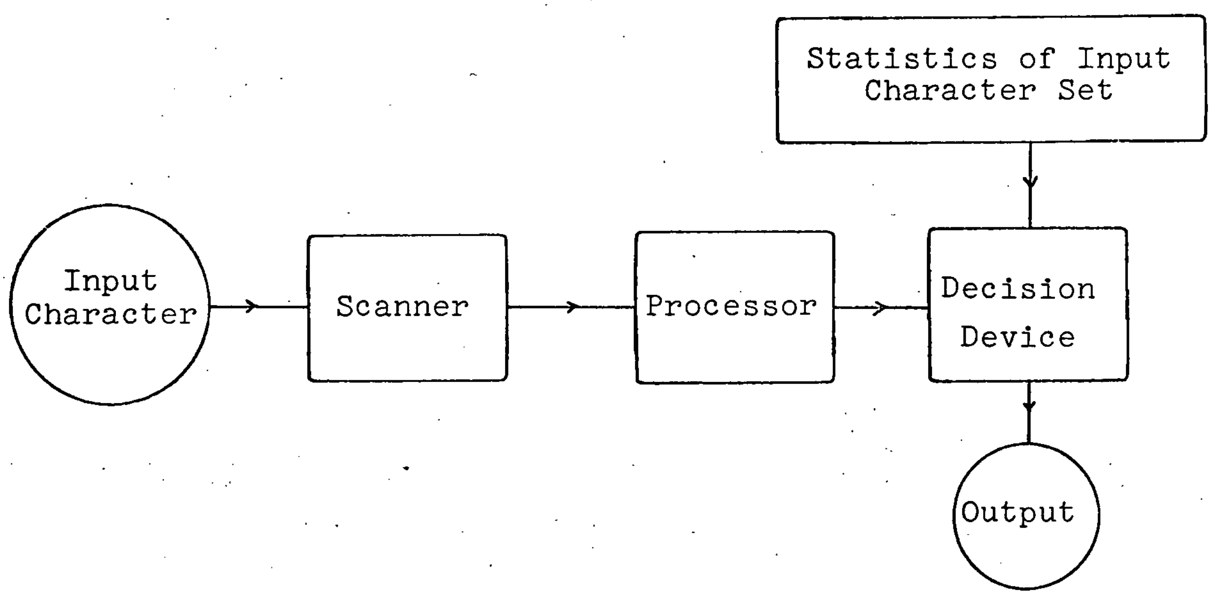


Fig. 1-1 Basic components of an OCR system.

The scanner transforms each character into electrical signals. These signals are then processed to yield a set of measurements. The decision device uses these measurements and the statistics of the input character set to identify the character. The probability of an identification error depends on the set of allowable characters, the statistics of the character set, the way in which the characters are transformed into electrical signals, the signal processing algorithm, and the decision algorithm.

An OCR machine would have many uses, some of which are:

1. A computer input device - an OCR device which could translate typewritten, handprinted or handwritten characters directly into machine language would eliminate the time consuming and costly process of key-punching programs and data.

2. A transducer for data communication - a device which could convert printed characters directly into signals for transmission to a distant point would be extremely useful.

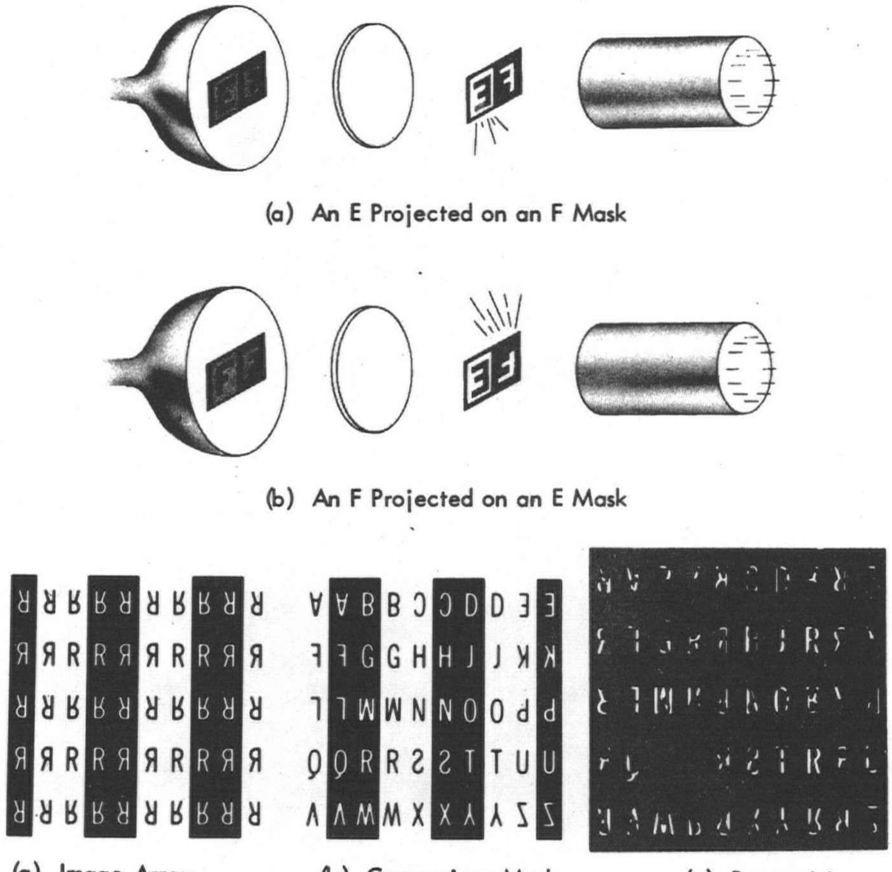
3. A sensor for machines which sort mail, packages, and other objects in accordance with identifying characters fall into this category.

4. An input for machines which transforms characters into non-visual stimuli - one such machine is a reading machine for the blind.

1.2 A Brief Review of Previous Work on OCR

Many attempts have been made to build character readers. Some of these attempts have been partially successful, although the readers are very expensive. Most machines do not recognize a letter or character in a way that depends on the characteristic shape of the letter. For this reason, they recognize only a few of the hundreds of different type fonts.

The most common technique is to make an optical or electronic image of the unknown character and compare it with either an optical or electronic mask of all characters in the machine's "vocabulary" [2,3]. The mask which most closely fits the unknown character identifies the character. Usually the masks are applied both positively and negatively, in order to check both white and black areas. Optical mask matching is illustrated in Fig. 1-2.



(a) An E Projected on an F Mask

(b) An F Projected on an E Mask

(a) Image Array (b) Comparison Mask (c) Recognition

Fig. 1-2 Optical mask matching.

In electronic mask matching, the letter is read into computer memory using a flying-spot scanner, or an array of photocells, or some other similar device. The mask matching is done in memory rather than optically. Although the electronic matching technique is much faster than the optical scheme, the two methods are equivalent in principle and have similar error probabilities. If the image size, the type font, or the orientation of the unknown character is not almost identical to the mask, then positive identification will not be made.

A variation on mask matching, N-tuple matching, was used by Liu and Shelton [4]. Each N-tuple consists of five to nine points in a prescribed spatial arrangement, and has a prescribed assignment of black and white states for each point. These N-tuples are shifted with respect to the input character so that the N-tuples are tested for a match in all discrete positions on the character. It was found that N-tuple matching would be useful in a multifont machine only if many N-tuple comparisons were made. As a result, a large, fast and expensive computer would be required.

Performance data on character recognition using contour tracing is very scarce, but most encouraging [5,6]. To indicate the range of speed, cost and flexibility that existing machines have, a set of partial specifications for some of the commercially available optical readers obtained from [2] are presented in Appendix I. The error rates were given for only two of the six machines, the Philco, and Sylvania machines. Philco and Sylvania machines both claim an error rate of .01%. As can be seen from Appendix I, these machines are very expensive.

1.3 Printing Noise

Printing noise occurs when a character is not always written or printed in exactly the same way. The most common kinds of printing noise are listed below.

1. Variations in character style - The exact appearance of each printed character depends upon the type font. For this reason, multifont recognition machines should recognize characters from their overall general shape.

2. Type size variations - General purpose OCR machines must not be sensitive to character size variations.

3. Character orientation faults - Variations in orientation occur occasionally when a character is printed with a tilt from the vertical.

4. Character registration faults - Occasionally characters appear slightly above or below the printing line.

5. Character spacing faults - Some OCR devices depend on regular character spacing for correct recognition.

Orientation, registration, spacing faults cause incorrect positioning and make machine recognition difficult.

6. Touching characters - Touching characters are troublesome for OCR machines which require the individual characters to be separated for individual recognition.

7. Broken characters - Broken characters are troublesome for most OCR machines, especially those employing contour tracing.

8. Salt and Pepper Noise - Salt and pepper noise is

caused by a lack of ink when printing. The character produced is not completely black, but is mottled black and white. Thus, indistinct boundaries result.

9. Ink run - Ink run occurs when too much ink is used in printing. Ink run alters the shape of the character contour.

The most common causes of printing noise are variations in letter style and size. The next most common causes are registration and orientation errors; these faults occur mainly in newspaper text. Character spacing in some type fonts is proportional to letter width. All other sources of printing noise occur very rarely.

The above kinds of noise are also present in handprinted characters and handwritten words. Reliable statistics on relative occurrences of the various kinds of noise are not available. Previous attempts to recognize handwriting is discussed in [7,8] . Techniques for recognition of handprinted numerals are discussed in [1] .

1.4 The Contour-Tracing Method of OCR

The limitations and high cost of existing character recognition techniques motivated the search for new ones. Recently, Clemens [5] proposed a contour-tracing scheme in which the unknown character is recognized by the shape of its outside contour. A little work with a pencil and paper shows that if any white areas of a typewritten character completely enclosed by black are blackened, the letter is still recognizable from the exterior contour which remains. This statement applies to well-formed handprinted characters, and to handwritten words made by a good writer. Clemens tested his idea by using a flying spot scanner to make a spot of light follow the black/white interface around the outside of the typewritten characters. The trace started at the extreme left point on the letter and then proceeded in a clockwise direction around the outside of the letter. This contour trace yielded the time functions X(t) and Y(t), the horizontal and vertical co-ordinates of the scanning spot (see Fig. 1-3). The origin of the co-ordinate system is the starting point of the trace.

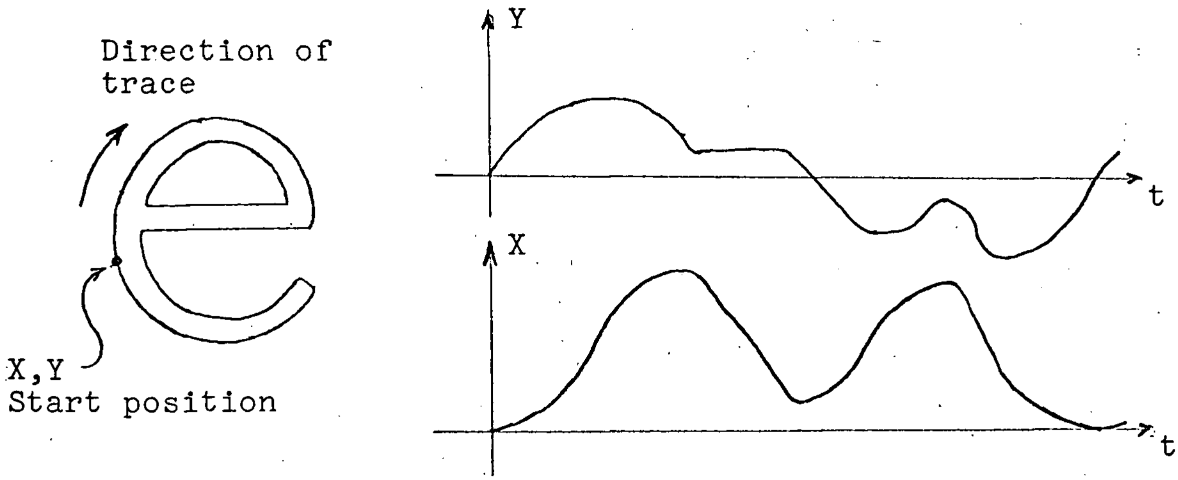
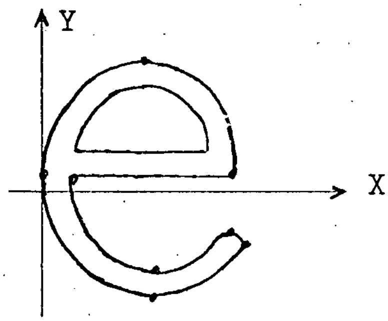


Fig. 1-3 An illustration of contour tracing.

Prominent local extrema in the X(t) and Y(t) functions result from sudden changes in contour curvature. The locations in X-Y space of these extrema are used to recognize the letters. Fig. 1-4 shows that joining the X and Y extrema by straight lines in the order in which the extrema occur yields a letter which is still recognizable. It appears that the location of prominent extrema provides sufficient information for recognition.



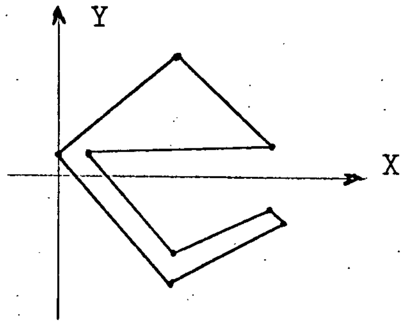


Fig. 1-4 Extrema on the contour trace.

Quantization of X(t) and Y(t), ink run, fuzzy edges and variations in type style cause spurious local extrema to appear along with the prominent extrema in X(t) and Y(t). Spurious local extrema in X(t) which result from type font variations rarely exceed W/4, where W is the letter's width. Spurious local extrema in Y(t) resulting from type font variations rarely exceed H/4, where H is the letter's height. Prominent extrema nearly always exceed W/4 and H/4. Clemens showed that spurious extrema could often be removed by hysteresis smoothing. A simple hysteresis smoothing circuit and smoothed output is shown in Fig. 1-5. The voltage E is approximately W/4, and is different for each character traced. For this reason, the character must be traced twice, the first time to measure the height and width, the second time to record the extrema of the smoothed X(t) and Y(t) functions.

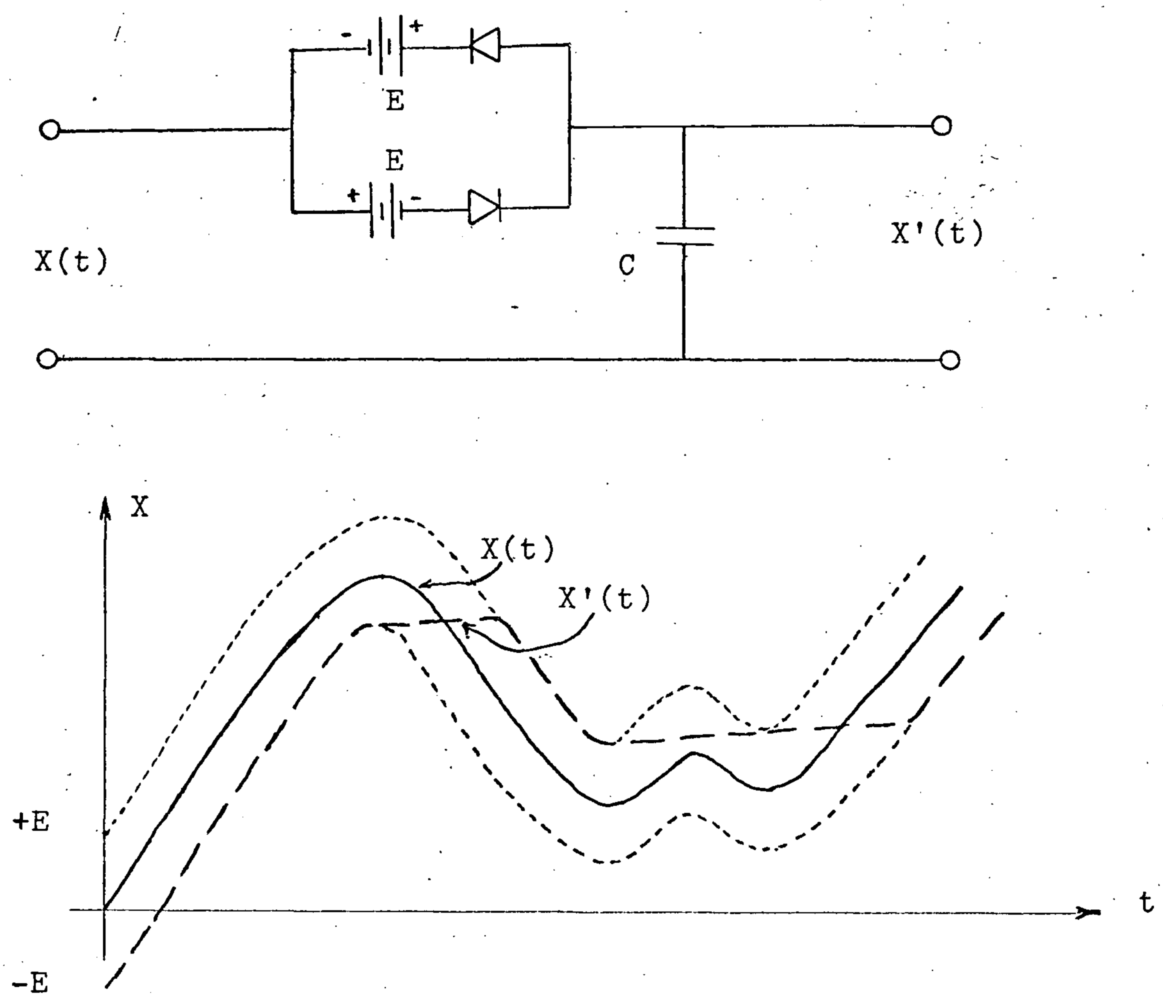
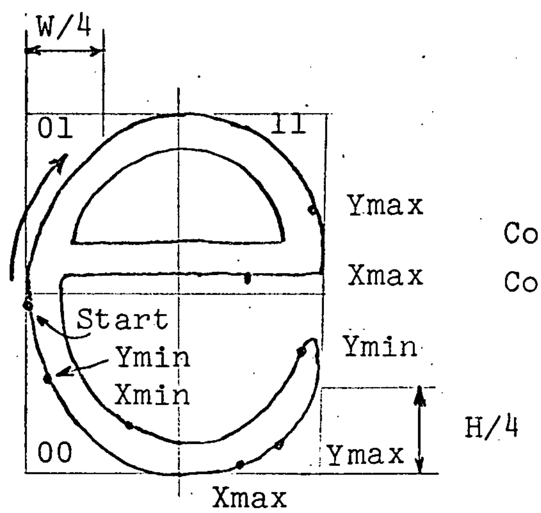


Fig. 1-5 Hysteresis smoothing.

