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# A DIGITAL COMPASS,

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BY DANIEL S. LENKO

RESEARCH AND TECHNOLOGY DEPARTMENT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A digital magnetic compass has been developed using a two axis Brown type ring core magnetometer as earth's magnetic field sensor. Bearing is derived via a trigonometric algorithm where a commercially available calculator chip performs the required mathematical computations. Designed primarily for slow moving applications, the portable digital compass has a 4 digit LED bearing display and may be operated on internal batteries or from an external AC power supply.

# SUMMARY

This report documents the work performed by the Naval Surface Weapons Center to develop an Electronic Digital Compass. The unit utilizes a two axis magnetometer to sense the earth's magnetic field and digital electronic technology to compute and display the bearing.

This work had been initially sponsored by NAVELEX (Project PIXIE) and completed under the sponsorship of NAVSEA (0333C) Task No. SF33-300-31B (Sensors for Moored Mines).

The author gratefully acknowledges the contributions of Wayne R. Grine for fabricating the unit.

Paul R. Wessel

PAUL R. WESSEL
By direction

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FIGURES



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# I. INTRODUCTION

The preliminary goal of this effort was the development of a digital compass to be used on a floating sensor platform providing bearing on a real-time basis. The objective expanded to include adjectives such as general purpose, portable, battery-powered digital compass that resolves bearing to 1°. Added in the hope of broadening the scope of possible applications the digital compass requirements dictate that minimum cost, miniaturization, and low power be realized wherever feasible.

Because a floating sensor platform would be characterized as a slowly moving object (in a rotational sense), the compass did not have to be particularly fast in its bearing determining process and thus led to circuit simplifications discussed later in the report. This unit incorporates the Brown two-axis magnetometer as earth's magnetic field sensor and bearing is processed using a straightforward trigonometric algorithm carried out by a calculator chip.

The remainder of the report begins with an overview section in which a synopsis of the digital compass is presented; this is followed by the general description. Here we will discuss in more detail the various functional blocks of the system. Finally, the discussion touches on some observations, degree of success, future improvements, etc., of the digital compass prototype.

## II. OVERVIEW OF DIGITAL COMPASS

The two-axis Brown magnetometer (axes are orthogonal) provides two bipolar analog signals which define sine and cosine functions when the sensor is positioned in earth's magnetic field. These two analog signals are digitized by means of a Siliconix 3½ digit A/D converter. After dividing the Y-axis magnitude by the X-axis magnitude, the arc tangent of this ratio produces the reference angle. To derive the bearing, a constant corresponding to each quadrant must be added or subtracted from the reference angle. It should be noted that 0° (360°) indicates the X-axis of the magnetomter is pointing due north; here the X-axis output is a maximum and positive while the Y-axis output is zero. Figure 1 summarizes the definitions and sign conventions assumed for the magnetic elements.

The digital compass employs a calculator chip, managed by a microcoded ROM controller, to perform the mathematic operations on the digitized magnetometer outputs in the bearing derivation process. Instead of having the operator manually enter the digitized magnetometer data into the calculator chip and actuate the correct functions, the entire key stroke sequence is completed automatically. Figure 2, in the form of a flowchart, depicts the programming algorithm of the digital compass. Very briefly the flow of events to determine bearing now follows:

1. The A/D converter begins a Y-axis conversion.

2. Upon its completion, the digitized information is loaded into the calculator while an X-axis conversion is processed.

3. After the 4 digits of the Y-axis are in the calculator, the "enter" function is actuated (RPN).

4. The X-axis digitized information (4 digits) is loaded into the calculator.

5. The "÷" function is keyed.

6. "Arc tangent" is then actuated.

At this point the reference angle has been determined. By decoding the signs of the X and Y axes the program branches into four possible directions.

7. (a) If Y is (+), and X is (+), then the process is complete and the reference angle is the desired bearing. So the program immediately returns to step 1. Bearings (0°-90°).

(b) If Y is (+) and X is (-), then the reference angle is changed in sign (made negative) and is added to 180°. It then returns to step 1. Bearings (90°-180°).

