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Magnetically Controlled Variable Logic*

Abstract: Magnetically controlled multipurpose logic provides a great flexibility and compactness. A matrix consisting of 2^n saturable magnetic elements for n variable inputs is controlled by an adjacent magnetic pattern recorded on a magnetic medium, which determines the logical function to be performed. Since 2^{2^n} magnetic patterns enable the performance of 2^{2^n} logical functions, great flexibility of system operation is possible. The selection of the required magnetic materials is described.

Application of the basic system to several special purpose machines is shown. In particular, the design of a computer using microprogramming techniques is described, and the application of this system to various serial and parallel computer operations is discussed.

Introduction

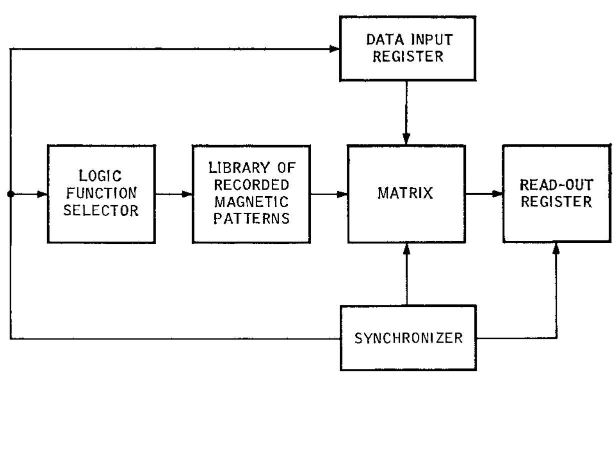
Special-purpose computers have been employed to solve specific problems with a high degree of efficiency by sacrificing the versatility obtainable with a general-purpose computer. This paper describes a magnetically-controlled variable logic which should permit a computer to combine the efficiency of the special-purpose computer and the flexibility of the general-purpose system.

Variable logic can be carried out by the use of multipurpose logic blocks arranged in the form of matrices to simplify the adaptation to various applications. Such logic blocks are also capable of performing, sequentially, a number of different functions; thus by microprogramming,[1] all logic combinations can be obtained. Flexibility can be attained by continuously changing, through indexing techniques, the function performed by the matrix.

Variable logic has been designed using matrices constructed of semiconductors or photoconductors.[2] Magnetic elements have frequently been used in the construction of multipurpose logic,[3] using coded instructions to selectively gate matrix networks. Since these instructions are normally stored in magnetic bulk storage, considerable circuitry can be saved if the magnetic storage directly controls the function of the multipurpose matrix. The variable logic described in this paper is directly controlled by prerecorded magnetic patterns that are superimposed upon the magnetic fields of the logic elements.

A schematic of a microprogramming computer system is shown in Fig. 1. The logic-function selector adapts the multipurpose block to perform different logic functions by selecting magnetic control patterns from a library recorded on a drum, disk, or tape. The synchronizer matches the data to any selected logic function. Thus, the same matrix can be used to perform different logic operations.

Figure 1 **Block diagram of microprogramming system.**



* This paper was presented at the Ninth Annual Symposium on Computers and Data Processing, Estes Park, Colorado, June 28, 1962.

Description of magnetically controlled logic element

A technique of controlling the matrix with a magnetic field from a recorded magnetic medium has been developed. The medium on which the pattern is recorded is placed adjacent to the magnetic elements of the matrix which can be in the form of ferrite cores. If a nongapped ferrite, such as a toroid, is placed into a magnetic field associated with a pattern recorded on a magnetic medium, the flux leaving the medium will pass through a section of the adjacent ferrite. Figure 2 shows how the external field passing through a toroid results in a region of higher reluctance and thus a constriction of the flux due to the alternating primary drive. If any section along the toroid is saturated, the reluctance of the total path is greatly increased, reducing the resultant flux flowing through the core. With a sense winding applied to the toroid, the effect of the presence or absence of the external field can be sensed by noting the decrease or increase in the induced voltage which is proportional to the $d\phi/dt$ caused by the alternating primary drive. The resulting sense-winding outputs are shown in Fig. 3. Waveform *b* shows the output signal when there is no applied bias or external field. Weak and strong external fields affect the outputs as shown for waveforms *c* and *d*, respectively.

The presence of a biasing field resulting from bias current greater than one-half the peak-to-peak drive (waveform *e*) has the same effect as a strong external field (*d*). Therefore, the total reluctance of the toroid to the primary drive can be controlled by either the external field or the biasing field, or by both. The effect of the external field can be measured by the percentage of modulation, as sensed by the induced voltage in the secondary winding:

$$\text{percent modulation} = \frac{\text{average envelope amplitude} - \text{minimum envelope amplitude}}{\text{average envelope amplitude}}$$

With remanent fields of 0.1 kG from 5.0 mils of NiCo at recording densities of 15 bits/in., modulation percentages of 90 have been observed. However, 30% modulation is more than adequate for sensing purposes and can be attained easily.

The reluctance of the ferrite element can be determined by sensing the secondary voltage induced by the transformer coupling, as shown in Fig. 2. In another technique (Fig. 4) the effective impedance of the primary winding of the element or elements being driven (which is a function of permeability) is sensed. For a nonlinear ferrite (having a square-loop waveform), the difference between the nonsaturated and saturated permeability is very great. The technique shown in Fig. 4 eliminates the secondary winding but results in a lower percentage of modulation than use of the transformer coupling. Transformer coupling was used, therefore, in the model that was built and tested.