Contour tracing with hysteresis smoothing can be made to minimize the effect of variations in character style and size. The effects of character size variations are removed by measuring the height and width. Spacing and registration errors are eliminated, since each character is located by a search scan. Clemens found that the contour tracing method of OCR is not sensitive to small character orientation faults. Touching letters can be contour traced and recognized as one character. Broken letters, however, are still troublesome. Fortunately, touching letters and broken letters occur very rarely.

Clemens' system recorded the extrema of the smoothed trace in the order in which they occurred in tracing around the letter. A little thought shows that there will always be two choices for a future extremum. Thus it was natural to use a binary number system to record the sequence of extrema. A digital one was recorded for each X extremum and a digital zero for each Y extremum. The resulting binary number was called the codeword. To indicate the locations of the various extrema, each character was divided up into four quadrants labelled 00, 01, 10 and 11. Each time an extremum was found, the quadrant in which the extremum occurred was recorded. The resulting number was called the co-ord word (co-ordinate word). An example of how the code and co-ord word are formed is given in Fig. 1-6.



Code word	1	0	1	1	0	0	1	0
Co-ord word	00	11	11	00	10	10	10	00

Fig. 1-6 Code and co-ord word formation.

Clemens used the codeword, the co-ord word and the height to width ratio, along with the table look-up facilities of a computer to recognize type-set letters. In testing his techniques, he scanned a transparency of a page of Time magazine, stored the points in a computer and simulated his contour trace. Over 3300 characters were encountered. The overall error rate was approximately 3%, including letters, and punctuation marks from both titles and text. It was predicted that had the facility for detecting ascenders and decenders been incorporated, the error rate would be approximately 1%. It was found that broken letters would be the only source of printing noise that could not be easily overcome. Some of the confusions made by the machine were among letters most easily confused by eye. For example, c and e were confused, as were i and l, r and p and B and D. Since confusions are not random substitutions of the other 25 letters of the alphabet, they can probably be reduced by some error correcting scheme.

Existing electronic components will permit tracing twice around an average letter in approximately one to two milli-seconds, assuming (conservatively) that 250 points on the contour are examined during each trace, and that examination of each point requires 1 μsec. The time quoted would allow for approximately 700 μsec to search for the next letter. Signal processing and decision making would be completed during the search for the next letter. The recognition rate would be between 500 and 1000 characters a second. Accuracy figures will not be available until various processing and decision algorithms have been investigated. The cost of the scanner is estimated at $5,000 or less. The cost of the processing and decision making part of system is estimated at $10,000.

It appears that typewritten characters can be recognized with considerable accuracy from the shape of their exterior contour alone, and the OCR system using contour tracing will be much less expensive than existing systems. More research on processing and decision algorithms is needed. In particular, algorithms should be devised which make efficient use of statistical constraints between characters. Also it seems worthwhile to try to extend Clemens' technique or a modified form of it to the recognition of handprinted characters and handwritten words.

1.5 Scope of this Thesis

The remainder of this thesis describes the design and construction of a contour-tracing scanner for an experimental OCR system. The specifications for the scanner are as follows:

1. The scanner must be able to follow the white/black interface around the outside of the characters at a high rate of speed. For a prototype machine, a tracing time for one character of 1 to 1.5 msec. would be required. For the experimental machine described in this thesis, a tracing time of 100 msec. is acceptable.

2. When the trace around one letter is complete, the scan must go into a search mode to find the next letter in

sequence.

3. The scanner must automatically go into the trace mode when the next letter is found.

4. The scanner must have enough resolution to be able to trace around characters having a wide range in size and style.

5. The scanner must be able to scan an entire line on a $8\frac{1}{2}$ inch wide paper.

6. When the scanner gets to the end of a line, it must search for the next line, return to the start of the next line, and automatically start searching for the first character.

The scanner was constructed to meet the first four specifications. The design was such that the basic scanner system would easily interconnect with the additional circuitry required to make the system trace a whole page.

II. METHODS FOR IMPLEMENTING CONTOUR TRACING

2.1 The Contour-Tracing Algorithm

Contour tracing consists of two basic scanning operations; search and trace. The search operation is used to find the leftmost point of a character. The search scan starts at a point just below the line of print and travels in a vertical direction to a point just above the line of print. If no black spot is seen, the trace is moved one increment to the right and the vertical scan is repeated. This search scan continues until the first black point is found.

The first black spot seen causes the system to switch to the trace mode. In the trace operation, a very simple contour-tracing algorithm is used to guide the trace around the outside of the character. This algorithm consists of three rules. To use these rules, the direction defined by the present point and the previously examined point is used as a reference direction.

Rule 1: If the point being examined is black, turn 90° to the left, move one increment, and test this new point.

Rule 2: If the point being examined is white, turn 90° to the right, move one increment, and test this new point.

Rule 3: If three consecutive turns in the same direction occur, turn in the opposite direction on the fourth turn.

The first two rules are essential for contour tracing a character. The third is an error correcting rule that tends to force the trace back to the black/white interface of the character if a wrong decision as to the colour of a point is made. Fig. 2-1 illustrates the contour trace.

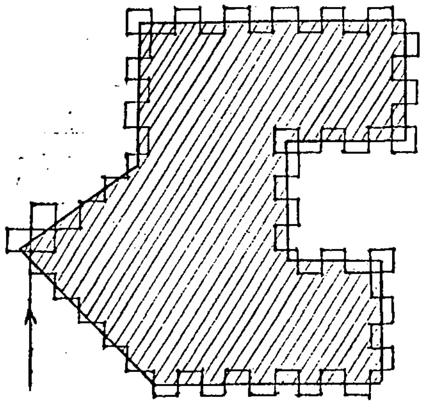


Fig. 2-1 An example of the contour-tracing algorithm.

Some thought shows that these rules cause the scanning spot to move around the outside of the character in a clockwise direction, and that the trace must hit every black spot on the character that is within one increment of the edge. It follows that the scanning spot always returns to the starting point, providing no error is made in deciding on the colour of any point.

To ensure a unique starting point for the trace, and to prevent the trace from breaking into the inside contour of letters, the line width of each character must equal or exceed two increments.

2.2 A General Contour Tracer

The general structure of four proposed contour-tracing systems to be described in the next section appears in Fig. 2-2.

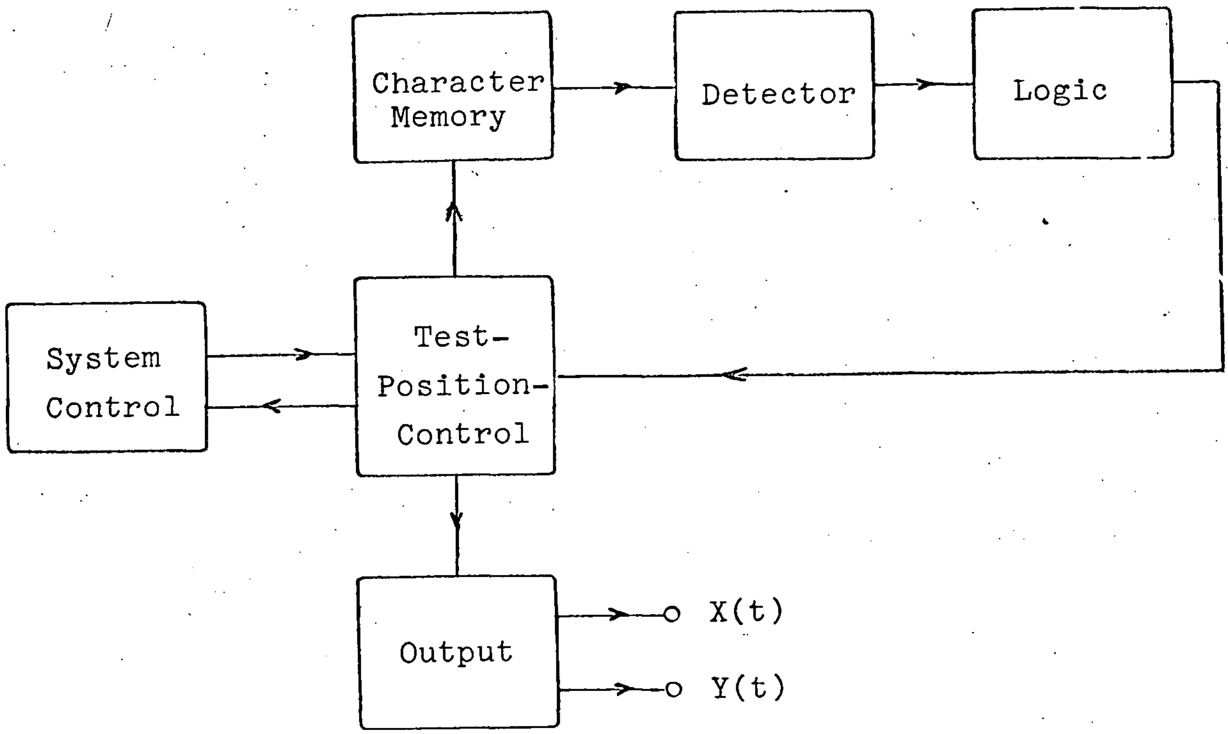


Fig. 2-2 A general contour tracer.

The shape of the character's outside contour is stored in the character memory. The character memory may be the actual printed page or a hardware memory. The location in memory to be examined is selected by the test-position-control block. The detector then ascertains whether the spot corresponding to that location is white or black. The signal from the detector is used by the logic network to calculate the co-ordinates of the next point to be examined. The test-position-control block then uses the logic block signal to select the next location to be examined. The output section of the system takes the signals from the test-position-control block and produces the two time functions, X(t) and Y(t). The main function of the system-control block is to use the signals generated by the test-position-control block to switch the system from the search to the trace mode, or from trace to search mode at the appropriate times.

2.3 Analysis of Four Proposed Contour-Tracing Scanners

In setting out to design a flexible contour-tracing scanner, many specific systems were considered. The four most promising systems are described below.

System 1: Photodiode Matrix

An optics system would be used to focus the image of the unknown character onto a two dimensional, 50 by 50, array of photodiodes (or phototransistors). This array would constitute the character memory. The test-position-control block would consist of two bi-directional shift registers, one for each axis of the array, so that any element of the array could be selected for examination by the detector. The detector would decide whether the light falling on that particular element came from a white or a black spot on the character. The logic block and the output portion of the system would function as described in Section 2.2. The output block would consist of two up-down counters and two digital-to-analogue (D/A) converters to produce X(t) and Y(t). The system-control block would have to control the repositioning of the array relative to the next character, in addition to controlling the system modes (search and trace). The time required for this mechanical repositioning would severely limit the rate at which a line of print could be scanned.

Furthermore, a 50 by 50 array of phototransistors would have to be a specially constructed item, not readily available and very expensive. As an example of the cost involved, a linear array of 126 photodiodes on 6 mil centres costs $788. [11]

System 2: Linear Photodiode Array and Core Memory

System 2 attempts to overcome the repositioning difficulty, the high cost and long delivery time inherent in System 1. In System 2, an optics system would be used to focus the printed characters onto a vertical, linear array of 50 photodiodes or phototransistors. The page would move relative to the array, and at a fixed increment in distance, the linear array would be sampled and deposited in the character memory (see Fig. 2-3).

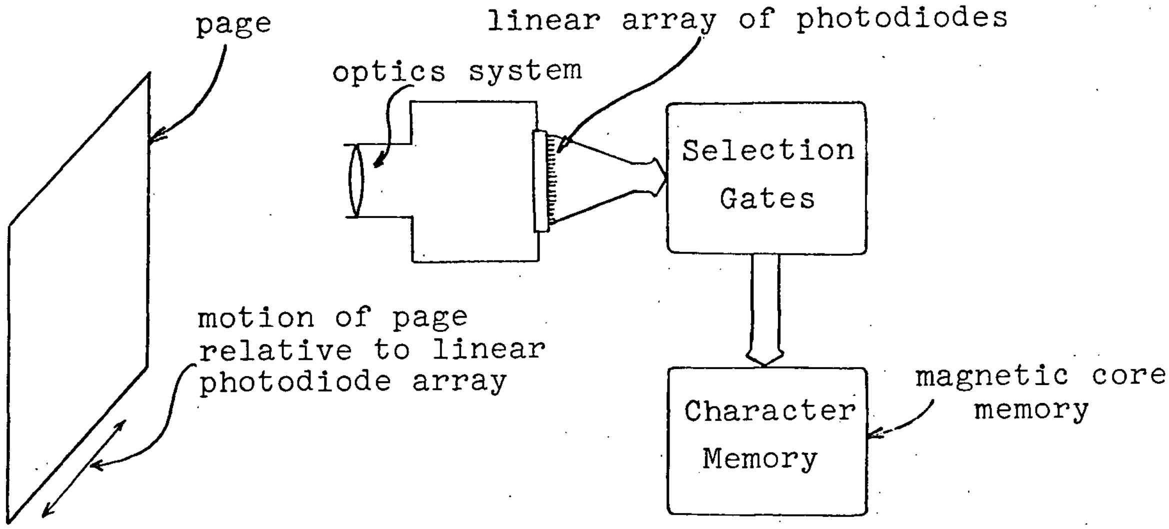


Fig. 2-3 Scanning with a linear array of photodiodes. The photodiode outputs are sampled and stored in a character memory.

The character memory would in all probability be a magnetic core array. Contour tracing would be carried out in the memory as described in Section 2.2. The detector, logic, test-position-control and output blocks would be similar to those described in System 1. If the time required to trace a character in memory is less than the time required for the photocell array to scan a character, then the memory would need to store only two complete characters and not all the characters on a line. The storing of the next character would be time shared with the tracing of the present character. The system control block would have to control the scan mode, the time sharing, and possibly the scanning rate.

System 2 has overcome the position-control problem by remapping the optical image of the character in memory. The electronic complexity of System 2 has increased over that of System 1. The cost of a core memory of 50 by 100 elements would probably be in the order of $5,000 to $6,000. This price would include core, core drivers, random access register, information register, and register indicators. This price is based on a quotation on a 256 words by 18 bits memory. [12] The delivery time would be approximately six months.

Because of the high cost and long delivery time associated with System 2, a third system was contemplated.

System 3: Oscilloscope and Photomultiplier - Discrete Scan

In System 3, the printed page becomes the character memory. The test-position-control block uses an X-Y oscilloscope as an electronically positioned light source. The signals to the oscilloscope are derived from up-down counters coupled to D/A converters. The light from the oscilloscope's cathode ray tube

(CRT) is focused onto the page by an optics system. The detector is a photomultiplier positioned to gather the light reflected from the page. The amount of light gathered determines whether or not the illuminated spot on the page is white or black. The logic block calculates the necessary co-ordinate changes as described in Section 2.2. The output signals are the X and Y oscilloscope input signals. The system control is essentially the same as described in Section 2.2.

Unfortunately, the resolving power of the CRT is not sufficient to allow any more than two characters to be traced at a time, since the optics system must reduce the size of the object by a factor of 10 (see Appendix V). In Appendix II, modifications to System 3 are proposed which will enable an entire line of print to be scanned. Another difficulty with System 3 is that there is very little light available from the CRT if good resolution is desired. Consequently, not much light will be reflected from the page.

The reasonable cost and the off-the-shelf availability of oscilloscopes and photomultipliers makes System 3 attractive. An X-Y oscilloscope costs approximately $1,500. A photomultiplier costs approximately $100.

System 4: Oscilloscope and Photomultiplier Analogue Scan

System 4 is similar to System 3 in principle, and it contains the essentially the same components, an X-Y oscilloscope and a photomultiplier. In System 4, however, the control signals to the oscilloscope are derived from two sinusoidal oscillators and two sample and hold (S & H) circuits. The oscillator frequencies are identical but their phase angles differ by $\pi/2$ radians. The output of the S & H circuits act as variable position signals for the X-Y oscilloscope. The held voltages on the two S & H circuits become the X and Y co-ordinates of the centre of the small circle produced by the two oscillators. When a transition from white to black is found, the X and Y deflection voltages are stored in the S & H circuits. The oscillators then cause the scanning spot to move in a circular arc until another white to black transition is found. At this point the S & H circuits are again triggered, and this new edge point becomes the centre of the next circle. Fig. 2-4 shows that the trace follows the outside contour of the letter.

Difficulty may be encountered in storing the analogue co-ordinates of the start position, since S & H circuits cannot hold a dc level without the voltage sagging with time.

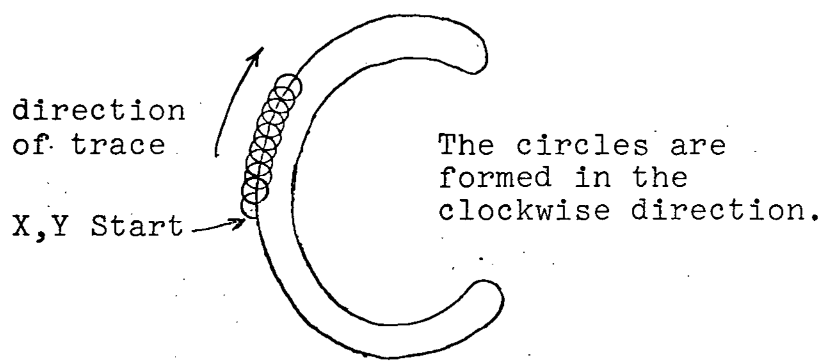


Fig. 2-4 Analogue method of contour tracing.

There is also another problem; if the above technique is adapted to tracing a line of characters, the design of the S & H becomes very difficult. A 70 space line at 40 increments per space has

2800 increments. A practical S & H will work between the limits of ± 10 volts; therefore each increment must be approximately 7 mv. The S & H voltage must be at least one order of magnitude more accurate than the smallest increment. To design an S & H circuit to operate over a range of 20 volts with an accuracy of less than 1 mv is extremely difficult.

2.4 Summary and Comparison of the Four Proposed Contour-Tracing Systems

The contour-tracing speed of System 1, which uses a two dimensional photosensitive array, is limited by the time required to mechanically position the array. Also, the array is very expensive.

System 2, which uses a magnetic core memory, should contour trace very quickly with a minimum of mechanical positioning problems. The major disadvantage is the high cost and long delivery time of core memory.

In System 3, tracing an entire line of characters and making effective use of low light levels will be the major problems to overcome. Appendix II describes two possible ways in which an entire line of characters may be contour traced. Low light levels can be tolerated if a very sensitive PM is used. Some tests, however, would have to be carried out to determine the sensitivity required. System 3 has the advantage that it may be built now, using relatively inexpensive and readily available components to scan two consecutive characters, and at a later date the system may be expanded to trace a whole line of characters.

System 4 may have a slight cost advantage over System 3, but it is not suitable for tracing an entire line of characters.

Since the X(t) and Y(t) waveforms from single characters are needed for research on recognition algorithms, System 3 was designed and built to trace two consecutive characters. The design was such that only minor modifications were required to enable the scanner to read an entire page. The cost of the system would be approximately $3,000. An additional $2,000 would be required to make the scanner read an entire line.