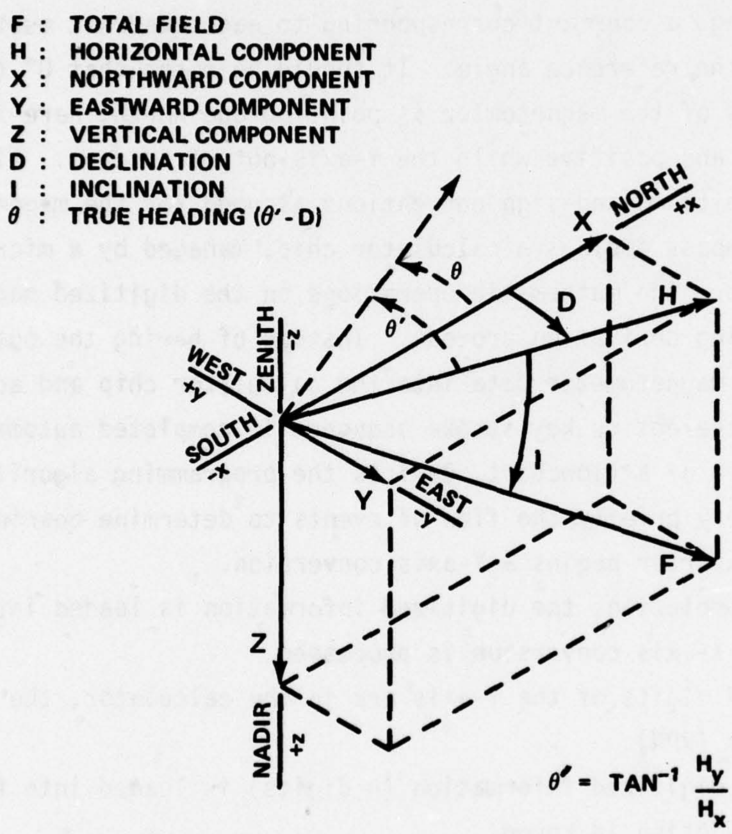


FIG. 1(U) DEFINITION AND SIGN CONVENTION FOR THE MAGNETIC ELEMENTS (U)