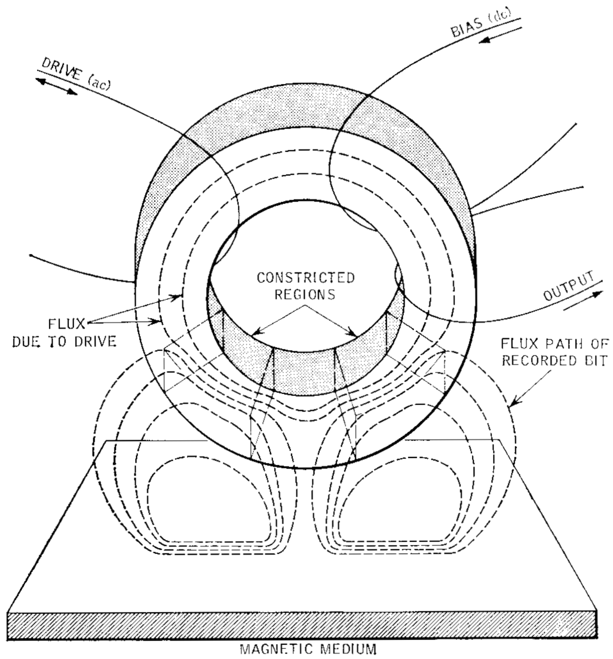


Figure 2 **Basic logic element.**

Figure 3 **Output waveforms.**

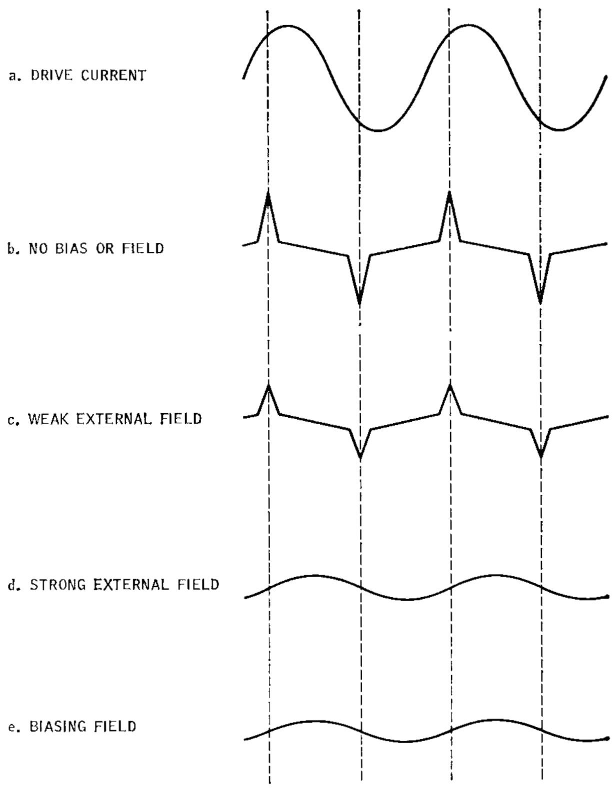
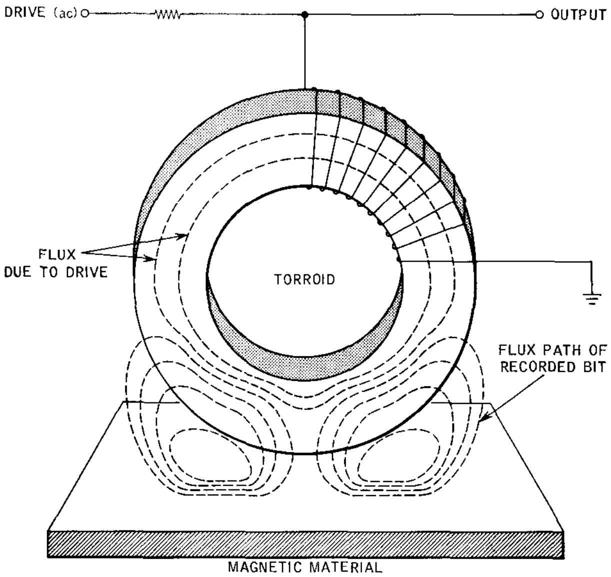
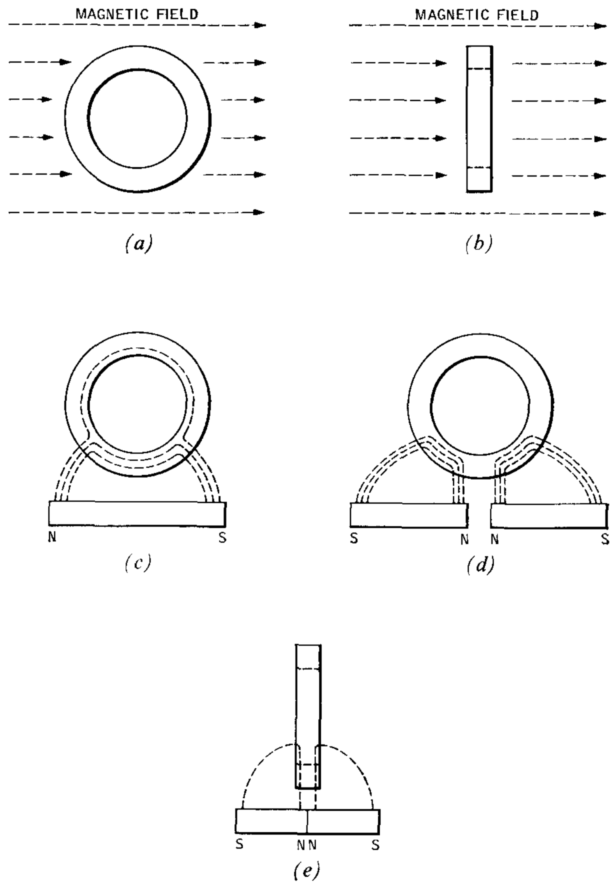


Figure 4 **Impedance sensing of basic element.**



Several experiments were performed to determine the influence of the magnetic field on a toroid. The magnetic field is a function of 1) the residual flux of the material, 2) the density of recording, 3) the thickness of the material, and 4) the type of recording process. The degree to which a toroid is saturated when placed in a given magnetic field is determined by its position relative to the field. When a toroid is placed in a uniform, external magnetic field, there is an easy direction of magnetization as

Figure 5 **Core orientations in magnetic fields.** *(a) core in uniform field, easy direction of magnetization, (b) uniform field, hard direction, (c) core in nonuniform field of printed magnetic pattern, easy direction, low saturation, (d) nonuniform field, easy direction, higher saturation, (e) nonuniform field, hard direction.*



shown in Fig. 5a. The more difficult direction of magnetization is shown in Fig. 5b. Figures 5c, 5d, and 5e show the orientation of a toroid relative to the nonuniform field of a recorded medium. Note that, in the orientation of 5c and 5d, the external field influences the portions of the toroid which are similar to the toroid of 5a.