III. DESIGN AND INSTRUMENTATION OF THE CONTOUR-TRACING SCANNER

3.1 Captive Scan Control Circuits

The basic contour-tracing scanner consists of a Tektronix RM561A oscilloscope with two 3A75 amplifier plug-ins, a Phillips 53AVP eleven stage photomultiplier (PM), an optics system and appropriate digital control circuits. The oscilloscope's cathode ray tube (CRT) has a fast decay P16 phosphor. The phosphor decays to 10% of the original intensity 120 nsec after the excitation is removed. The basic contour-tracing system, excluding some of the control circuits, appears in block diagram form in Fig. 3-1.

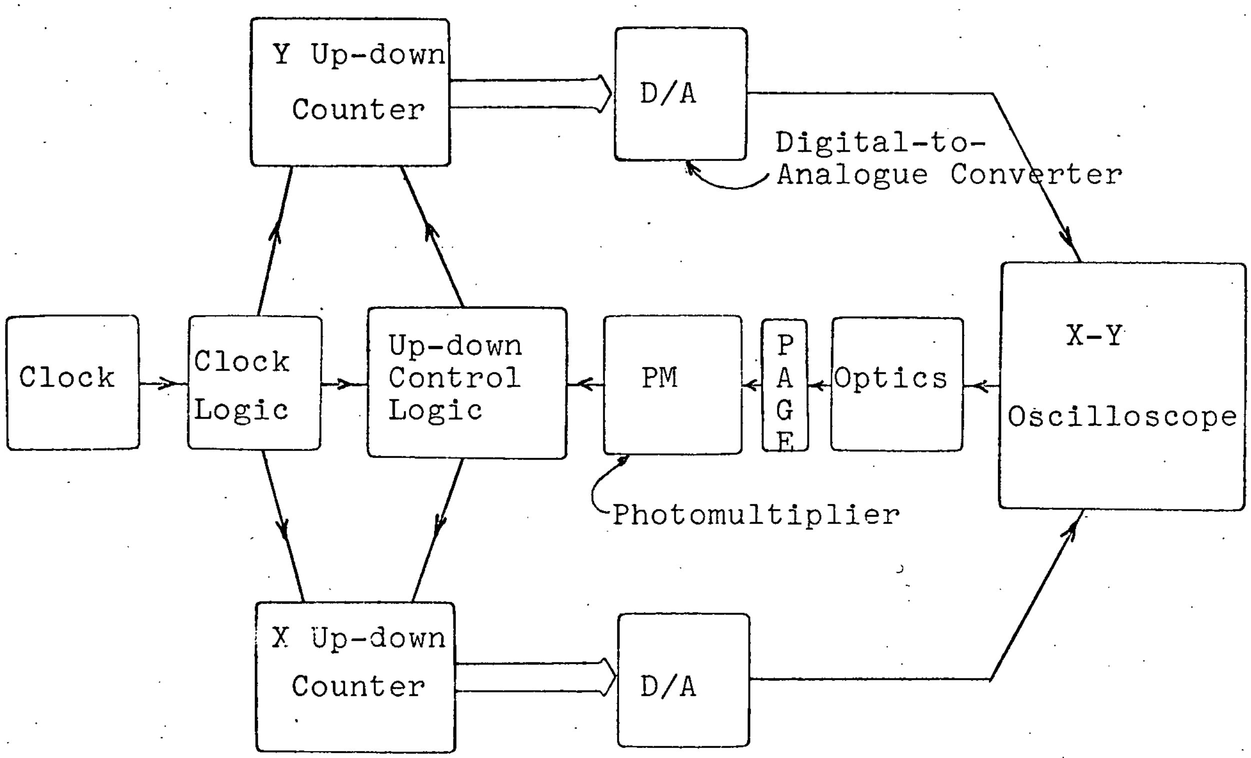


Fig. 3-1 Block diagram showing the basic parts of the contour-tracing scanner.

The X and Y counters are each six bit digital counters designed to count up or down, depending upon the digital signals applied to the counter control terminals. The D/A converters convert the six bit digital output from each counter to an analogue voltage proportional to the value of the digital number. The up-down counter and the D/A converter are discussed in detail in Appendices III and IV, respectively. The D/A converter outputs are coupled directly to the X and Y inputs of the X-Y oscilloscope.

The first two rules for contour tracing (Section 2.1) imply a short term memory, since the scanning spot needs to know the direction from which it came if it is to turn in the proper direction.

The switching functions required to implement the above rules are now derived. Let P be the digital photomultiplier signal. If the illuminated spot on the page is black, P = 0 and if the spot is white, P = 1. Let X_i and Y_i be the up-down digital control signals to the X and Y counters respectively. If X_i or Y_i is one, the respective counter counts up. Similarly, if X_i or Y_i equals zero, the respective counter counts down. Let X_{i+1} and Y_{i+1} be the new up-down signals for the X and Y counters respectively, calculated from the current values of X_i, Y_i and P. To determine Y_{i+1}, the P and X_i signals must be considered, since P represents the colour seen by the PM and X_i specifies the direction from which the trace came. Similarly, X_{i+1} is a function of P and Y_i.

The truth tables for X_{i+1} and Y_{i+1} are shown in Fig. 3-2.

Y_i	P	X_{i+1}
0	0	1
0	1	0
1	0	0
1	1	1

X_i	P	Y_{i+1}
0	0	0
0	1	1
1	0	1
1	1	0

Fig. 3-2 Truth tables for up-down logic control.

It is seen that these truth tables are consistent with the two tracing rules given above. If the symbol $\oplus$ indicates the Exclusive OR function then the truth table may be replaced by the equations

$$Y_{i+1} = X_i \oplus P$$
$$X_{i+1} = \overline{Y_i \oplus P}$$

The function $\overline{A \oplus B}$ is slightly easier to realize using NOR gates than the function $A \oplus B$. For brevity the symbol $\bar{\oplus}$ will be used to denote the complemented Exclusive OR function.

The decision to increment the counters in either the up or the down direction must be made before the counting pulse reaches the counters. For this reason, two clock pulses equally spaced from each other in time are used. These two clock pulses are called clock 1 and clock 2. Clock 1 is used to trigger alternately the X and Y counters, and clock 2 is used alternately to set the counter control terminals according to the value of P and the previous direction of travel. The circuit in Fig. 3-3 calculates the counter control signals.

After the X counter has been toggled by clock 1, X_i and P are read by the $\overline{\oplus}$ circuit and $\overline{P \oplus X_i}$ is obtained and routed to the J-K terminals of FF_y. The clock 2 pulse is gated to make FF_y assume the state determined by its J-K terminals.

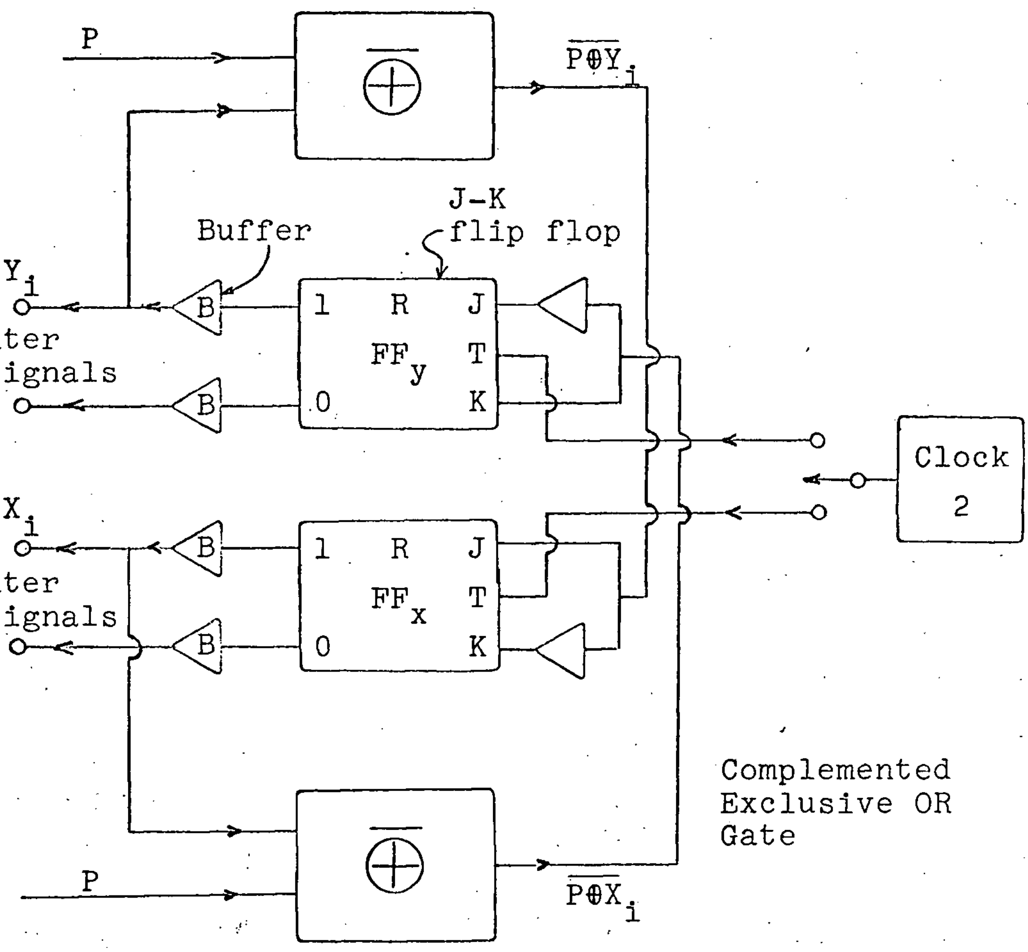


Fig. 3-3 Up-down control circuitry. The symbol $\overline{\oplus}$ denotes the complemented Exclusive OR operation.

After Buffering, the output of FF_y becomes the Y counter up-down control signals. In a similar way, the X counter up-down control signal is derived from $\overline{P \oplus Y_i}$. It should be noted that FF_x and FF_y form the short term memory necessary to remember from where the trace came. In the search mode, both FF_x and FF_y are held in the reset state, causing both the X and Y counters to count up.

The switching of clock 1 alternately to the X and Y counters must be synchronized with the switching of clock 2 alternately to FF_x and FF_y. Fig. 3-4 shows a suitable synchronizing system.

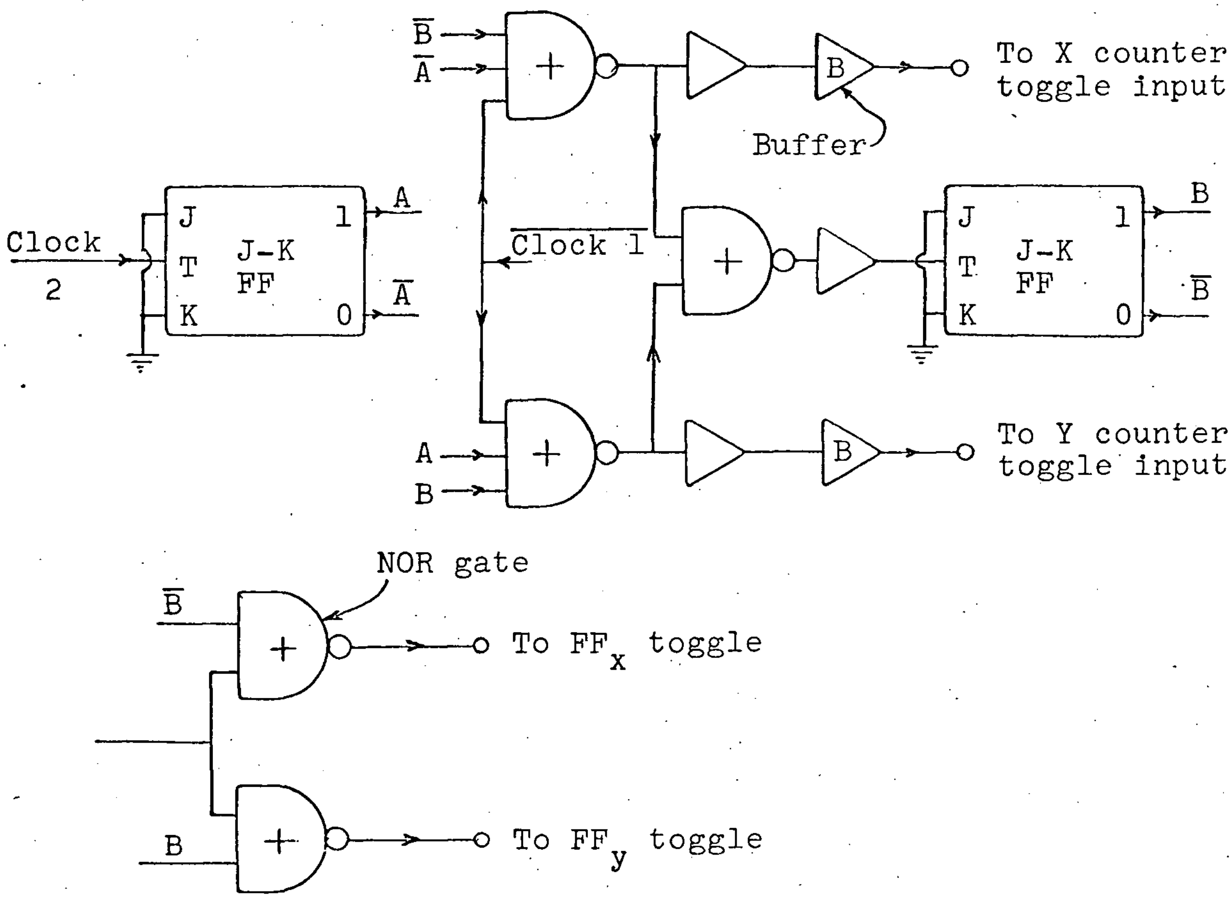


Fig. 3-4 Toggle pulse synchronization circuitry.

From Fig. 3-4 it follows that if A = B when the clock 1 pulse arrives, then the clock 1 pulses are dispatched alternately to the X and Y counters and the clock 2 pulses are dispatched alternately to FF_x and FF_y. If $A \neq B$ when the clock 1 pulse arrives, neither counter receives a pulse and thus the B signal does not change. When the next clock 2 pulse arrives, the A signal changes and the system is again synchronized.

The steering gates and the flip flops which produce the A and B signals are all contained in the block in Fig. 3-1 labelled clock logic. Additional gates are provided to inhibit the X counter pulses during the search mode in a way that produces a sequential vertical scan.

In Fig. 3-3, the $\overline{\oplus}$ gates, FF_x, FF_y, and the steering gates for directing the trigger pulses to FF_x, FF_y are all contained in the block labelled up-down logic. The clock 1 and clock 2 pulses are approximately 200 nsec wide and are produced from monostable multivibrators in the block in Fig. 3-1 labelled clock. The optics block in Fig. 3-1 is discussed in Appendix V.

3.2 System Control Circuitry

The main function of the System Control circuitry is to switch the system from the search mode to trace mode and back again at the correct times. Consider now the electronic measurements that must be made to achieve system control. The system must switch from the search to the trace mode when the leftmost portion of the character is contacted. After tracing around the character twice, the system must prepare to switch back to the search mode. Circuitry must be designed to tell the system when two successive traces have been completed, after which the search scan must again be initiated at the rightmost portion of the character. Circuitry must also be designed to detect and store Xmax (the rightmost portion of the character).

Fig. 3-5 shows circuitry which will detect each complete contour trace.

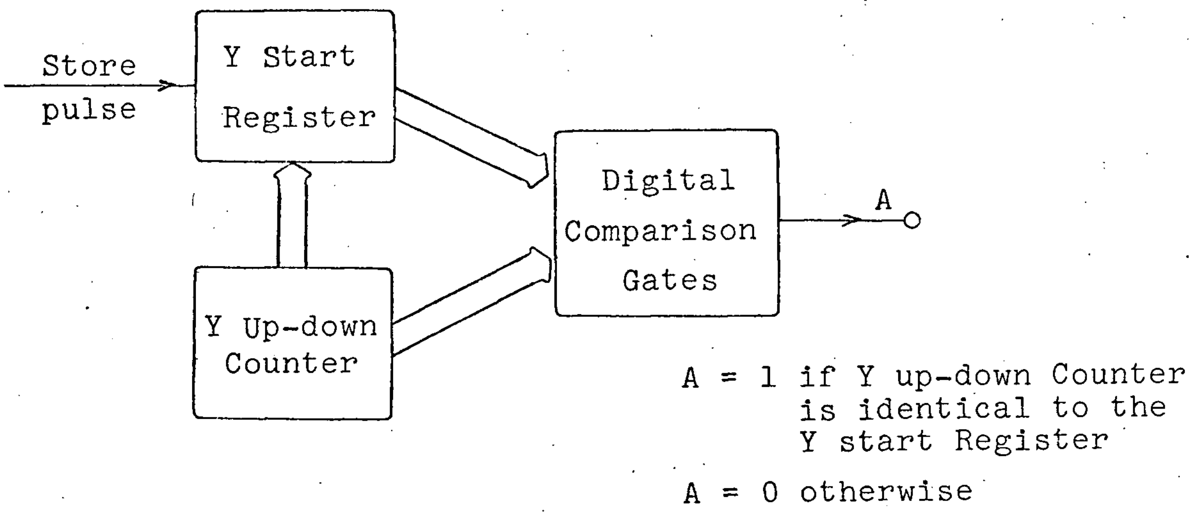


Fig. 3-5 Circuitry for determining a complete contour trace. Only the circuits for the Y co-ordinate are shown, circuits for the X co-ordinate are identical.

When the system switches from the search to the trace mode (mode 1 to 2) a pulse is applied to the toggle input terminals of the X and Y start registers causing the co-ordinates of the trace's starting position to be stored. The digital comparison gates compare the binary numbers contained in the X and Y registers and the X and Y up-down counters and indicate if the numbers are identical. Each time the X and Y counters return to the start position, a monostable multivibrator produces an output pulse. A two-bit counter counts the number of monostable pulses and after three pulses a set-reset flip flop (S-R FF) is set to indicate that two traces have been completed.

The circuitry illustrated in Fig. 3-6 is used to detect and store the Xmax co-ordinate. The Xmax counter is a six-bit up counter with its triggering pulse gated as follows. Only if the digital comparison gates indicate that the corresponding bits of the X up-down counter and the Xmax counter are identical and that the X up-down counter is to count up will the Xmax counter count up in synchronism with the X up-down counter. The result is that the Xmax counter counts up to Xmax and remains there.