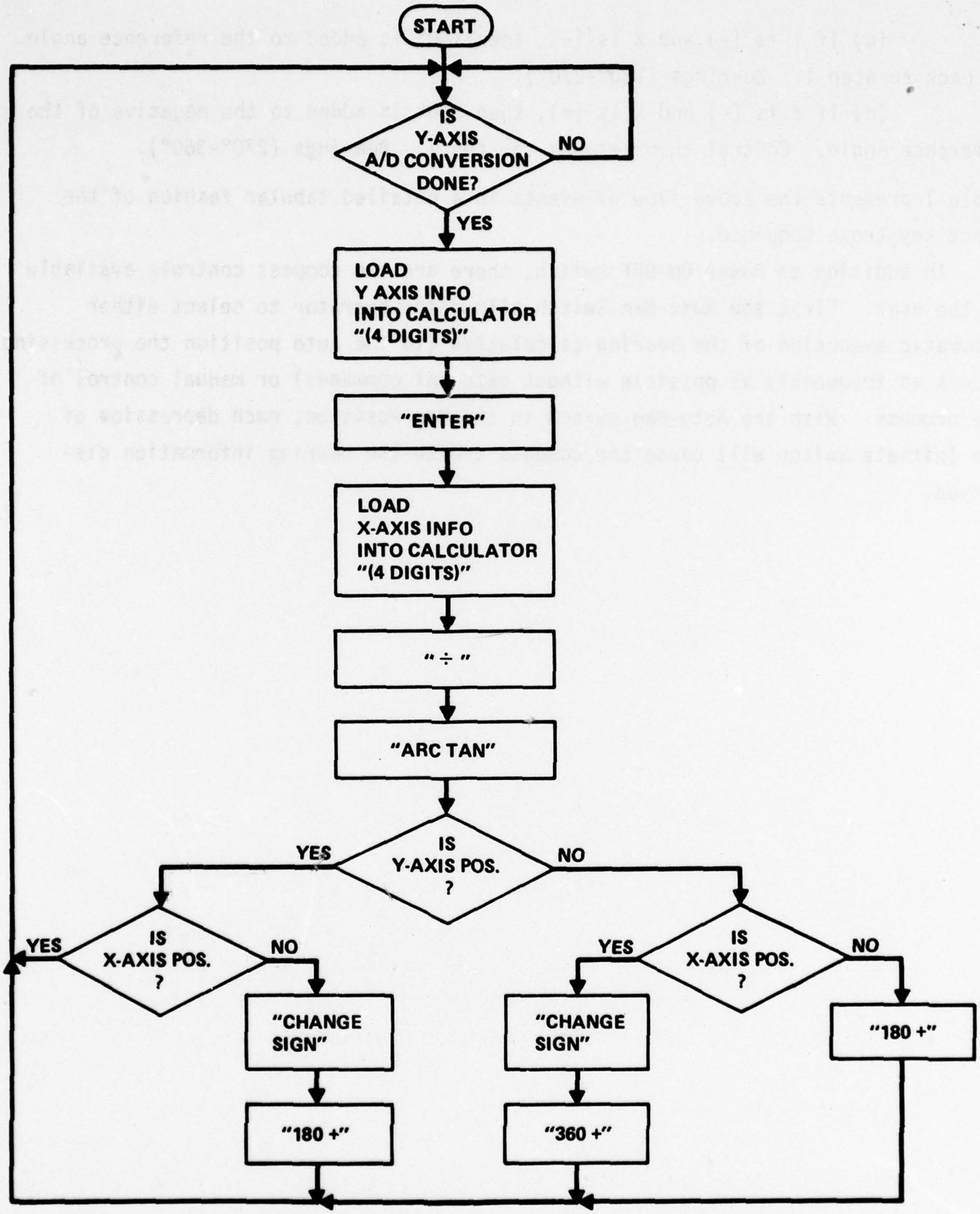


FIG. 2(U) DIGITAL COMPASS PROGRAM SEQUENCE

(c) If Y is (-) and X is (-), then 180° is added to the reference angle. Go back to step 1. Bearings (180°-270°).

(d) If Y is (-) and X is (+), then 360° is added to the negative of the reference angle. Control then returns to step 1. Bearings (270°-360°).

Table 1 presents the above flow of events in a detailed tabular fashion of the exact keystroke sequence.

In addition to Power ON-OFF switch, there are two compass controls available to the user. First the Auto-Man Switch allows the operator to select either automatic execution of the bearing calculation (in the auto position the processing occurs as frequently as possible without external commands) or manual control of the process. With the Auto-Man switch in the Man Position, each depression of the Initiate Switch will cause the compass update the bearing information displayed.

Table 1. Detailed Program Keystroke Sequence (Reverse Polish Notation)

| | | | |
|---|---|---|---|
| Start: | NOOP | (No operation) | |
| | D1 | (MSD) | Load 4 digits of Y-axis A/D conversion into calculator |
| | D2 | | |
| | D3 | | |
| | D4 | (LSD) | |
| | EN | (enter) | |
| | D1 | (MSD) | Load 4 digits of X-axis A/D conversion into calculator |
| | D2 | | |
| | D3 | | |
| | D4 | (LSD) | |
| | ÷ | (Y/X) | |
| | arc tan | (reference angle = arc tan (Y/X)) | |

| X axis: (+) Y axis: (+) | X axis: (+) Y axis: (-) | X axis: (-) Y axis: (-) | X axis: (-) Y axis: (+) |
|---|---|---|---|
| ↓ | ↓ | ↓ | ↓ |
| Go to start (Bearing = ref angle) (0°-90°) | CS (Change sign) | NOOP | CS |
| | 1 | 1 | 3 |
| | 8 | 8 | 6 |
| | 0 | 0 | 0 |
| | + | + | + |
| | Go to start (90°-180°) | Go to start (180°-270°) | Go to start (270°-360°) |

## III. GENERAL DESCRIPTION

The Digital Compass Functional Block Diagram is shown in Figure 3. Each block will be discussed individually with mention being made to its part in the overall system configuration. A complete circuit schematic appears at the end of the report in Figure 12.

a. TWO-AXIS BROWN MAGNETOMETER.

As stated before this magnetometer is used as the earth's magnetic field sensor. Reference 1 provides a detailed description of this unit. The two-axis outputs are fed to the 2 to 1 analog multiplexer inputs.

b. 2 TO 1 ANALOG MULTIPLEXER.