Since the flux density is a maximum at the poles in the magnetic medium, a higher degree of saturation results when the core is placed in the position shown in 5d. The thickness of a toroid is usually much less than the diameter; thus, the orientation shown in 5e permits higher-

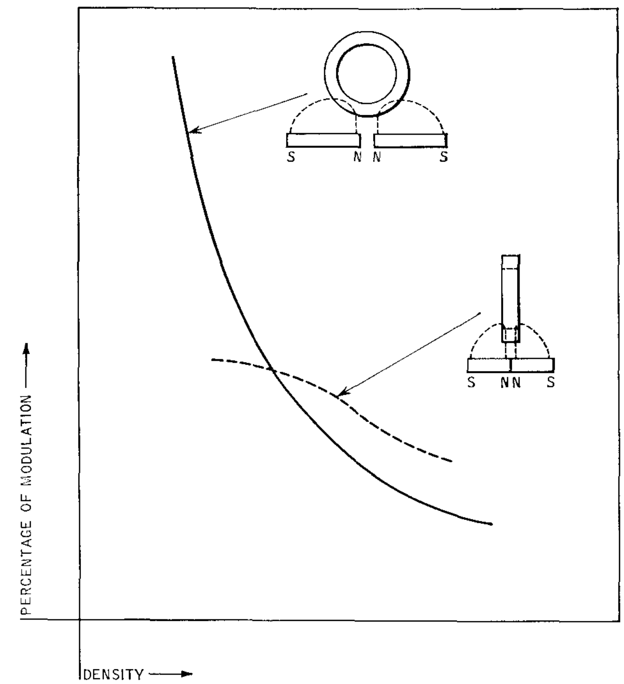


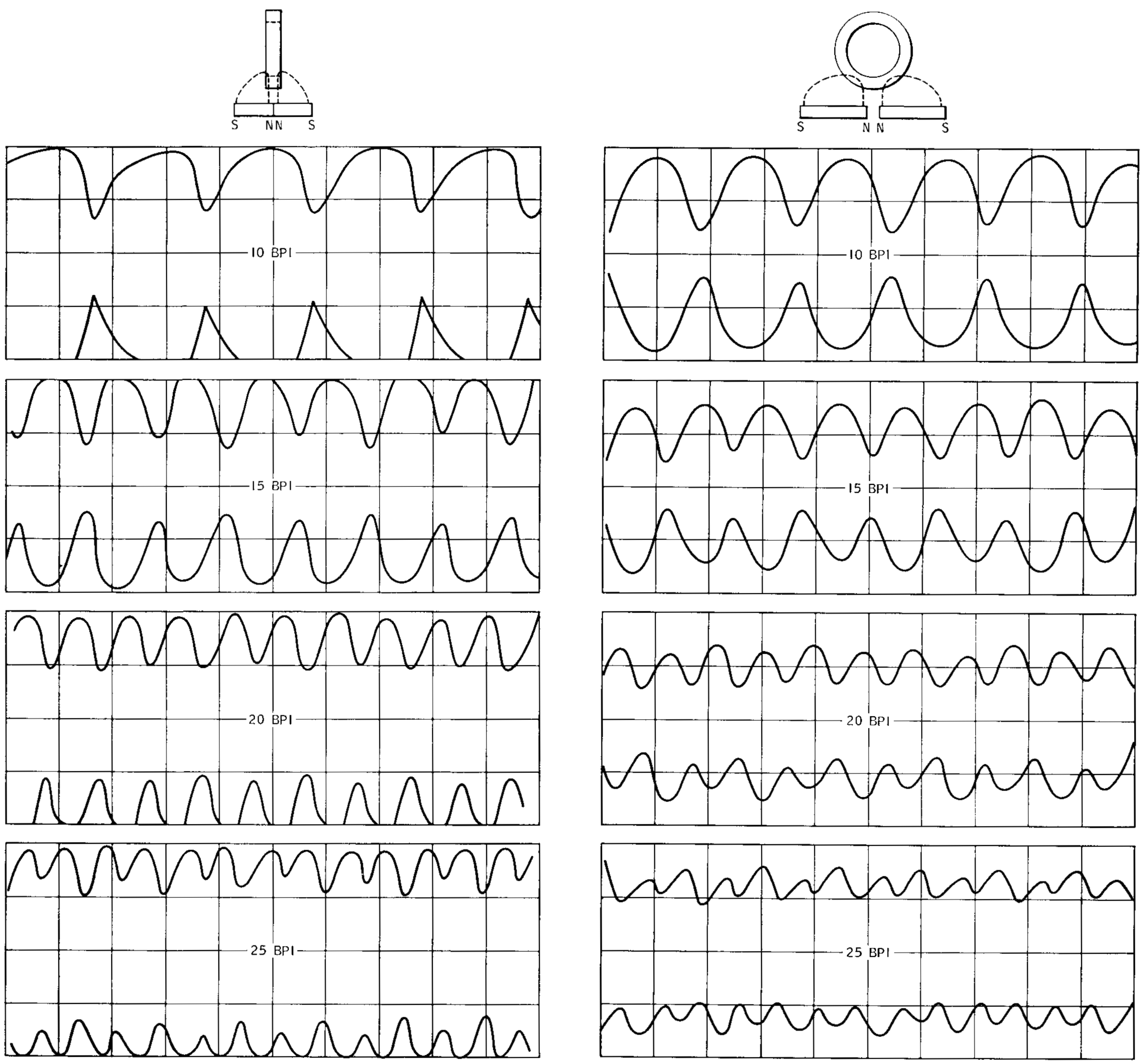
Figure 6 **Percentage of modulation vs density for two core orientations.**