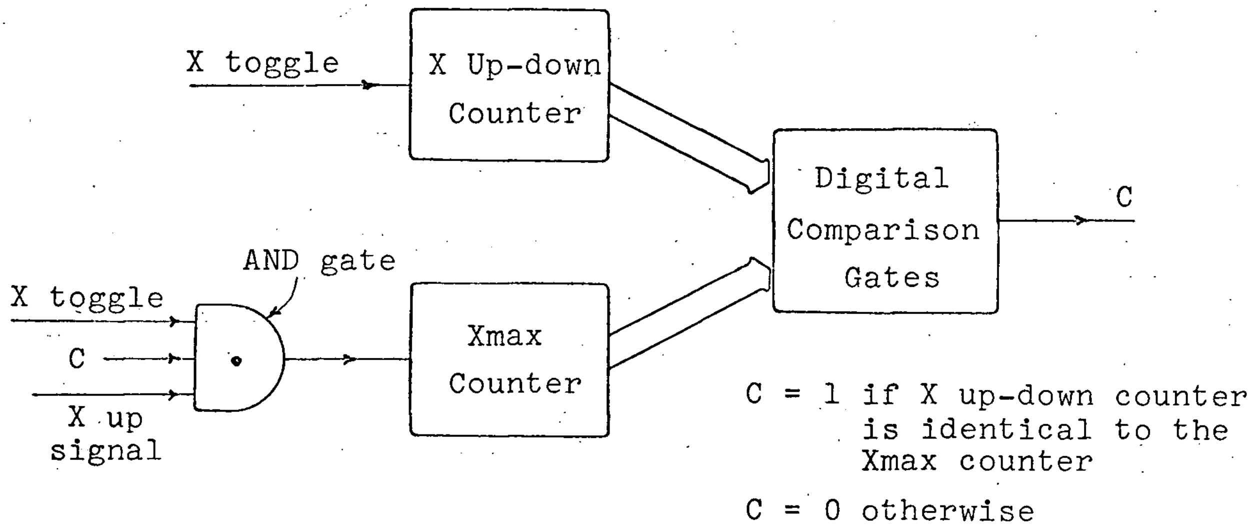


Fig. 3-6 Circuitry for storing Xmax, the rightmost point on the character being scanned.

The quickest way to proceed to Xmax after two complete traces is to jam transfer Xmax into the X up-down counter. Unfortunately, this operation complicates the circuitry associated with the up-down counter. For this reason, a much simpler, although slightly slower, method was adopted. After the second complete trace is detected, the trace is allowed to continue until Xmax is again detected at which time the system is switched back to the search mode.

The current mode (search or trace) is stored in a set-reset flip flop (S-R FF). The first black spot seen by the PM during the search mode causes the mode S-R FF to set, putting the system into the trace mode. The S-R FF cannot be reset until two traces have been completed and the count on the X up-down counter is equal to Xmax.

The system control circuitry was designed to enable the automatic controls to be replaced by external manual controls. The manual control is achieved with five toggle switches. Activating a switch merely grounds an input to a gate on a circuit card. The controls are as follows:

Stop Switch - removes the clock pulses from the system.

External/Internal Switch - selects either an internal pulse source or an external pulse source to produce the clock pulses.

Reset Switch - resets the X and Y counters.

Search Switch - Activating this switch causes the system to go into the search mode. The system is prevented from entering the trace mode by causing the system to effectively see a white PM signal.

Trace Switch - This switch causes the system to remain in the trace mode. The system is prevented from returning to the search mode by disabling the gate controlling the resetting of the mode flip flop.

3.3 Error Correction Circuits

When the above system was built and tested, it was found that the tracing spot sometimes became trapped and made four consecutive turns to either the right or left. This trap did not seem to be a result of a logic error, as the trapped trace was generally right on the edge of the character. It was postulated that the spot of light from the CRT was landing on neither a white spot nor a black spot but on an edge, and the PM had difficulty in determining the colour of the reflected light on a consistent basis. Perhaps a reason for this difficulty is hysteresis in the response of the PM. After seeing many white spots in a row, the PM will correctly detect only spots which are entirely black; a partially black spot will be called white. Thus, it is possible for the PM to initially examine a partially black spot, call it black and then proceed to three totally white spots. When the trace returns to the initial spot, it now because of hysteresis, sees the spot as being white, and the trace becomes trapped.

What is needed is the third rule in the contour-tracing algorithm (Section 2.1); after three consecutive turns in the same direction, turn in the opposite direction on the fourth turn. The operation of the circuitry required to realize this rule can be understood with the aid of Fig. 3-7.

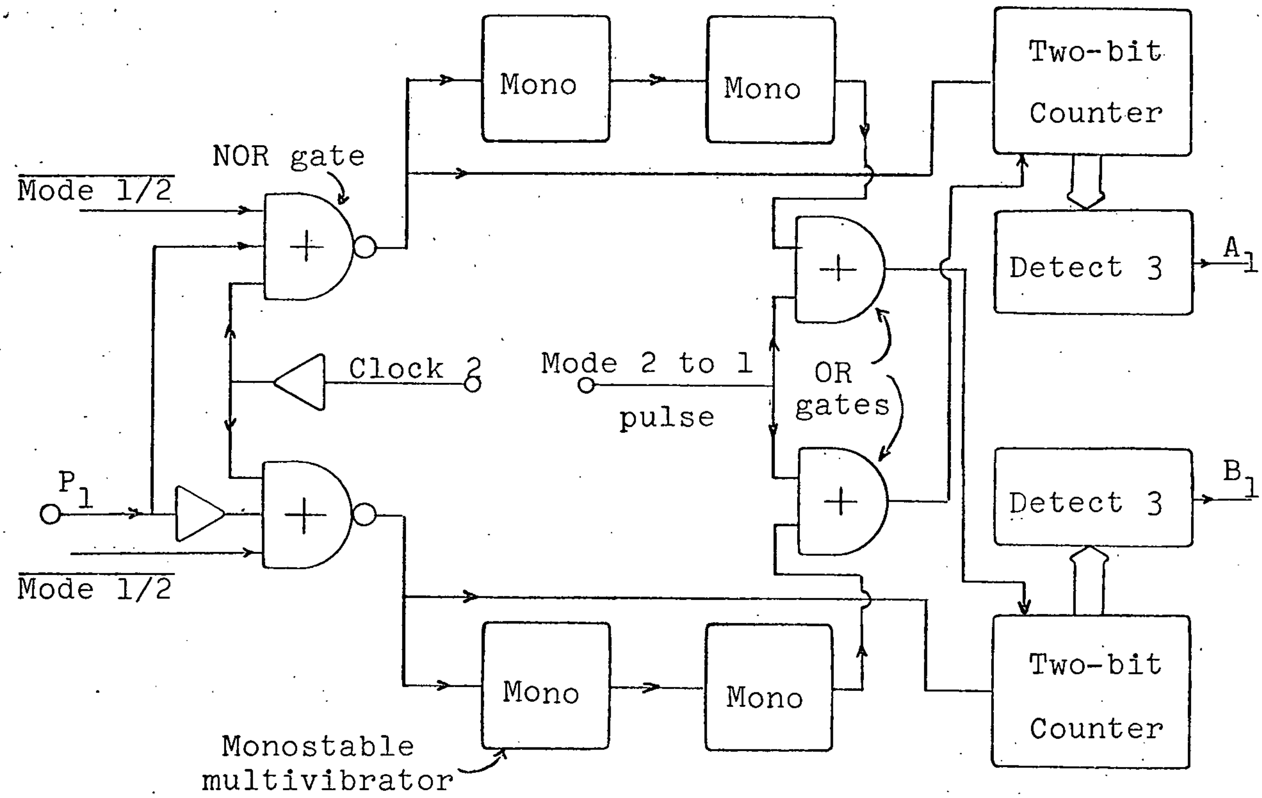


Fig. 3-7 Circuitry for counting three consecutive turns in the same direction.

Two 2-bit up counters are provided and the toggle pulses from clock 2 are gated into one of the two counters. The counter selected depends on the value of P_1 (derived from P as will be shown later). The output binary numbers from each of the two-bit counters are routed to two input NOR gates which detect the count of three. The toggle input of one counter resets the other counter via a delay monostable multivibrator. Consequently the output of one of the two input NOR gates will indicate when three consecutive turns in the same direction occur. In Fig. 3-7, $A_1 = 1$ if three consecutive left turns are made ($P_1 = 0$), and $B_1 = 1$ if three consecutive right turns are made ($P_1 = 1$). Signals A_1 and B_1 are used to modify the value of P for the fourth turn. Consider the following truth table and the corresponding circuit in Fig. 3-8.

A_1	B_1	P	P_1
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	Ø
1	1	1	Ø

$$P_1 = A_1 + \overline{B}_1 P$$

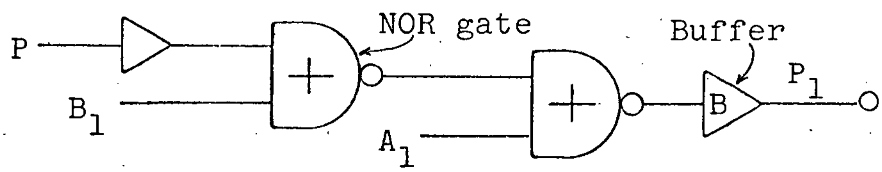


Fig. 3-8 Error correction circuitry.

From the above circuit diagram and truth table, it can be seen that if $A_1 = B_1 = 0$, $P_1 = P$, and if A_1 or $B_1 = 1$, P_1 is changed in accordance with the third contour tracing rule. The above circuit was added to the up-down logic card to modify P to P_1.

An additional problem arose in the testing of the original system. Sometimes the system would begin searching after only one complete trace around the letter or sometimes the system would become trapped in the trace mode. One possible reason for these difficulties lies in the fact that it is possible in applying the three contour tracing rules to return to the starting point without completely tracing the letter. Refer to Fig. 3-9.

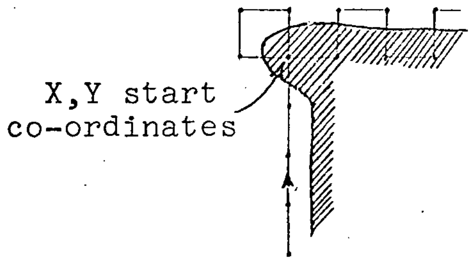


Fig. 3-9 A troublesome starting point.

In this case the counter counting the number of complete traces around the character receives an erroneous signal. Since the trace must make three consecutive turns in the same direction before it can return to its start position (or else go completely round the character), the A_1 and B_1 signals can be used to inhibit the false count signal on the start position counter. The circuit illustrated in Fig. 3-10 was added to the miscellaneous one card to achieve the error correction.

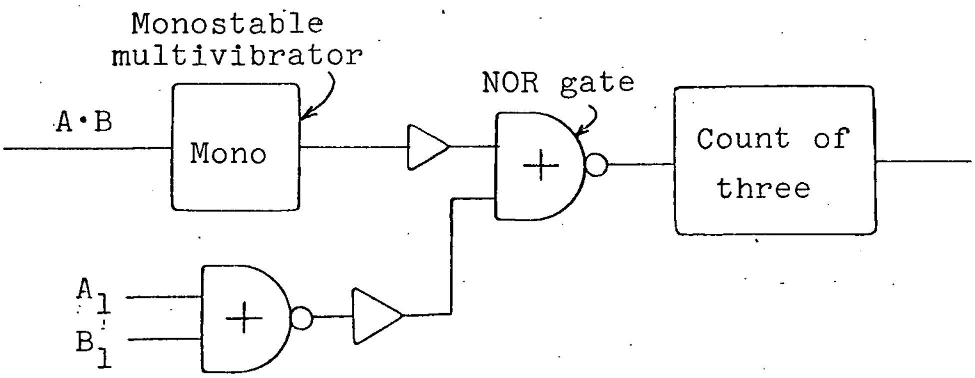


Fig. 3-10 Starting point error correction circuitry.

A block diagram of the complete contour-tracing scanner appears in Appendix VI.

IV. RESULTS OF SYSTEM TEST

4.1 A Brief Review of the System Operation

The contour tracer has two modes of operation, search and trace. In the trace mode, each of the X and Y up-down counters is triggered alternately and in such a way that the contour-tracing rules are obeyed. In the search mode, a sequential vertical scan is used to find the leftmost portion of the next character. When the first black spot is seen by the PM, the system switches from the search to the trace mode. The system can return to the search mode only after the charcter has been traced twice and the trace has returned to Xmax.

In order to determine the number of times a character has been completely traced, the X and Y co-ordinates of the start position must be stored in digital registers. Digital comparison gates are used to compare the count on the up-down counters to the values stored in the X and Y start registers so that the system knows when the starting position is again reached. A small binary counter is used to count the number of times the system returns to the start position. The Xmax register is an up counter, suitably gated so that it counts up to the maximum deviation in the X direction (Xmax) and remains there until after two character traces have been completed.

4.2 Contour-Tracing Results

Initial tests using Letraset characters indicated that the contour tracer will operate successfully at clock rates up to 200 kHz. For a clock rate of 200 kHz and a linear resolution of approximately 40 increments per character, the time required to trace twice around a character is approximately 10 ms. It was found that acceptable contour tracing could be achieved using only 20 increments per character if Letraset characters were used, but 35 to 40 increments per character were required to successfully contour trace the typewritten characters from the Hermes Ambassador electric typewriter. Increased resolution is required because the typewritten characters have very narrow line widths. Even with 40 increments per character, the close spacing of the serifs and the narrow line width made the lower case M from the Hermes typewriter difficult to trace.

The system was tested on many different characters from several sources. Exhaustive tests were not carried out on all characters in any given font, but almost all characters attempted were traced successfully. It was found that characters from a conventional typewriter using an old, conventional typewriter ribbon could not be contour traced due to poor black/white contrast on the page. Fig. 4-1 shows photographs of the oscilloscope trace for characters from a Letraset sheet (sheet 210). Also shown are the X(t) and Y(t) waveforms. To yield more detail in X(t) and Y(t) waveform pictures, only 1 complete trace around the letter is shown. In Fig. 4-2 contour traces are shown

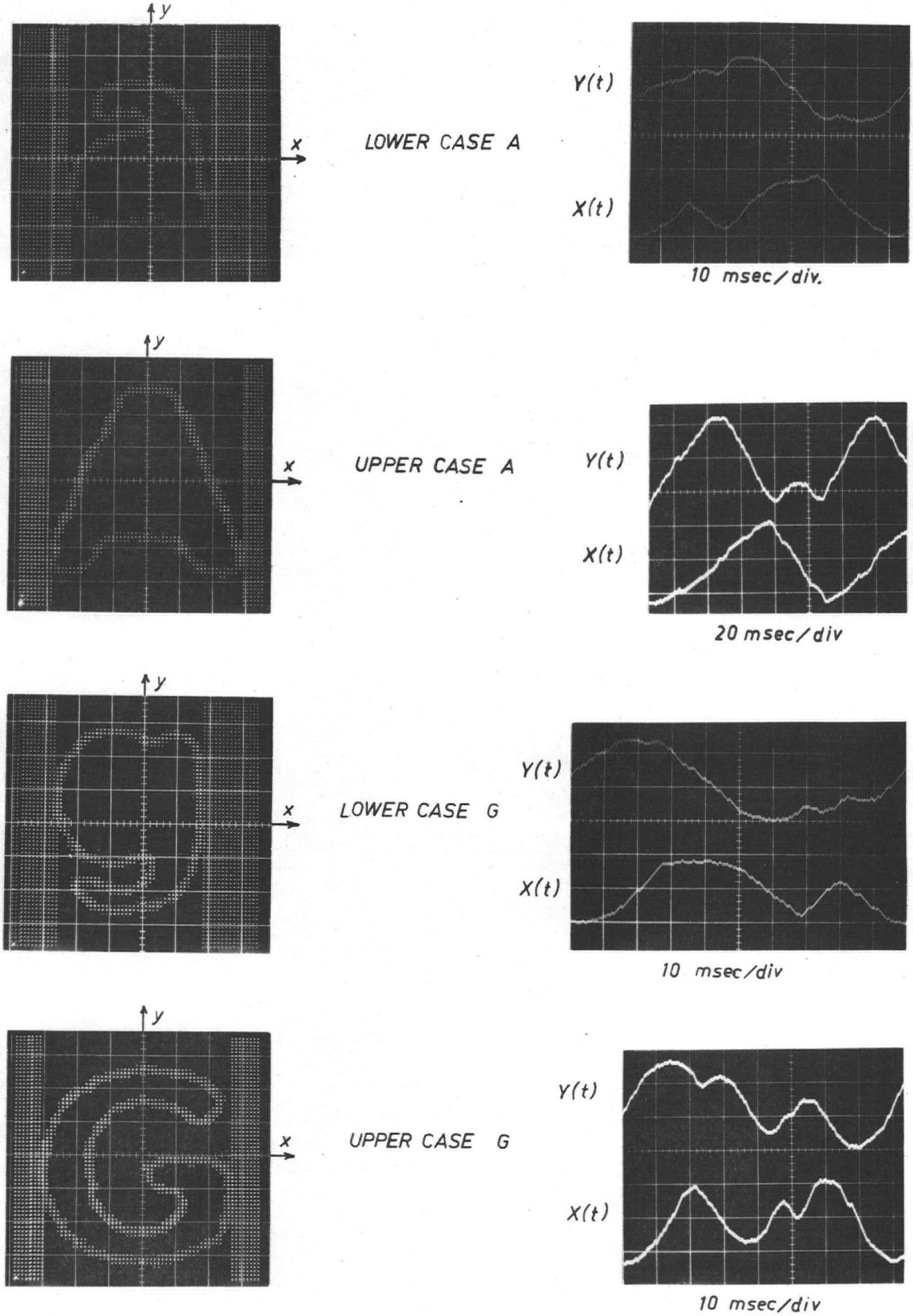


Fig. 4-1 Contour-tracing results; characters are from Letraset sheet 210.