Because of the slowness of the calculator chip both during data entry and calculations, it was decided that instead of having two A/D converters (one for each axis of the magnetometer) one A/D converter would suffice. This would be accomplished by first A/D'ing the Y axis and then the X axis. Under the direction of the Control Logic hardware, this multiplexer switches on two SPST CMOS Analog Transmission Gates (½ of Siliconix DG201) alternately. The 2 to 1 Analog Multiplexer gates either the X or Y axis of the magnetometer to the input of the A/D converter.

c. A/D CONVERTER.

The Siliconix LD111/LD114 A/D Converter is employed in the digital compass. Factors leading to this selection are its reasonably low power consumption, BCD output format, and interface options. The A/D conversion technique is that of quantized charge-balancing in which an accuracy of .05% (of reading) is achieved. This unit also samples bipolar signals and has an internal auto-zeroing process. With a clock frequency of 71.5KHz, a conversion is completed every 86ms in a free-running fashion. In this application the interface options used are the Serial/Sequential digit scan where BCD data is shifted out in serial form with the least significant bit (LSB) of the least significant digit (LSD) outputted first. On command from the Control Logic, the serial data is loaded into a 16-bit serial-in/parallel-out shift register (two 74C164's). The Programming Logic then loads this BCD data into the calculator chip for processing. The

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1. Scarzello, J.F., and Usher, G.W., "SPVD Magnetic Sensor Development," NSWC/WOL/TR 76-58, June 1976 (Unclassified).