density packing of the recorded patterns. The orientation in 5d exhibits a higher percentage of modulation at a low-pattern density (see Fig. 6); however, as the density increases, both the horizontal and vertical flux components saturate the core and the percentage of modulation is low. The orientation shown in Fig. 5e exhibits a higher percentage of modulation at higher densities since the core will be saturated only by the stronger vertical components of the recorded magnetic field. For applications that require a magnetic medium in motion the orientation shown in Fig. 5e permits greater sequential logic rates for a given speed of the magnetic medium. Figure 7 shows modulation of sense winding outputs obtained under dynamic conditions (for the core orientations shown in Figs. 5d and 5e) for various pattern densities. All further results stated in this paper were obtained with the orientation of Fig. 5e.

Magnetic recording media

To obtain fields of adequate strength, magnetic media,

Figure 7 **Logic element outputs for two core orientations at various recording densities.** *Core material: manganese-zinc ferrite with additives; core dimensions: 19/32/6; velocity of magnetic medium: 100 in./sec; coating of magnetic medium: NiCo; thickness of coating: 1.8 mils; interrogation frequency: 300 kc/sec.; horizontal scale: 500 μsec/div.; vertical scale: 50 mV/div.*



such as Alnico I, Vicalloy I, and NiCo, with remanent flux densities[4] of 7.2, 8.8, and 8 to 10 kG respectively, were used. However, magnetic compositions containing percentages of iron, vanadium, and cobalt involve rolling or casting processes. Extensive machining and annealing are necessary to achieve the required flatness. NiCo was selected as a magnetic-recording medium for the feasibility model as it can easily be plated on a machined substrate.

Since the output from a core decreases as the spacing between the core and the recording medium increases, and since matrix flatness is difficult to achieve, hydrostatic support of the variable matrix elements could be used to maintain constant spacing. To show feasibility, however, the variable matrix concept was not complicated by such support. In all the instances cited in this paper, recordings were made with conventional ring heads. Poles were generated by switching the direction of the recording current in a Non-Return-to-Zero (NRZ) mode of operation.

For the magnetic-material thicknesses and recording wavelengths considered here, the field strength is approximately proportional to the recording wavelength.[5] Figure 8 shows the effect of coating thickness on the percentage of modulation, which is related to the variation in the intensity of the field penetrating the ferrite.

For example, 30-mil Vicalloy was tested and found to give acceptable modulation percentages up to recording densities of 100 bits/in. However, the recording process for the thicker materials necessitates the use of a high-power drive circuit. Although this is not a limitation when recording at low frequencies, recording at higher frequencies is desirable for dynamic programming applications. The magnitude of the desired recording current presents severe demands on the associated recording circuitry. Therefore, it is desirable for these applications to reduce the recording medium thickness and thus the magnitude of the recording current.

Ferrite cores

The field that penetrates the ferrite is a function of the remanence of the coating material, the coating thickness, the density of recording, the length of the magnetic path, and the width of the recorded bit relative to the core width. To increase the effect of the field from the recording medium, ferrites of small size and low coercivity are most desirable. The size of a toroidally-shaped ferrite is described by dimensions *ID/OD/H*, where *ID* is the inside diameter, *OD* is the outside diameter, and *H* is the height. Toroids of 19/32/6 mils and 19/32/3.5 mils were sintered of a material consisting of manganese and zinc ferrite with additives. The H_c is 0.4 and 0.32 oersteds respectively. Reduced height decreases the cross-sectional area and thereby decreases the flux required to produce saturation. Both core sizes were tested with the same recordings on

Figure 8 **Percentage of modulation vs magnetic-medium coating thickness.** *Core material: manganese-zinc ferrite with additives; core size: 19/32/6.5; separation between core and magnetic medium: 1.0 mil; recording density: 15 bits per in.*

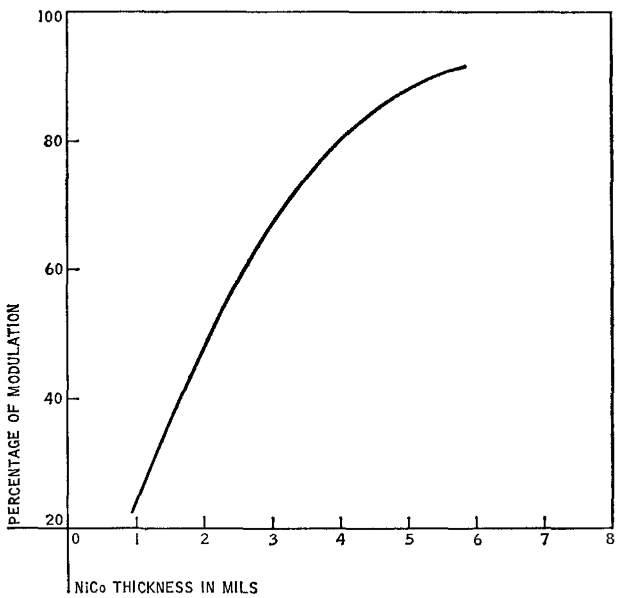
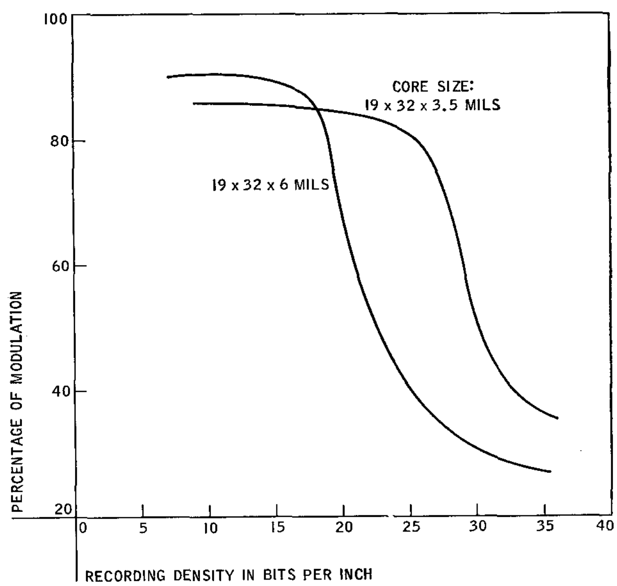