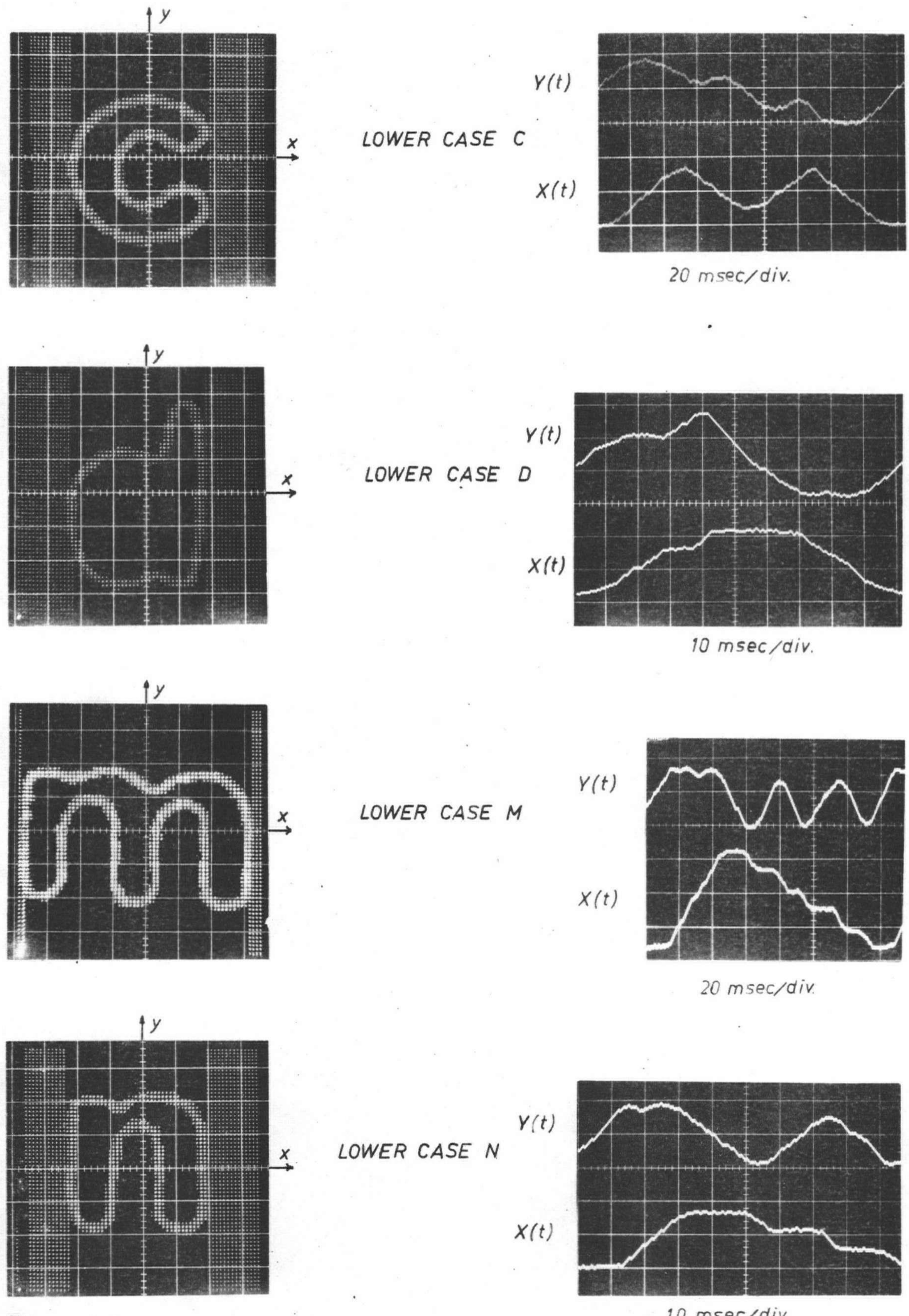


Fig. 4-1 cont'd Contour-tracing results; characters are from Letraset sheet 210.

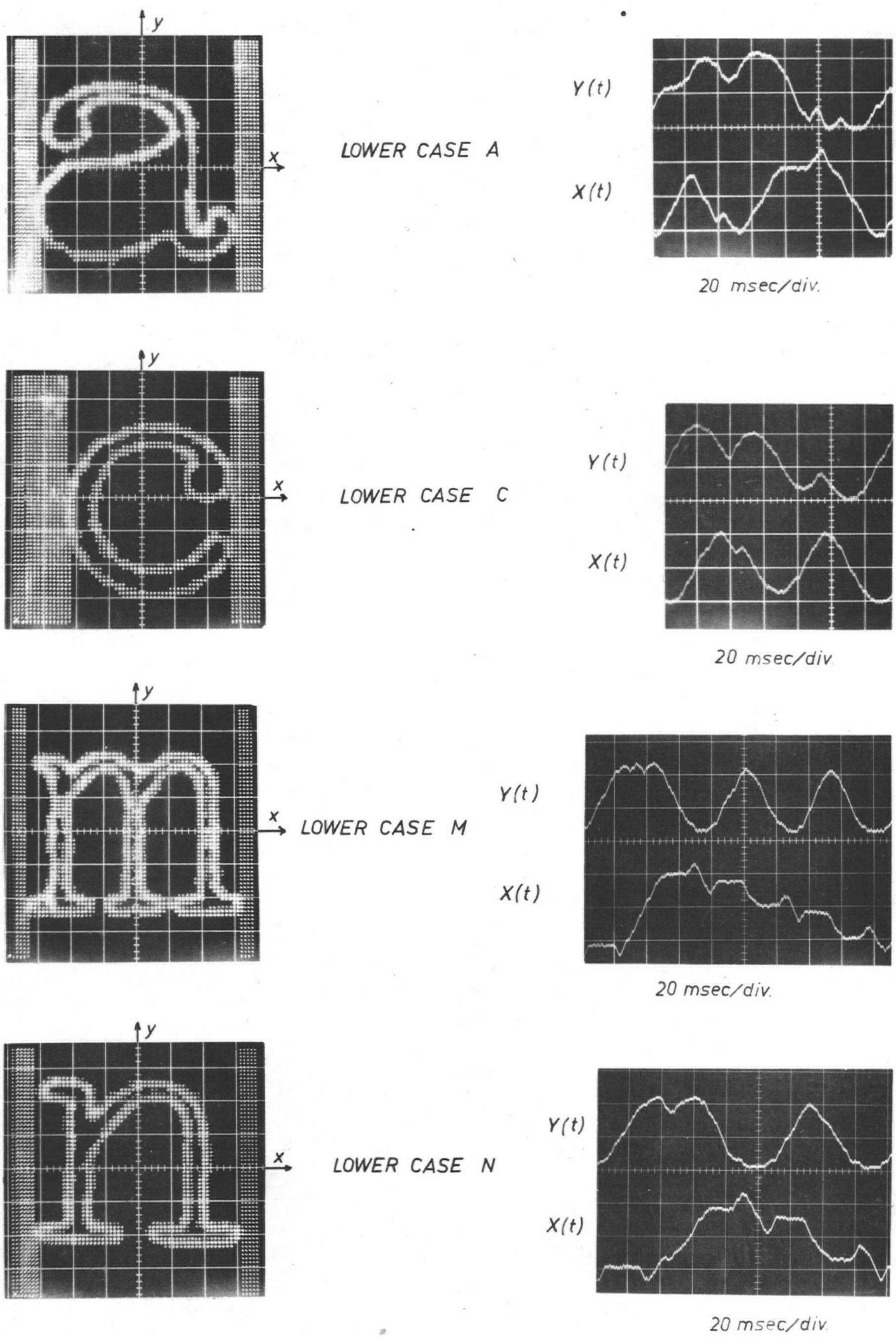


Fig. 4-2 Contour-tracing results - typewritten characters (Hermes Electric)

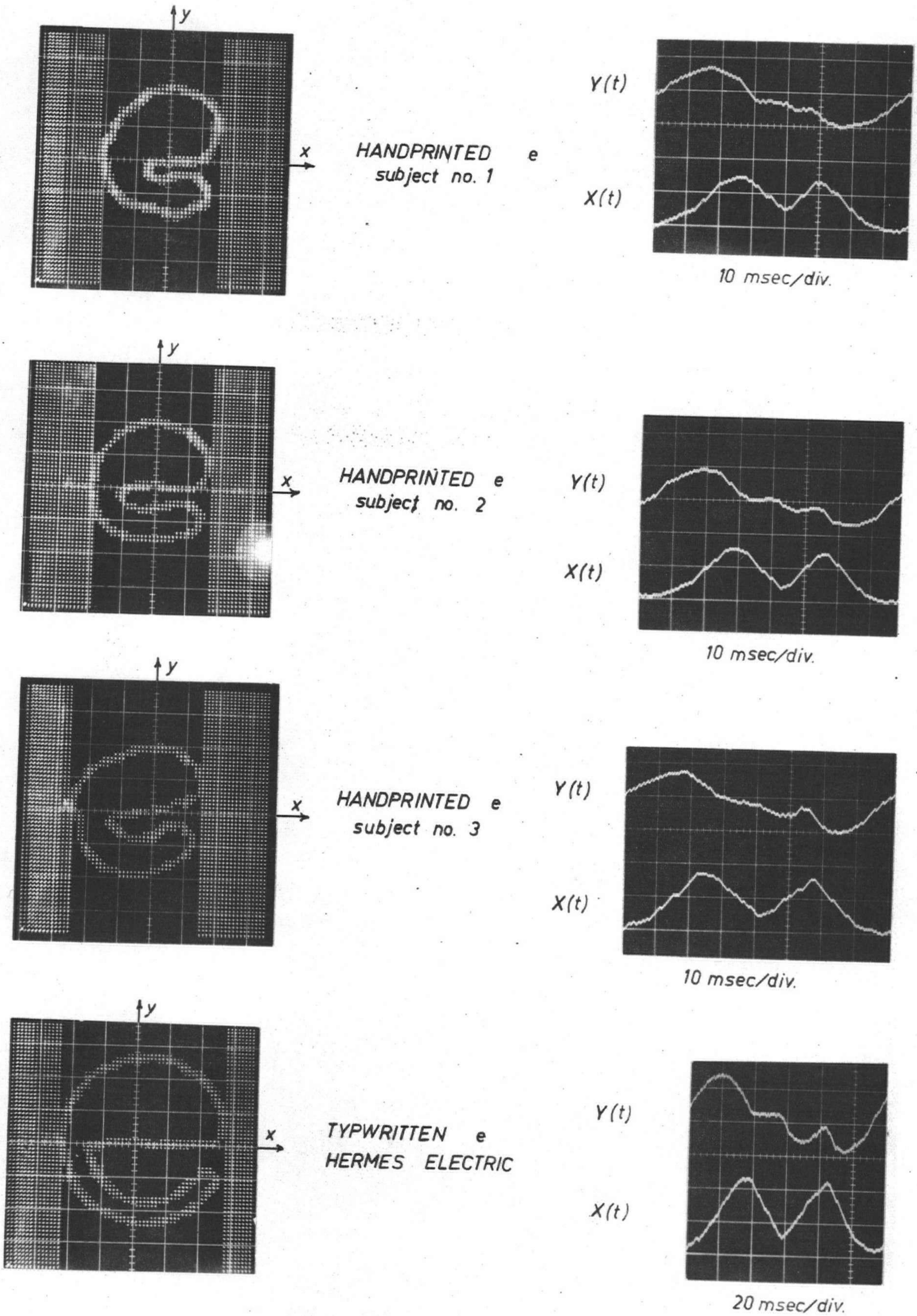


Fig. 4-3 Contour-tracing results - handprinted and typewritten characters.

for several characters from a Hermes electric typewriter along with their respective X(t) and Y(t) waveforms. The system was also tested using some handprinted characters. The results are shown in Fig. 4-3 along with a sample from the typewriter. The conditions for all the tests shown in Figs. 4-1 to 4-3 were as follows:

Clock rate:	10 kHz
X-Y oscilloscope sensitivity:	2v/div.
X(t) vertical sensitivity:	5v/div.
Y(t) vertical sensitivity:	5v/div.
Sweep rates:	as labelled

The resolution in each of Figs. 4-1 to 4-3 was approximately the same, 35 to 40 increments per character for lower case letters and approximately 50 increments per character for capital letters.

4.3 Problems Encountered in Contour Tracing

The major difficulty encountered during contour tracing was the system's tendency to become trapped in the trace mode. It was postulated that the PM would sometimes make an incorrect decision as to the colour of a point that falls on a character boundary, with the result that the trace moves away from the black/white interface by more than one increment. Rule three in the trace algorithm would then bring the trace back to within one increment of the letter edge. However, if the PM decision error is committed while the trace is in the vicinity of Xmax, then the Xmax counter may become elevated to a count that may never be reached by successive tracings of the character. If the PM decision error is made at the beginning of a character, the X and Y co-ordinates that are stored to represent the start position, may never be returned to in subsequent tracings of the character.

In order to test the hypothesis that faulty signals from the PM cause the system to become trapped in the trace mode, the PM and the optical system were disconnected from the system and were simulated by a PDP-9 computer. A capital letter N was drawn graphically, and the correct PM output signals were determined by hand and stored in 143 eighteen bit words in the computer. The computer program caused the stored PM information to be delivered sequentially to the contour-tracing electronics system. The purpose of the simulation was to test the electronics portion of the system; if this portion were not performing according to design, the system would not respond correctly to the computerized PM signals. Correct response of the electronics system to the computer signals would indicate that contour-tracing errors are caused by inadequate optical resolution and/or PM decision errors. Fig. 4-4 shows a photograph of the contour trace with results from the computerized PM signals. A photograph of a contour trace made by the actual system which uses the PM and optical system appears in Fig. 4-5. It is seen that the trace made by the computer simulated PM signals is never any wider than two increments, whereas the regular contour trace in Fig. 4-5 is, for the most part, three increments wide and in places four increments wide. It is apparent that the electronic circuitry is performing

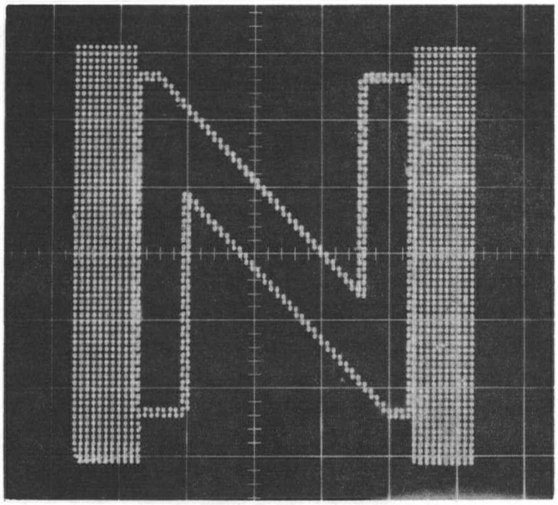


Fig. 4-4 Contour trace of an upper case N using a PDP-9 computer.

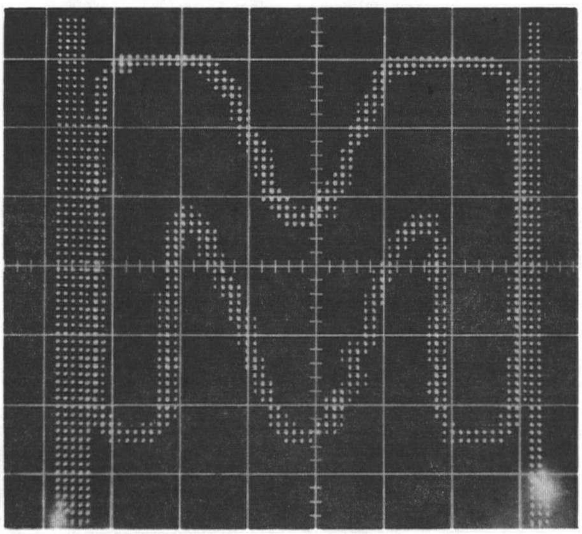


Fig. 4-5 Upper case M contour trace from a Letraset 210 sheet.

as designed and that the optics and PM portion of the system causes the tracing errors.

There are several solutions to the above problem, some of which are listed below.

1. If a high quality flying-spot scanner were used instead of the oscilloscope, then a much smaller spot size could be expected. [13] A smaller spot size would decrease the probability of the spot landing on an edge and would be expected to increase the system resolution. This solution could be very expensive.

2. The character could be re-mapped into a magnetic core memory. The contour tracing would be done on the stored image, as described in connection with System 2 in Chapter II. Since the character image in memory is constant, there would be no difficulty in returning to the start position or to Xmax. This solution is very similar to system design number 2 discussed in Chapter II.

4.4 Suggestions for Further Work

For research into various algorithms for character recognition, the present contour-tracing scanner can be used with a tape recorder to provide the X(t) and Y(t) signals for computer analysis. A prototype contour tracing machine must not however be prone to getting trapped in a character trace. Of the two solutions proposed in Section 4.3, the second seems most practical. Consider the advantages inherent in a system similar to System 2 discussed in Chapter II.

1. The system could operate in daylight.

2. Remapping the character into memory would eliminate the problem of inconsistently reading the colour of the examined spot.

3. Decision operations could be made very quickly in core memory (1 μsec or less).

4. In comparison with the other contour-tracer designs, System 2 would present only minor problems in contour tracing a complete line of characters. The mechanical positioning problems inherent in the other three designs have been exchanged for increased electronic complexity in System 2. Increased electronic complexity can be handled relatively inexpensively and efficiently with commercially available magnetic core memories and digital integrated circuits.

Further investigation into the design of System 2 would reveal the design specifications, the approximate cost and the expected instrumentation problems. To improve the performance of the existing system, further research into specifications and cost of a better flying-spot scanner would be needed.