Figure 9 **Percentage of modulation vs recording density for two sizes of core.** *Core material: manganese-zinc ferrite with additives; coating of magnetic medium: NiCo; thickness of coating: 5 mils; separation between core and magnetic medium: 1.0 mil.*



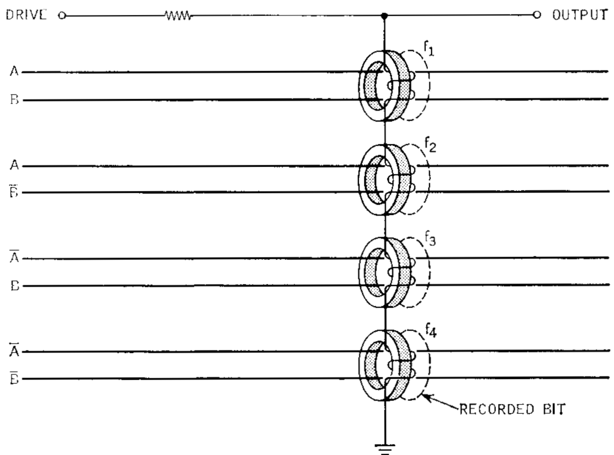


Figure 10 **A 2-input, 4-core matrix.**

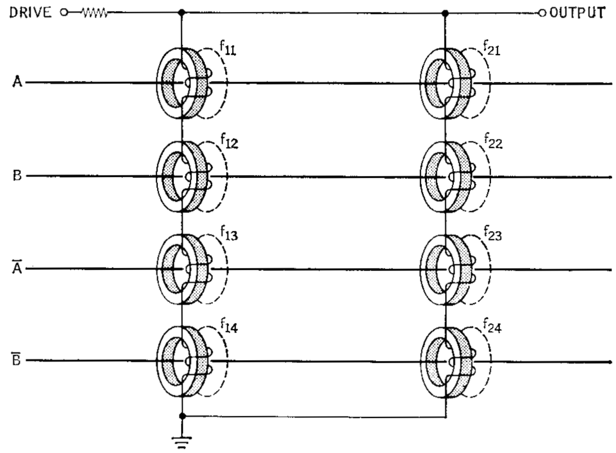


Figure 11 **A 2-input, 8-core matrix.**

a 5-mil coating, and oriented as in Fig. 5e to gain maximum bit density.

Figure 9 shows the percentage of modulation versus recording density for these two cores. Note that the minimum usable wavelength of recording is approximately equivalent to ten times the core height. This is considerably less than the limit of resolution which was anticipated to occur when the wavelength equals the core height. Thus, it appears that the decrease in the field strength is the major factor in limiting the usable bit density or wavelength associated with the recorded bit.

Matrix configuration

The basic magnetic elements (ferrite cores) may be arranged into a variable matrix in many ways, and the element may have one or more input windings which bias the core. Figure 10 shows a two-input array in which each core is wound with inputs forming all combinations of the inputs. Thus if there are n inputs there are n input windings in addition to drive and sensing windings. The array shown in Fig. 11 employs additional cores to reduce the input windings to one per core.

Table 1 demonstrates that all 16 possible logic functions are available for both wiring techniques. Hence the number of cores can be varied to accommodate desired fabrication techniques or packing density requirements. By referring to Fig. 10, it can be noted that current in any of the input (A, $\bar{A}$, B, $\bar{B}$) windings, or an externally applied magnetic field (symbolically represented as f_1, f_2, f_3, f_4), will saturate the respective cores. Let the presence of a saturating external field be indicated by a ONE and the absence of an external field by a ZERO. Saturated cores exhibit a negligible impedance and voltage drop because the permeability ratios of nonbiased to biased cores are 100 to 1. The change in the magnetic state of the core about the biased point is small when the core is driven by an alternating current. Hence, if all the cores are saturated, the output would be at ground potential. Let us now specify that, at sample time, there always be current in either the "true" or "complement" condition of the inputs. By inspection of the data input windings, it is apparent that, at sample time, input currents will cause three of the cores to be saturated, regardless of the input data.

For example, suppose it is desired to sense the presence of input A by observing an output whenever input A is present. Table 1 shows that this situation requires external saturating fields f_1 and f_2 to produce low permeability in cores 1 and 2. If the logic condition is satisfied, i.e., A is present, there is no current in $\bar{A}$ and either core 3 or 4 will have an output depending on whether there is current in line B or $\bar{B}$, respectively. The data carried on line B is a DON'T CARE condition in this case. If A is not present, note that there will be current in the $\bar{A}$ windings, and that all cores will be in a low-permeability state, thus preventing an output. Low permeability in cores 1 and 2 is caused by the external fields f_1 and f_2 and in cores 3 and 4 by the current in input lines $\bar{A}$.

As another example, consider the program needed to produce an EXCLUSIVE OR function. The function A EXCLUSIVE OR B is identically equal to $A\bar{B}$ or $\bar{A}B$ and requires the presence of fields f_1 and f_4. If $A\bar{B}$ is present, the output is the result of core 3 not being saturated. If either AB or $\bar{A}\bar{B}$ is the data input, cores 2 and 3 are simultaneously saturated and an output is prevented. By referring to Table 1 any of the 16 functions possible with two variable inputs can be performed.