APPENDIX I

COMPARISON OF SOME COMMERCIALLY AVAILABLE OCR MACHINES

Compiled by Robert A. Wilson,
3005 Fairmount Street, Dallas, Texas 75201

MANUFACTURER, and NAME AND MODEL NO. OF MACHINE → / CHARACTERISTICS ↓	FARRINGTON OPTICAL SCANNER, MODEL 1P	IBM 1428 ALPHAMERIC CHARACTER READER, MODEL 3	PHILCO GENERAL PURPOSE PRINT READER	CONTROL DATA 915 PAGE READER, RABINOW ELECTRONICS	RECOGNITION EQUIPMENT, INC. ELECTRONIC RETINA [7] CHARACTER READER	SYLVANIA ELECTRONIC SYSTEMS DIV [5] UNIVERSAL PAGE READER	REMARKS
GENERAL DATA	///////////	///////////	///////////	///////////	///////////	///////////	
Scanning method employed	Stroke anal.	Rotating disk	Flying spot	Column of photocells	Retina of photocells	Flying spot	
Core memory built-in? (1 K = 1,000 characters)	No core	No. See note 1	Yes. 4K & up	No. See note 1	Yes. 8 to 64K	Not known	*One "K" = 1,000 characters
Compatibility with other computer systems	Yes. General	No. IBM only	Yes. General	No. CDC only	Yes. General	Yes. General	
Delivery time from date of order	1 yr	6 mo	1 yr	6 mo	1 yr	Not known	
INPUT MEDIUMS OTHER THAN REGULAR PRINTED PAGES	///////////	///////////	///////////	///////////	///////////	///////////	
Microfilm option	No	No	No	No	Yes	Yes	
Preprinted form pages	Yes	Yes	Yes	Yes	Yes	Yes	
PRINT-READING ABILITY (VOCABULARY)	///////////	///////////	///////////	///////////	///////////	///////////	
Standard letterpress fonts	No	No	No	No	Yes	Yes	
Standard typewriter fonts	No	No	Yes	No	Yes	Yes	
Special stylized (OCR) fonts only, and kind	Farr.Selfchek	IBM font only	Not limited	OCR only	Not limited	Not limited	
Computer lineprinter print	Yes*	Yes*	Yes	No	Yes	Yes	*When equipped with special OCR font.
Capitals only, or caps. & lower case (l.c.) intermixed	Caps. only	Caps. only	Caps. & l.c.	Caps. only	Caps & l.c.	Caps & l.c.	
Mark sensing (manual marking) available	Yes	Yes	Yes	Yes	Yes	Yes	
No. of alphanumeric characters in vocabulary	60	42	Up to 10 typewriter fonts	Approx. 50	Unlimited*	Unlimited*	*But prototype character patterns must be stored in correlation circuitry.
PAPER SIZES HANDLED	///////////	///////////	///////////	///////////	///////////	///////////	
Maximum page or document (D) size, in inches	13 X 8.5	4 7/3 x8 3/4D	11 X 8.5	12 X 14	14 X 14	11 X 8.5	
Minimum page or document (D) size, in inches	4.5 X 5	2-1/3 X 3 D[2]	3 X 5	4 X 2-1/2	3-1/4 X 4-7/8	Not known	
Can sizes be intermixed, within reasonable limits?	Yes	No	Yes	Not known	Yes	Yes	
SCANNING SPEEDS	///////////	///////////	///////////	///////////	///////////	///////////	
No. of characters per second (cps)	250	480 (max)	Up to 2000	370	2400 max	2200 max	
No. of lines scanned per second on one page*	5	2	Not known	2.7	approx. 12	Not known	*Depends on no. of characters in line.
No. of full text pages read per minute*	Not known	Does not read full page	Up to 20	5.5	12 to 30	Not known	*Depending on amount of print on page.
OUTPUT MEDIUMS AVAILABLE	///////////	///////////	///////////	///////////	///////////	///////////	
Magnetic tape (the usual output medium)	Yes	Yes	Yes	Yes	Yes	Yes	
Punchcards	Yes	Yes	Yes	Yes	Yes	No	
Punched paper tape	Yes	Yes	Yes	Yes	Yes	Yes	
Typewriter	No	Yes	Yes	Yes	Yes	Yes	
Teletype or comparable data transmission device	Yes	Yes	Yes	Yes	Yes	Not known	
REJECT HANDLING	///////////	///////////	///////////	///////////	///////////	///////////	
Operator can handle on-line	No	No	Yes	Yes	No	Yes [6]	
Reject pages (1)marked, (2)offset, (3)separately stacked	1, 2	1, 2	1, 3	1, 3	1, 2, 3,	3.See note 6	
PRICES FOR BASIC SYSTEM	///////////	///////////	///////////	///////////	///////////	///////////	
Purchase, including 1 yr maintenance charge	$156,000	$164,000	$525,000	$132,000 [4]	$455,000	Not known	
Lease, monthly rental (includes maintenance charge)	4,235	3,475	14,000	3,500	13,500	Not known	
CAN INSTRUCTIONS BE STORED IN OPTICALLY READABLE FORM?	No	No	Yes [3]	No	No	Yes	

FOOTNOTES

1. This machine has no built-in core memory of its own, but uses the core storage of the computer to which it is attached.
2. For example, stubs from punchcard utility bills or gasoline credit card statements
3. By Philco Auto-Load, using pre-printed forms on which instructions may be coded in binary form with a pen.
4. Includes magnetic tape unit, but no maintenance charges.
5. Not yet sold commercially. It is understood that a prototype machine with the above-listed characteristics has been built and tested in plant, with primary application being the scanning of technical journals for mechanized information retrieval and machine translation purposes.
6. Unreadable characters are displayed in their immediate context on a viewing scope for manual correction via a console typewriter.

"Electronic Retina" is a registered trademark of Recognition Equipment, Inc.

APPENDIX II

MODIFICATIONS REQUIRED TO TRACE AN ENTIRE LINE OF CHARACTERS

A 2.1 Analogue Method of Tracing a Full Line of Characters

Because of the limited resolution of the oscilloscope CRT, no more than one or two characters can be traced at a time using the photomultiplier-oscilloscope design. A modification to the design has been developed to enable a whole line of characters to be traced. In this modification, a signal proportional to the average horizontal position of the trace on the page is subtracted from the horizontal trace signal, and the difference signal is displayed on the CRT. Since the average position signal is subtracted from the trace signal, the CRT need only be wide enough to display the contour of one character.

Consider that the page containing the line of characters to be traced is mounted on a moveable carriage, and let the horizontal position of the carriage be denoted by X_c. Let $V_c = K_cX_c$ be the output voltage from a linear potentiometer mechanically coupled to the carriage, where K_c is a constant of proportionality. If AV_T is the analogue voltage proportional to the digital number V_T on the X-axis up-down counter, then the deflection signal to the CRT can be written as follows.

$$X_s = K_s(AV_T - K_cX_c) \qquad \text{A 2.1}$$

Where K_s is a constant of proportionality. The subtraction is effected in a differential amplifier. If V_T is considered fixed and X_c is allowed to vary by ΔX_c, then the change ΔX_s, in X_s is

$$\Delta X_s = -K_s K_c \Delta X_c. \qquad \text{A 2.2}$$

A change in ΔX_s in spot position on the CRT face causes the image of the spot to move a distance of $\Delta X_c'$ where

$$\Delta X_c' = m \Delta X_s \qquad \text{A 2.3}$$

The constant m is the magnification of the optical system. For proper operation, the CRT spot must track the carriage motion, thus $\Delta X_c' = \Delta X_c$. Therefore,

$$-\frac{1}{m} = K_s K_c \qquad \text{A 2.4}$$

To trace a line of 70 characters at 40 increments per character, a 12 bit up-down counter is required. The maximum useable CRT screen width is 6 cm and the required optical magnification, m is -.1 (see Appendix V). A practical D/A converter output range is ± 10 volts. If 100 increments are desired in a 6 cm deflection, then the constants in equation A 2.1 are as follows:

$$A = .0049 \text{ volts/increment}$$

$$K_s = 12.25 \text{ cm/volt}$$

$$K_c = .815 \text{ volts/cm.}$$

There are several instrumentation problems associated with this system. Each increment in tracing voltage is approximately

5 mv, and the position of the carriage must be measured an order of magnitude more accurately than a tracing increment. Consequently, two voltages each with a magnitude of approximately 10 volts must be subtracted accurately to 500 μv. Thus a common-mode rejection ratio of 20,000 is required. A Tektronix type 3A3 differential amplifier plug-in will satisfy these specifications up to 100 kHz. The output of the D/A converter and the potentiometer must have very little noise, since the oscilloscope deflection signals are very small. The potentiometer must, of course, be a very linear function of horizontal carriage position. A 12 bit D/A converter may be difficult to build and keep tuned since the current dividing resistors must be very accurate.

It should be noted from equation A 2.4 that a change in the optical magnification, m, requires that the product $K_s \cdot X_c$ be changed accordingly. Since K_c is proportional to the voltage across the carriage position potentiometer, it is easily adjusted.

A 2.2 Digital Method of Tracing a Full Line of Characters

If the above system proves to be unsatisfactory, it can be modified to overcome some of the difficulties mentioned above. Instead of subtracting two analogue signals in a differential amplifier, the carriage position could be digitized using a linear encoder. The two digital signals V_T and X_c would then be subtracted digitally. The carriage position should be digitized to 15 or 16 bits, since X_c must be known more accurately than a tracing increment. The result of the subtraction operation would be a 9 or 10 bit number which would be converted to an analogue deflection signal.

The digital subtraction has removed the problems associated with the differential amplifier. Also the D/A converter requirements have been reduced to 10 bits from 12. The digital subtractor has also eliminated the problem of low signal levels. If operation is desired over a large range of optical magnification, m, the digital number, X_c, representing the carriage position must be scaled if the oscilloscope deflection is to track the carriage motion. This scaling can be achieved by mechanically scaling the linear encoder or by digital multiplication of the binary number corresponding to the carriage position by a digital scale factor. For small changes in m, tracking can be achieved by adjusting K_s.

The analogue method for tracing a full line of characters would cost $1000 to $1200, the main cost being for the differential amplifier. The digital version would cost between $3000 and $4000, the main cost being for the linear encoder.

APPENDIX III UP-DOWN COUNTER

The up-down counters used in the contour-tracing scanner are parallel counters. The term parallel is used because all of the flip flops are triggered simultaneously. The main advantage of a parallel counter over a ripple counter is in the speed of operation. An up-down ripple counter has a propagation time of approximately 60 nsec per bit, whereas a parallel up-down counter has an overall delay of only 15 to 20 nsec (the time required to complement a J-K flip flop).

The decision to complement an individual flip flop in a parallel up counter is made by negative logic "AND" gates whose outputs are connected to its J and K (set and reset) terminals. Consider the following binary sequence for counting pulses in Fig. A3-1.

Pulse Number	Binary Number
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

Fig. A3-1 Up-counting sequence.

It will be noticed that the least significant bit (LSB) complements each time a pulse arrives. The other bits complement on the pulse immediately following the time when all the bits of lesser significance are all digital ones. Fig. A3-2 shows a parallel up counter.

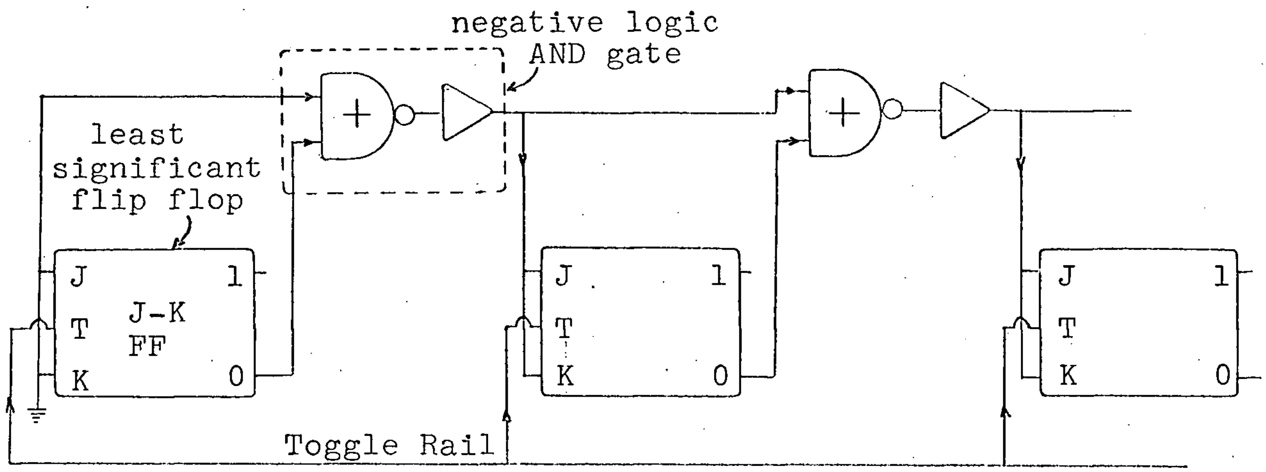
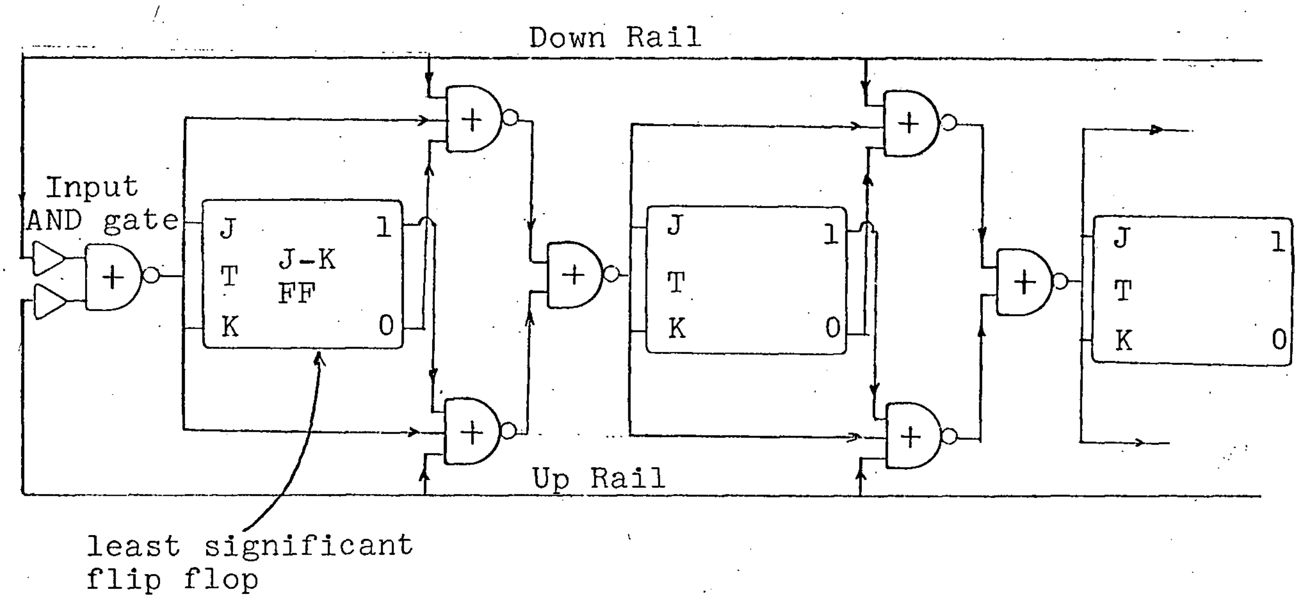


Fig. A3-2 Parallel up counter.

The negative logic AND gates are used to detect one states of lesser significance. Since the AND gates detect 0's rather than 1's, the complement of the flip flop state is used as an input. The output of each AND gate is connected to the J-K terminals of the flip flop corresponding to the next most significant bit and to the input of the next AND gate. Since a J-K flip flop only complements when both the J and K terminals are at zero, a given flip flop is complemented only when all the flip flops of lesser significance are in the one state.

A down counter results if a decision is made to complement a flip flop if all the flip flops of lesser significance are in the zero state. To make an up-down counter, a symetrically similar set of gates is added to detect the occurrence of lesser significant zeros. Selection of either the count up or count down function is accomplished by providing signals to disable either the up-count or the down-count gates as shown in Fig. A3-3.

In the contour-tracing scanner, there was no requirement for the up-down counter to have a disabled mode. For this reason the input AND gate on the least significant flip flop was not included on the counter cards. When the counter was built and tested, it was found that there was a propagation time of approximately 100 nsec through each stage of gating. To reduce this propagation time, the two input NOR gates used to drive the J-K terminals of the flip flops in Fig. A3-3 were built from discrete components in order that speed-up capacitors could be used. The effect of speed-up capacitors was to reduce the propagation time to approximately 30 to 40 nsec per stage.



Up rail = 1 Down rail = 0		counter counts up
Up rail = 0 Down rail = 1		counter counts down
Up rail = 1 Down rail = 1		counter disabled
Up rail = 0 Down rail = 0		operation not defined

All toggle inputs to the flip flops are tied in parallel and driven by a 200 nsec pulse.

Fig. A3-3 Parallel up-down counter.

APPENDIX IV

WEIGHTED-RESISTOR DIGITAL-TO-ANALOGUE CONVERSION CIRCUITRY AND ERROR ANALYSIS

A 4.1 Weighted-Resistor Digital-to-Analogue (D/A) Circuits

After considering the two methods of D/A conversion, the weighted-resistor technique was chosen over the R-2R ladder network [14,15].

A weighted-resistor D/A converter is shown in Fig. A4-1.

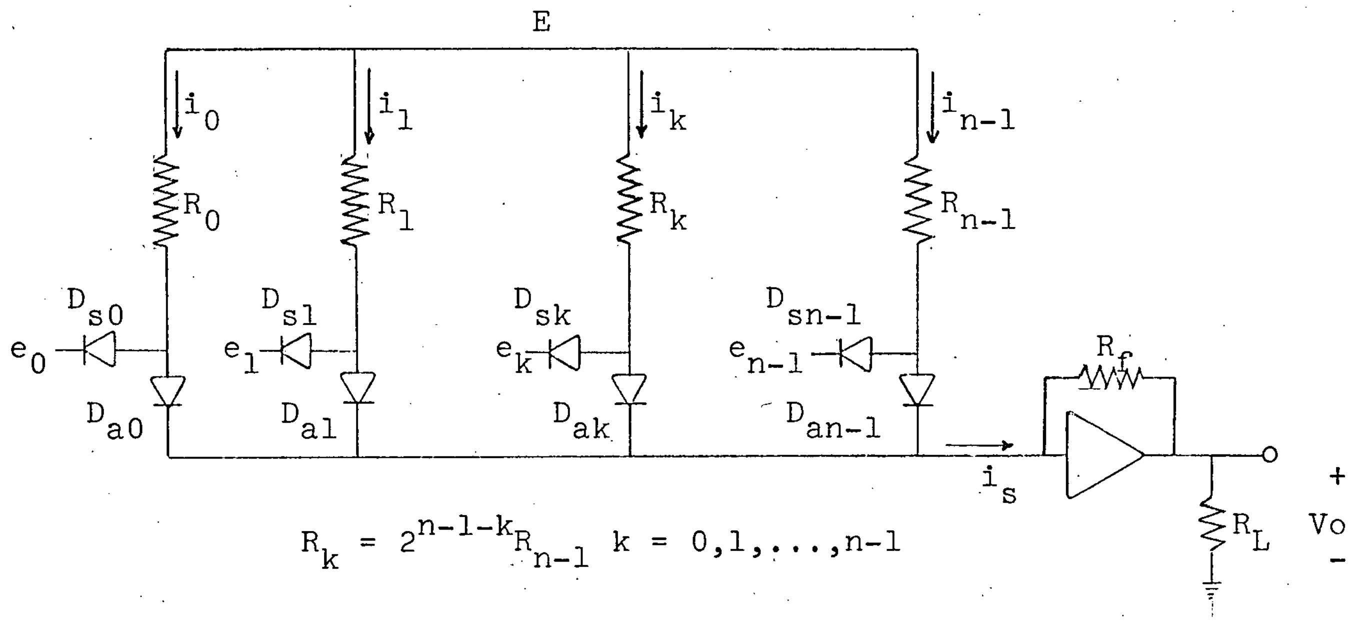


Fig. A4-1 Weighted-resistor D/A converter circuit.

The operational amplifier is used to sum the currents contributed by each branch in the current-divider network. The diodes D_{sk} and D_{ak} are current switches, which force the current, i_k, to flow either toward the operational amplifier or into the switching-signal source, e_k. If e_k is + 1.5 volts,

D_{sk} is reverse biased, D_{ak} is forward biased and the k^{th} branch current is routed to the operational amplifier. If e_k is - 1.5 volts, the k^{th} branch current is routed into the switching signal source. The signals e_k are derived from the corresponding flip flop outputs.

The weighted resistor D/A circuit has two main advantages over the R-2R ladder circuit. These advantages are as follows:

1. The current, i_k, corresponding to the k^{th} bit can be adjusted independently from the other bit currents by adjusting resistor R_k.

2. Only one highly accurate reference supply (E) and n current switches are necessary for the weighted-resistor D/A converter whereas in the R-2R ladder network, n accurate, switched voltage source drivers are needed.

A 4.2 Steady State Errors in the Weighted-Resistor D/A Converter

In analysing the steady-state errors, the operational amplifier may be modeled as shown in Fig. A4-2.