Figure 11 is similar to Fig. 10, except that all possible outputs as a result of the variable impedance of the parallel network must be considered. In both the 4-core array with two inputs per core (Fig. 10), and the 8-core array with one input per core (Fig. 11), the number of variable

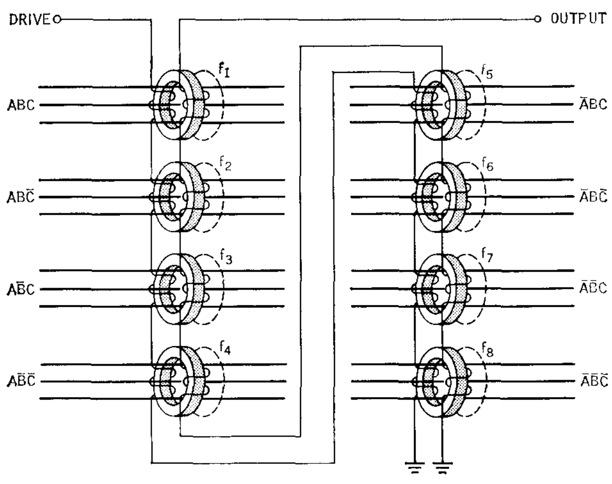
Table 1 **Magnetic patterns required to produce logic functions**

	2 Cores/Variable				4 Cores/Variable							
Logic Function	f_1	f_2	f_3	f_4	f_{11}	f_{12}	f_{13}	f_{14}	f_{21}	f_{22}	f_{23}	f_{24}
0	1	1	1	1	1	1	1	1	1	1	1	1
1	0	0	0	0	0	0	0	0	0	0	0	0
A	1	1	0	0	1	1	0	1	1	1	0	1
$\bar{A}$	0	0	1	1	0	1	1	1	0	1	1	1
B	1	0	1	0	1	1	1	0	1	1	1	0
$\bar{B}$	0	1	0	1	1	0	1	1	1	0	1	1
AB	1	1	1	0	1	1	0	1	1	1	1	0
$A\bar{B}$	1	1	0	1	1	1	0	1	1	0	1	1
$\bar{A}B$	1	0	1	1	0	1	1	1	1	1	1	0
$\bar{A}\bar{B}$	0	1	1	1	0	1	1	1	1	0	1	1
$A + B$	1	0	0	0	1	1	0	0	1	1	0	0
$\bar{A} + B$	0	0	1	0	0	1	1	0	0	1	1	0
$A + \bar{B}$	0	1	0	0	1	0	0	1	1	0	0	1
$\bar{A} + \bar{B}$	0	0	0	1	0	0	1	1	0	0	1	1
$A \forall B$	1	0	0	1	1	1	0	0	0	0	1	1
$\overline{A \forall B}$	0	1	1	0	1	0	0	1	0	1	1	0

1 = Recorded bit (magnetic field)
0 = No bit (no magnetic field)

functions is 2^{2^n}, where n equals the number of input variables. In general, the number of cores is 2^n where the n-input winding per core array is used and $n2^n$ where the single-input winding per core array is used. Figure 12 shows the matrix for three inputs using transformer sensing. For simplicity, only the magnetic field patterns for the add and carry functions of the possible 256 are demonstrated. With conventional core-storage sensing techniques, 30% modulation of the signal permits reliable detection of the matrix output. As can be seen for the core arrangement of Fig. 12, only one of the cores remains unbiased for all the combinations of functions required. All others are biased to saturation to minimize their contribution to the matrix output signal. Thus the modulation achieved in a single core determines, primarily, the output of the complete matrix.

Figure 12 **A 3-input, 8-core matrix.** *To perform a* SUM *function, fields f_1, f_4, f_6, f_7 must be present; to perform a* CARRY *function, fields f_1, f_2, f_3, f_5 must be present.*



Applications of variable logic

• *Code conversion*

Where the logic function is infrequently changed, a code-conversion device or translator is needed when various data transmission facilities having different coding systems are to share a common processing unit. This translator, to be useful, must be capable of converting from one of the possible codes to any one of the other codes. For such an application prerecorded patterns on magnetic cards can be changed manually to alter the logical operation that the matrix performs. Data in a serial mode can be processed at core-switching speeds. With such a universal device, the fabrication and stocking of parts is simplified. The logical functions performed could also be easily interchanged in the field.

- *Dynamic program loops*

The previous example considered an application where the variable matrix remained stationary relative to the logic pattern on the magnetic medium. A dynamic mode of operation can also be envisioned in which the logic pattern (program) can either move continuously or be incremented relative to the matrix. In each case, a means for synchronizing the data and logic patterns must be provided. Both the logic pattern and the information may be recorded on the same magnetic medium. If the logic-pattern density equals the information density then a new logic pattern or microprogram step is required for each bit of the word.

Method I

The logic patterns and information may be recorded on separate areas of the magnetic medium. In this case, a means for recording the information as well as the logic pattern must be provided. When the information is to be processed, it would be read into the matrix or matrices in synchronism with the appropriate logic pattern. The outputs could, in turn, be recorded for future processing.

Method II

It is also possible to modify the logic pattern in accordance with the information that the matrix is to process. The information need be stored only temporarily, rather than recorded, unless the same information is to be used again for different operations. If any input function is equal to ONE, then the logic pattern under the cores which are associated with this input function would not be altered; when the input function equals ZERO, then the logic pattern is modified by recording the bits under all cores associated with this function.

The data-modified-logic pattern could be recorded in one pass or the logic pattern could be pre-recorded and modified by data in another pass. For repetitive operations with different data, logic patterns modified by new information must be generated. For the above systems, where the data is synchronized on a bit-by-bit basis with the logic pattern, the speed of operation is limited by the density of the recorded pattern and by the velocity of the recording medium. This approach requires less hardware than that of Method I.

Method III

Repetitive operations on the information may be performed more rapidly if the logic pattern conditions the matrix for a time sufficiently long to permit many data bits to be processed for each pattern. This can be accomplished by appropriate synchronization of the data with the logic patterns, which could be recorded on two different magnetic disks moving at different speeds; or on the same disk, by using different bit densities. By such synchronization, the word length may be made variable. Of course, to have the ability to branch rapidly, additional matrices would be necessary.

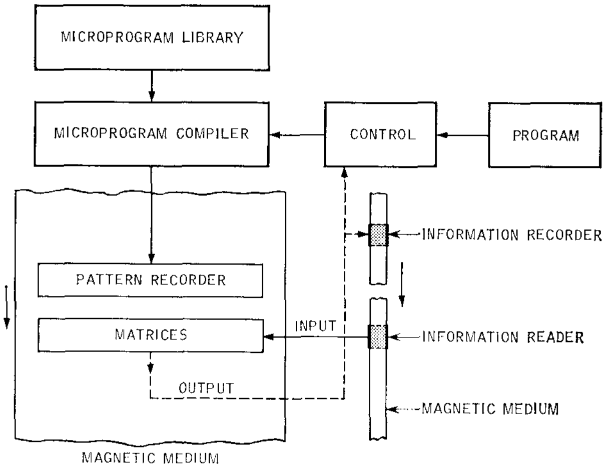


Figure 13 **System 1, program compiled by recording of microprograms.**

Variable-logic systems

Methods I, II, and III may be incorporated into different systems which can be classified into two groups depending on the method of handling of programs. The two methods of handling are described as follows.

- *Continuous method*

The program is compiled from appropriate microprograms on a continuous, dynamic basis. The microprogram compiler under program control selects the appropriate microprograms from the library. These are in the form of logic patterns and can be recorded with a multitrack recording head just ahead of the matrix or matrices. In the system shown in Fig. 13, the information is recorded on a separate medium and is read in synchronism with the logic patterns under the matrix. This information provides the input to the matrix. Output results can in turn be stored by recording, or be fed directly to other matrices. The physical spacing between recording heads and the matrix has the effect of instruction look-ahead. To permit branching, an interlock is necessary. Alternatively, branching can be accomplished by switching to a different matrix which is positioned adjacent to the desired subroutine.

- *Scanning method*

In this system, a library of subroutines or individual instructions is prerecorded on a magnetic medium which may be in the form of a disk. This could be accomplished "off-line" with a single recording head at low recording speeds. The logic pattern on this disk may be indexed to the desired position relative to the matrix (Fig. 14). Alternatively, the disk may rotate continuously and the matrix inputs and outputs could be synchronized with the appropriate logic pattern on the disk. This logic-scanning system is primarily suitable for low-processing-speed applications where the program flexibility, which this system permits, can effectively be exploited; for example, a manually-controlled desk calculator.

Variable-logic feasibility model

The feasibility model was organized in a manner similar to the system shown in Fig. 13. Two 3-input, 8-core matrices were employed so that the sum and carry functions could be generated concurrently. These matrices use the 3-input array shown in Fig. 12. The logic patterns are recorded on a drum serially by track through the manual positioning of a single recording head.

A photograph of the feasibility model is shown in Fig. 15. It consists of a drum, recording head, and matrices. The drum is four inches in diameter and is coated with 5 mils of NiCo with a maximum runout of 5 microns. The recording head is mounted on a notched bar which is parallel with the axis of the drum. This provides an easy means of recording the tracks that align with the cores of the matrices. The recording head is driven with a 0.5-ampere, NRZ signal through 50 turns wound on a laminated core of mu-metal, 15-mils wide, with a gap of 10 mils. The lower portion of the photograph shows a phenolic block, aligned parallel with the axis of the drum, containing the wired-core matrices. Figure 16 is a photograph of the matrix, with potting material removed to show the relationship of the 19/32/6 mil cores.

The sensing heads B, L, and R, which are cores similar to those used in the matrix, are located adjacent to the prerecorded timing tracks which provide the synchronizing control for both recording and operating programs. As shown in Fig. 17, Core B controls the bit rate, L the logic rate, and R the start and stop of the program. Once the pattern for a program (such as the one that includes the instructions to SUBTRACT and COMPARE) is recorded, the data is recorded on tracks A and B opposite the desired logic functions to be performed. The WRITE head, WH, is positioned on track C and the program is started by gating R to the logic counter. The result is recorded on track C via sense amplifier SA from Matrix 1.

This model proved that all of the 16 cores used for Matrices 1 and 2 gave uniform signals when affected by the complex field pattern. With a bias current of 250 mA and an alternating drive of 400 mA peak-to-peak, at 100 kc/sec, an output voltage of 200 mV was observed from each matrix. This was approximately equivalent to that observed from a single core. When operated at 20 bits/in.,