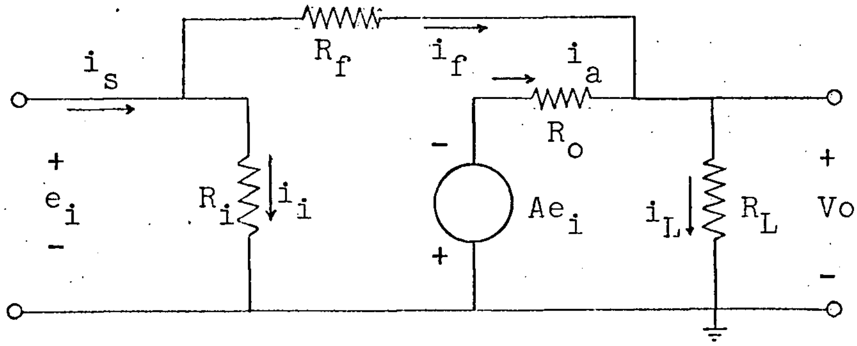


Fig. A4-2 Operational amplifier model.

In Fig. A4-2

$$Vo = -i_s R_f/(1 - K_r) \qquad \text{A 4.1a}$$

$$\text{where } K_r = \frac{R_L(R_o + R_f) + R_o R_f}{R_L(R_o - AR_f)} \; \frac{R_i + R_f}{R_i} \qquad \text{A 4.1b}$$

For an ideal operational amplifier, the open loop gain, A and the input resistance, R_i are infinite, while the output resistance, R_o is zero. Thus K_r is equal to zero. For a non-ideal amplifier, the non-zero value of K_r merely scales the output voltage.

From equation A 4.1a, the relative error in the output voltage can be calculated by considering the errors in the input current i_s.

$$i_s = \sum_{k=o}^{n-1} \left[a_k \left(\frac{E - V_{dk} - e_i}{R_k} + i_{ok} \right) - (1 - a_k) i_{ok} \right] \qquad \text{A 4.2a}$$

$$R_k = 2^{n-1-k} R_{n-1} \quad k = 0,1,\ldots,n-1 \qquad \text{A 4.2b}$$

For an ideal operational amplifier and ideal diodes, the operational amplifier input voltage, e_i; the forward voltage across the k^{th} switching diode, V_{dk}; and the k^{th} diode leakage current, i_{ok} are zero and the accuracy of the current, i_s, depends only on the accuracy of the current dividing resistors, R_k. The parameter a_k is either 0 or 1 depending on the binary number being converted to an analogue voltage. For non-ideal components, the error in i_s due to V_{dk}, e_i and i_{ok} must be calculated.

$$\Delta i_s \doteq \sum_{k=0}^{n-1}\left[\frac{\partial i_{sk}}{\partial R_k}\Delta R_k + \frac{\partial i_{sk}}{\partial e_i}\Delta e_i + \frac{\partial i_{sk}}{\partial V_{dk}}\Delta V_{dk} + \frac{\partial i_{sk}}{\partial i_{ok}}\Delta i_{ok}\right] \qquad \text{A 4.3a}$$

$$i_{sk} = a_k\left(\frac{E - V_{dk}}{R_k} + i_{ok} + \frac{e_i}{R_k}\right) - (1 - a_k)i_{ok} \qquad \text{A 4.3b}$$

The error due to V_{dk}, and the error due to i_{ok} when $a_k = 1$ need not be considered, since R_k can be adjusted to compensate for these errors. However, when $a_k = 0$, the leakage current does produce an error in i_s. The error due to the resistor tolerance must also be calculated.

In order to calculate the error in i_s due to e_i, an upper bound on e_i must be found. In Fig. A4-2

$$e_i = \Delta e_i = \frac{VoR_fR_o}{R_t(R_o - AR_f)} \qquad \text{A 4.4a}$$

$$R_t = \frac{R_oR_fR_L}{R_oR_L + R_oR_f + R_fR_L} \qquad \text{A 4.4b}$$

It should be noted that $AR_f \gg R_o$ and that by the use of a low impedance current booster on the output of the operational amplifier, R_o can be made much less than either R_f or R_L. Therefore $R_o \doteq R_t$. Consequently the amplifier input voltage can be approximated by

$$e_i \doteq -\frac{Vo}{A} = -\frac{R_f}{A}\sum_{k=0}^{n-1} a_k\frac{E}{R_k} \qquad \text{A 4.5}$$

It is desired to compute the ratio of the error in i_s, Δi_s caused by Δe_i, Δi_{ok}, and ΔR_k with respect to a least significant bit (LSB) current. Let the magnitude of these relative errors be $\delta i_s\big|_{e_i}$, $\delta i_s\big|_{i_o}$ and $\delta i_s\big|_{R_k}$ respectively. Some algebra shows these errors to be:

$$\delta i_s\Big|_{e_i} \leq \frac{2^{n+1}R_f}{AR_{n-1}} \qquad \text{A 4.6}$$

$$\delta i_s\Big|_{i_o} \leq \frac{n i_o 2^{n-1} R_{n-1}}{E} \qquad \text{A 4.7}$$

$$\delta i_s\Big|_{R_k} \leq (2^n - 1)\,\frac{\Delta R_k}{R_k}\,. \qquad \text{A 4.8}$$

In equation A 4.8, all resistor tolerances were assumed equal. The result shown in equation A 4.6 is in agreement with the result found in [15]; however, it should be noted that the bound on $\delta i_s\big|_{e_i}$ can be tightened by an additional factor of two if the following argument is considered. The calculations that led to equation A 4.6 were made assuming the operational amplifier summed only currents flowing in one direction. If current bias is added to the operation amplifier input to shift the output voltage until it is symmetric about zero volts, the maximum input current to the operational amplifier is halved and thus e_i and $\delta i_s\big|_{e_i}$ are halved. See equation A 4.5.

$$\delta i_s\Big|_{e_i\ \text{symmetrical output voltage swing}} \leq \frac{2^n R_f}{AR_{n-1}} \qquad \text{A 4.9}$$

For a symmetrical output of ± 10 volts, a most significant bit (MSB) current of 30 ma, E = 30 volts, A = 5×10^4, n = 12 and a maximum diode leakage current of 10 na for a reverse bias of 1 volt bounds on the relative errors due to e_i and i_s were found to be:

$$\delta i_s \Big|_{e_i} \leq 2.7\%$$

$$\delta i_s \Big|_{i_o} \leq .8\%$$

From the above it can be seen that for up to 12 bits, the errors caused by the operational amplifier and the switching diodes in the D/A converter are either small or can be compensated for. Thus the main limitation to producing an accurate D/A converter for $n \leq 12$ lies in the current dividing resistors.

Since the output voltage is linearly related to i_s from equation A 4.1, the error in Vo with respect to a LSB in output voltage, δVo, is equal to $\delta i_s \Big|_{R_k}$ if the errors $\delta i_s \Big|_{e_i}$ and $\delta i_s \Big|_{i_o}$ are neglected. The relative output voltage error δVo is plotted against resistor tolerance for $2 \leq n \leq 12$ in Fig. A4-3.

A 4.3 Speed Limitations in the Weighted-Resistor D/A Converter

There are two main limitations on conversion speed in the weighted-resistor D/A converter; the switching and settling time of the diodes and the slew rate of the operational amplifier.

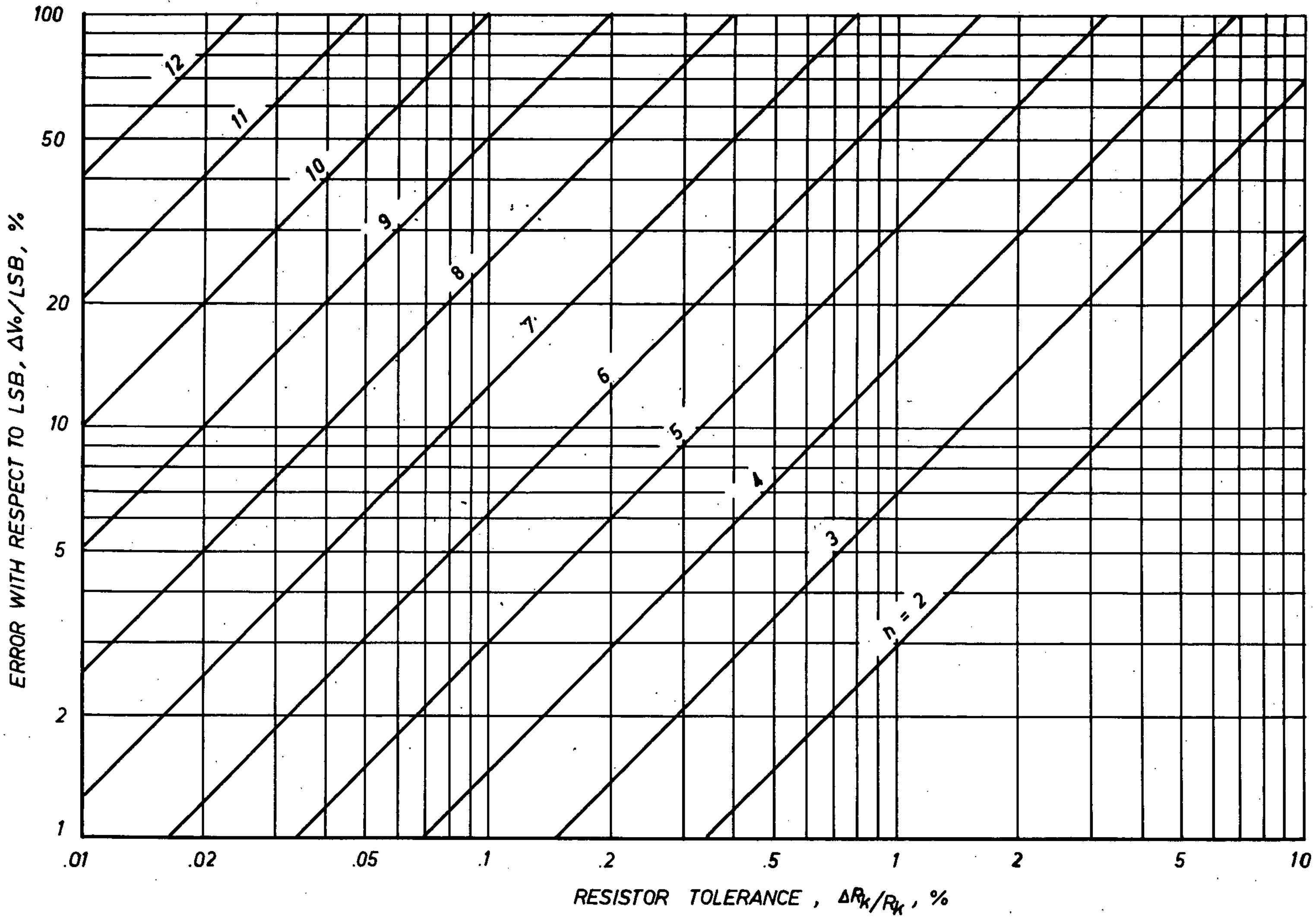


FIG. A4-3 CURRENT DIVIDING RESISTOR TOLERANCE FOR WEIGHTED-RESISTOR DIGITAL-TO-ANALOGUE CONVERTERS ALL RESISTOR TOLERANCES CONSIDERED EQUAL. V_o IS THE ANALOGUE OUTPUT VOLTAGE. LSB IS THE OUTPUT VOLTAGE INCREMENT CORRESPONDING TO A CHANGE IN THE LEAST SIGNIFICANT BIT. n IS THE NUMBER OF BITS.

To make an estimate of the settling time of the diodes, one must consider the diode junction capacitance and the diode recovery time. The recovery time or switching time of the 1N4154 diode can be calculated as shown on the specification sheet on the 1N4154 to be approximately 6 nsec for 30 ma of forward current. The junction capacitance for the 1N4154 diode is approximately 4 pf. The voltage across the diode only changes by 1.5 volts, so the junction capacitance can be considered to be charged by a constant current source. The worst case will occur on the LSB, since the charging current is smallest in this case. For n = 10, and a MSB current of 30 ma, the LSB current is 60 μa. The charging time t_c is

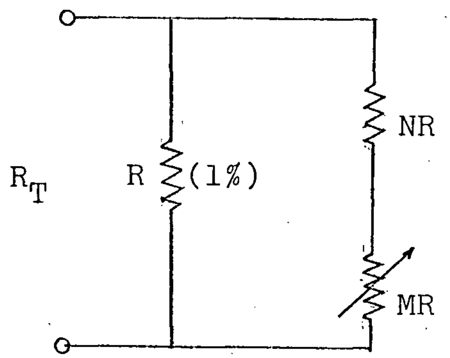
$$t_c = \frac{Cv}{i} = 100 \text{ nsec.}$$

The junction capacitance is discharged through the low forward resistance of a conducting diode, which is approximately 7.5K at a forward current of 60 μa. The time constant is approximately $4 \times 10^{-12} (7.5 \times 10^3) = 30$ nsec. The junction capacitance can be considered fully charged after 150 nsec (5 time constants). Thus for a 10 bit D/A converter, operation at a 1 MHz rate seems quite reasonable from consideration of switching and settling time of the diodes.

The slew rate of the operation amplifier limits the maximum rate of change of the output voltage, Vo. There will be transients initiated by each change in the digital number, however the proper appliaction of a small capacitor across the feedback resistor will reduce these transients to an acceptable level.

A 4.4 Resistor Trimming Circuitry

There was an immediate need for an 8 bit D/A converter with an accuracy of at least 1/2 LSB ($\delta Vo \leq 1/2$) for another project as well as for a 6 bit D/A converter for the contour-tracing scanner. Thus an 8 bit D/A converter with an accuracy of 1/4 LSB (δ Vo $\leq$ 1/4) was designed. From Fig. A4-3, it is seen that a resistor accuracy of .1% is required. The configuration shown in Fig. A4-5 was used to construct a resistor accurate to .1% from inexpensive components.



$$R_T = \frac{(N+M)R}{(N+M+1)}$$

Fig. A4-4 Circuit for adjusting R_T to the required accuracy

To achieve a temperature stability which exceeds that of the ordinary resistors, a 1% resistor was used for the resistor R. The configuration shown in Fig. A4-4 has certain advantages over a series combination of a 1% resistor and a small trimming resistor. The parallel configuration minimizes the inductive effect of a potentiometer, since less than 10% of the current passes through it. If more adjustment is required on a given resistor, the resistor NR can be changed to give the desired adjustment without the necessity of changing a 1% resistor.

If R_T is the combined resistance of the three resistors, then

$$R_T\text{max} = \frac{(N + \text{Mmax})\ R}{(N + \text{Mmax} + 1)} \qquad \text{A 4.10}$$

$$R_T\text{min} = \frac{NR}{N + 1} \qquad \text{A 4.11}$$

$$\frac{R_T\text{max} - R_T\text{min}}{R_T} \geq \frac{\text{Mmax}}{(N + 1)\ (N + \text{Mmax})} \qquad \text{A 4.12}$$

where $R_T$max and Mmax are the maximum values of R_T and M respectively. If M can be set to an accuracy of ΔM, then the maximum accuracy that R_T can be set to is

$$\frac{\Delta R_T}{R_T} = \frac{\Delta M}{(N + M)\ (N + M + 1)} \qquad \text{A 4.13}$$

The worst case occurs when M = O. Therefore,

$$\frac{\Delta R_T}{R_T} \leq \frac{\Delta M}{N(N + 1)} \qquad \text{A 4.14}$$

If Mmax $\simeq$ N $\simeq$ 10, and if M is adjustable to 1% ($\Delta M = .1$) then $\Delta R_T/R_T \leq .1\%$ as required. It follows from equation A 4.12 that the total range of adjustment of R_T is approximately 5%.

If the MSB current, i_{n-1}, is 15 ma then the switching diode voltage drops can be measured to determine the compensation required in the resistors R_k. One such measurement gave a range in voltage drops varying from .73 volts at I_f = 15 ma to .48 volts at I_f = 120 μa. For a reference voltage

(E) of 30 volts, the error due to the diode drops varies from 2.4% to 1.6%.

Since the range of adjustment on the resistors in the network is approximately 5%, all the resistors R_k were calculated to be approximately 2% low to compensate for the error due to the forward drop across the diodes. Fig. A4-5 shows the set of resistance values chosen for the 8 bit D/A converter.

Nominal Resistance R_k OHMS	R(1%) OHMS	MmaxR OHMS	NR OHMS	Range of Adjustment of R_T
2K	2.1 K	22K	18K	5.5%
4K	4.12K	47K	33K	6.3%
8K	8.25K	100K	68K	6.3%
16K	17.4 K	100K	120K	5.3%
32K	34.0 K	220K	270K	4.7%
64K	68.1 K	470K	470K	6 %
128K	133 K	1 meg.	1.2 meg.	4.4%
256K	267 K	2.2 meg.	2.2 meg.	5.1%

Fig. A4-5 Resistance values for a weighted-resistor 8 bit D/A converter

If more resolution is required for resistors R_k, the resolution on the trimming potentiometer MR may be increased, or the range of adjustment may be decreased or a combination of both may be used.

A 4.5 D/A Current-Switch Driver Circuits

The D/A converter must take the signals from the binary number source and convert them to suitable current switching signals of ± 1.5 volts. Consider the circuit in Fig. A4-6.

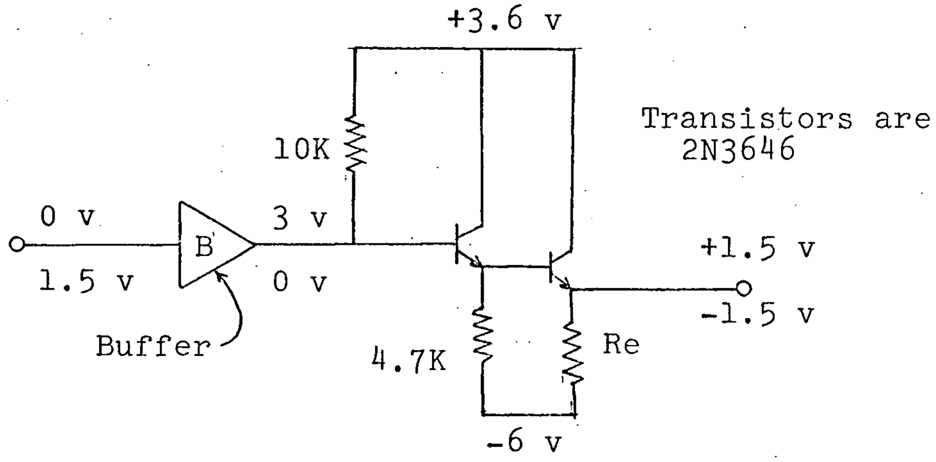


Fig. A4-6 Current-switch driver circuit

Since the k^{th} driver must be capable of accepting the current i_k from the k^{th} branch of the current divider, the resistor Re must be adjusted on the most significant drivers to be able to accept this current. For currents i_k less than or equal to 7.5 ma, Re = 470Ω is adequate. For higher currents, Re must be reduced.