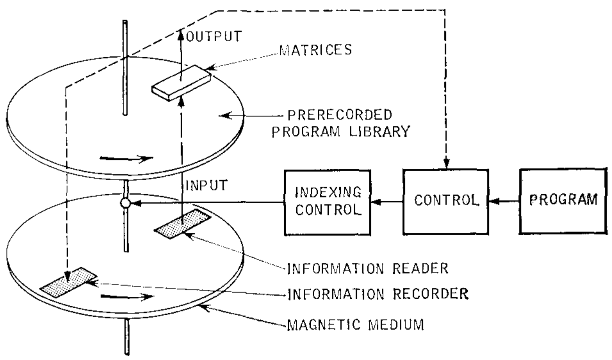


Figure 14 **System 2, prerecorded program indexed to matrix.**

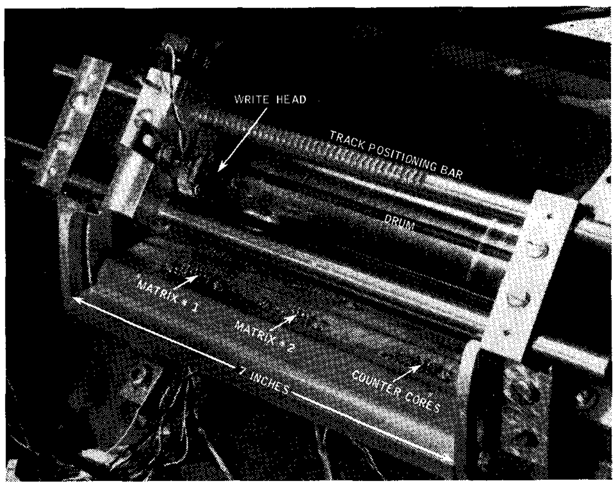


Figure 15 **Feasibility model of variable logic system.**

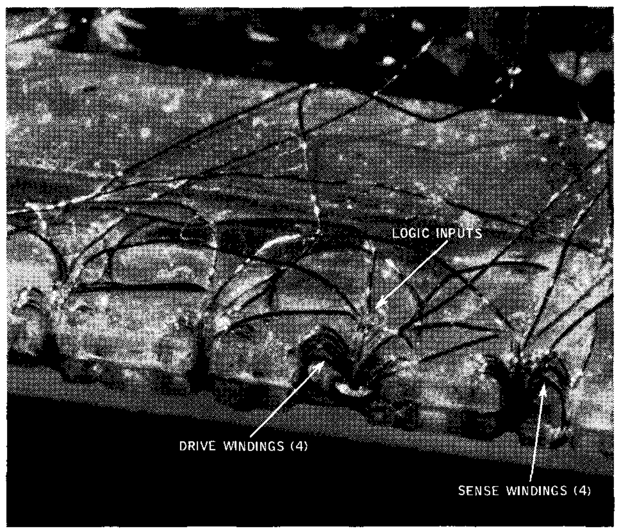


Figure 16 **Detail showing cores and windings in feasibility model.**

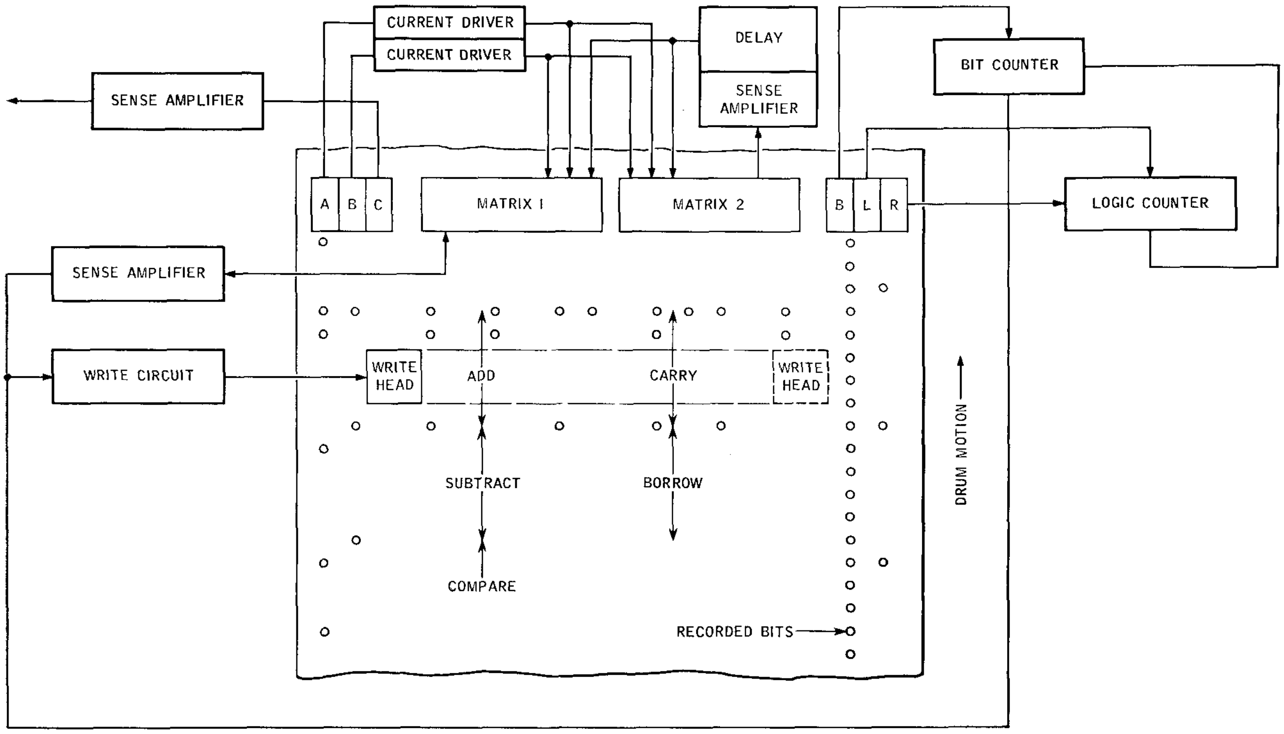


Figure 17 **Schematic diagram of feasibility model.**

a 60% modulation was reliably sensed with a core-to-drum spacing that varied from 1.0 to 1.5 mils.

Conclusions

The feasibility of matrix control by recorded magnetic patterns has been shown. A 30% modulation can be achieved with existing core materials at a bit density of 35 bits/in., using a 5-mil NiCo recording medium. The 30% modulation is adequate for reliable sensing of the matrix output. With cores of lower coercivity, the thickness of the recording medium could be reduced, with a corresponding increase in bit density. The separation between the matrix and the recording medium is critical and care must be taken to maintain a minimum separation over the length of the matrix. A 1.0-mil separation is adequate to achieve satisfactory results.

System applications of this device require a careful study of desired operating parameters. The degree of branching and the size of the programs would determine whether the system would be designed as a prerecorded indexing system or as a dynamic recording system. Cores and magnetic recording materials presently in use are satisfactory for the prerecorded system.

Logic speed is limited by the ferrite switching time instead of by the pattern density and media speed when one logic pattern per word is used. The dynamic recording technique, although technically feasible, requires costly recording circuitry for the parallel recording of logic patterns on the medium. Because of the strong magnetic fields required to record on these media, the requirements for magnetic head-driver circuits are more stringent than those for more conventional magnetic recording. The development of elements more sensitive than toroids could make such a system more economically attractive.

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Received November 21, 1963