APPENDIX V DESIGN OF THE OPTICS SYSTEM

A 5.1 Contour-Tracing Scanner Optical Requirements

The function of the optics system is to focus the spot of light from the CRT onto the page. If the size of an average character is about 2 mm square, and if approximately 30 increments are required in each dimension, then a spot of light of about .06 mm diameter is required on the page. The spot size on the CRT is approximately .6 mm in diameter (the diameter varies with the intensity setting), therefore, a size reduction by a factor of 10 is required. Since a photomultiplier (PM) will be used to collect the light reflected from the page, there must be enough room between the lens and the page to enable the PM to be placed so that the light will be collected at as small an angle of reflection as possible and as close to the page as is practical. The optical system should be designed to gather the maximum amount of light consistent with low optical distortion, reasonable cost, and availability of optical components. A 55 mm f/1.8 Super-Takumar Asahi Pentax camera lens was purchased to do some tests on gathering light from a page using a RCA 931A photomultiplier. The Pentax lens gave the required definition and working distance (distance between the page and lens) for the 931A PM. The tests showed, however, that a much more sensitive PM was required. As a result, a Phillips 53AVP was ordered. The 53AVP however, is a larger tube and requires greater working distance. The working distance required for the

53AVP was calculated graphically to be 3 inches. This increase in required working distance causes a change in optics design.

Some preliminary calculations based on the thin lens approximation showed that for a working distance of 3 inches (in a thin lens, the working distance and the image distance are the same) and a magnification of $-.1$, the object distance was 30 inches and the focal length 6.9 cm. If a useable lens diameter of 1.5 inches is assumed, then the optical system input solid angle of light can be calculated to be 1.9×10^{-3} steradians. In view of the long length required, the light gathering ability and the distortion expected in a simple thin lens optical system, it was decided to investigate a thick lens optical system.

A 5.2 Results of the Thick Lens Optics Investigation

A study of thick lens optical systems [10] revealed that it was possible to use the Pentax lens in a modified configuration to yield a shorter optical system with the required working distance. Briefly, this was achieved as follows.

The locations of the principle planes, P_2 and P_2', in the Pentax lens were found using an optical bench. It was found that if a diverging lens was used in front of the Pentax lens, the image space principle plane (located at P') for the overall optical system could be forced outside the lens and toward the image plane. See Fig. A5-1.

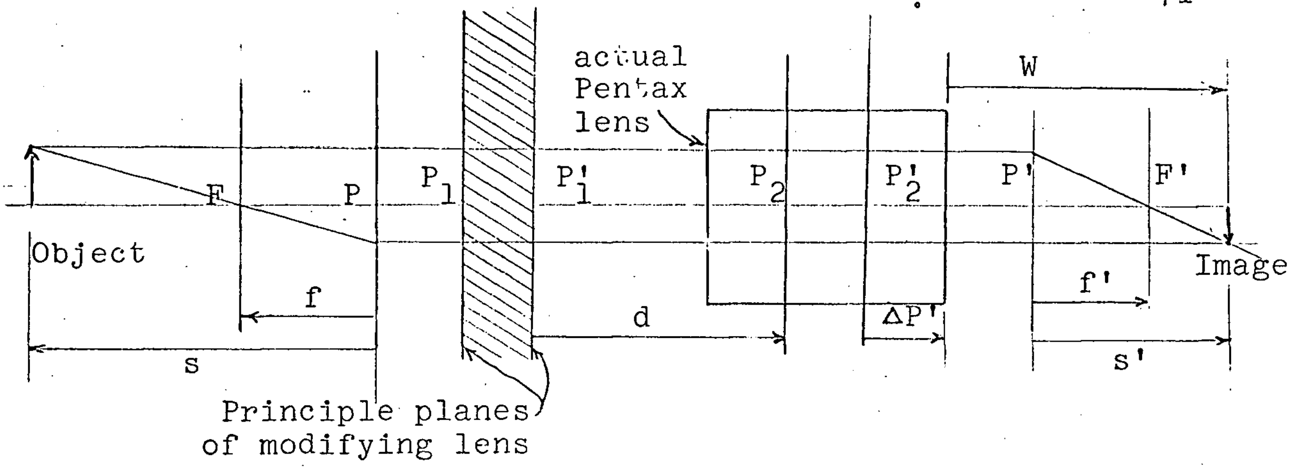
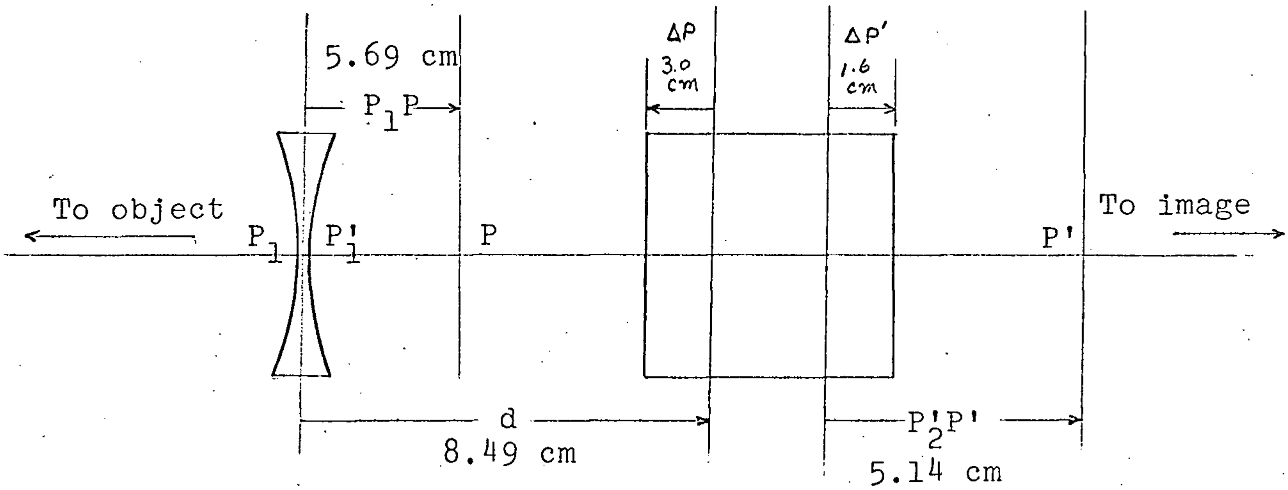


Fig. A5-1 Scanner optical system.

Since s' is measured from P', s' may be decreased without decreasing W, the working distance, provided P' is forced closer to the image plane. It was necessary to calculate the required focal length, f_1' of the diverging lens and the separation distance, d, between the Pentax lens and the diverging lens. Appropriate equations were derived and solved yielding the optical system shown in Fig. A5-2.



$f' = 3.7$ cm
$W = 7.62$ cm (3 inches)
$f_1' = -6.1$ cm
$f_2' = 5.5$ cm
$s = 40.7$ cm
$s' = 4.07$ cm

Fig. A5-2 Final optical system design.

The overall focal length, f' was calculated to be 3.7 cm and the input solid angle of light to the optical system was found to be 1.32×10^{-3} steradians. For an image distance of 4.07 cm, the working distance was found to be 7.62 cm or 3 inches.

To allow for small adjustments in the magnification and to exclude extraneous light, a telescope adjustable in length was built to hold the lens. The magnification was made adjustable from -.092 to -.11.

APPENDIX VI THE SYSTEM BLOCK DIAGRAM

The overall block diagram of the contour-tracing scanner is presented in Figs. A6-2 and A6-3. The symbols used in the block diagrams are defined in Fig. A6-1.

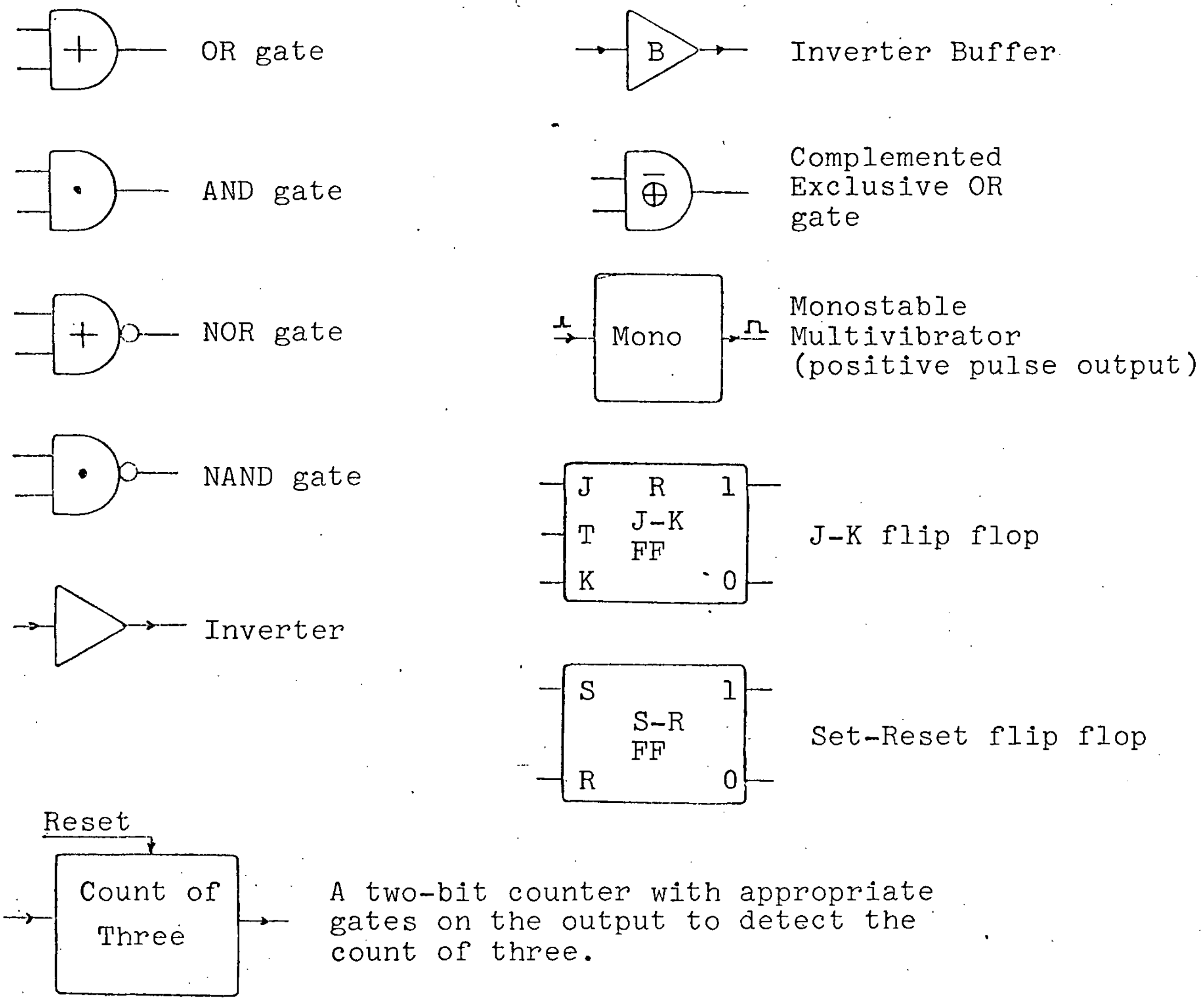


Fig. A6-1 Definition of symbols and terminology.

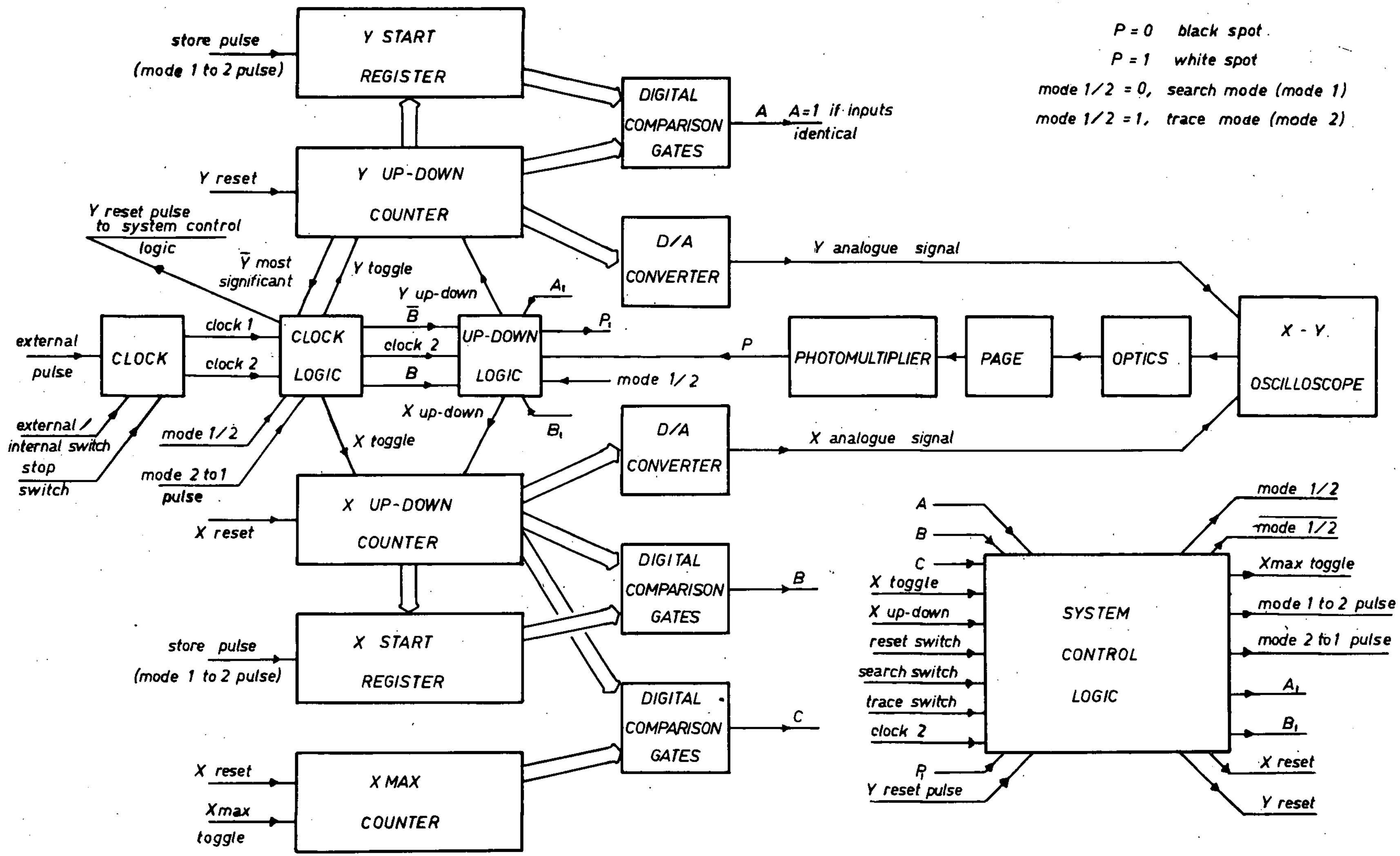


FIG. A6-2 SYSTEM BLOCK DIAGRAM

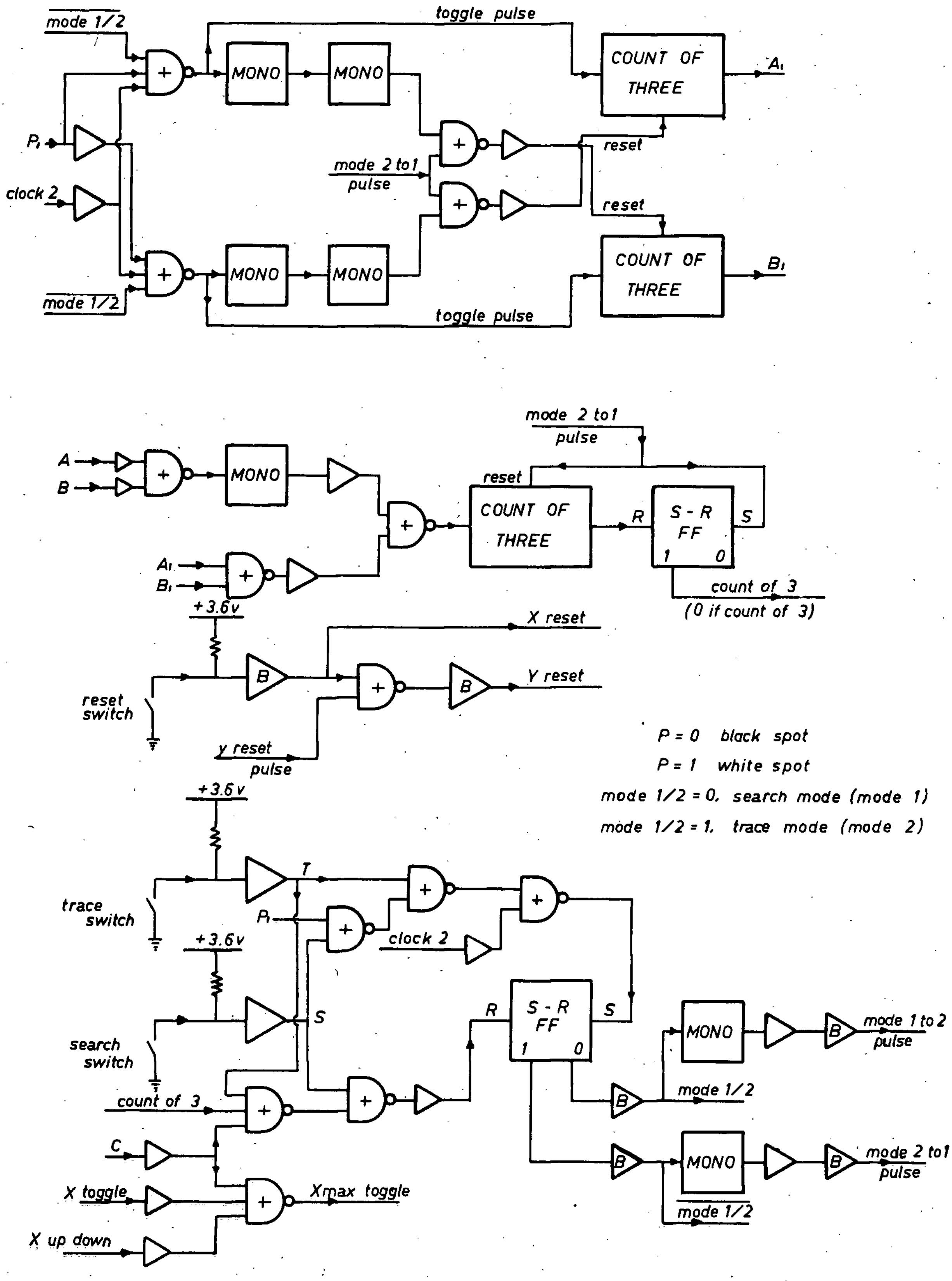


FIG. A6 - 3 SYSTEM CONTROL LOGIC

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