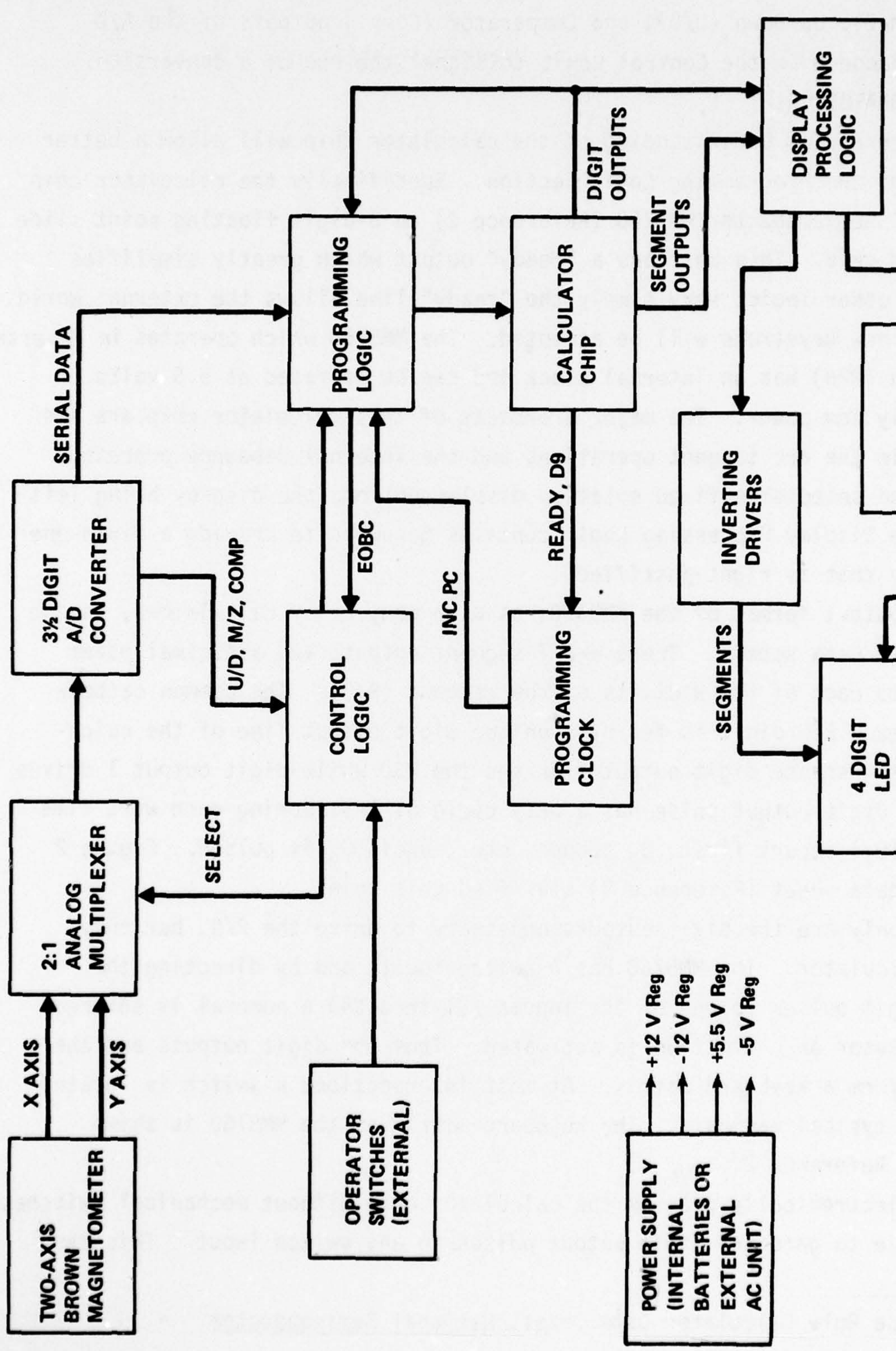


FIG. 3(U) DIGITAL COMPASS. FUNCTIONAL BLOCK DIAGRAM (U)

Measure/Zero (M/Z), Up/Down (U/D), and Comparator (Comp.) outputs of the A/D converter are decoded in the Control Logic to signal the end of a conversion.

d. CALCULATOR CHIP.

A superficial understanding of the calculator chip will allow a better understanding of the Programming Logic Section. Specifically the calculator chip is the National Semiconductor MM5760 (Reference 2) an 8-digit floating point slide rule calculator chip. This unit has a "ready" output which greatly simplifies interfacing to other logic; very simply the "ready" line allows the external world to know when a new keystroke will be accepted. The MM5760 which operates in Reverse Polish Notation (RPN) has an internal clock and can be operated at 5.5 volts consuming fairly low power. The major drawbacks of this calculator chip are its lack of speed in the arc tangent operations and the internal debounce process. Also there is no selectable fixed notation display option, the display being left-justified. The Display Processing Logic contains hardware to provide a fixed-one decimal display that is right-justified.

The output format of the MM5760, as with many other calculators, is one of a multiplexed data scheme. There are 7 segment outputs and a decimal point which connect to each of the 9 digits of the readout (R/O). The common cathode (or anode) of each R/O digit is fed by a unique digit output line of the calculator. In this instance digit output 9 drives the MSD while digit output 1 drives the LSD. Each digit output pulse has a duty cycle of 1/9; during each word time digit pulse 1 ($D_1$) occurs first, $D_2$ second, etc., until $D_9$ is pulsed. Figure 2 of the MM5760 data sheet (Reference 2) clarified this point.

Not only are the digit outputs necessary to drive the R/O, but they program the calculator. The MM5760 has 4 switch inputs and by directing the appropriate digit pulses to one of the inputs (K1 thru K4) a numeral is entered into the calculator or a function is activated. Thus the digit outputs and the switch inputs form a keyboard matrix. At most intersections a switch is located representing a typical keyboard. The keyboard matrix of the MM5760 is shown in Figure 3 of Reference 2.

To electronically program the calculator chip without mechanical switches, one must be able to gate any digit output pulses to any switch input. This can

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2. MM5760 Slide Rule Calculator Data Sheet, National Semiconductor.

be achieved by using a 9:1 multiplexer (the 9 digit outputs are the inputs to the multiplexer) followed by a 1:4 demultiplexer (whose outputs feed the 4 switch inputs of the calculator chip). The control of the multiplexer/demultiplexer is performed by the Programming Logic discussed next.

e. PROGRAMMING LOGIC.

Primarily this hardware section, under the supervision of a microcoded ROM Controller, is responsible for programming the calculator with the A/D converter data and the keystroke sequence necessary to process that data. This block consists of a program counter, the keystroke sequence and control PROM (I) (Programmable Read Only Memory), keyboard matrix PROM (II), the 9:1 data multiplexer and the 1:3 demultiplexer. In addition, there are the 16-bit shift register and 4 data multiplexers which are used in storing and loading of the A/D BCD data.

The original design was based upon the use of PROM's organized in a 32 word x 8 bit configuration. This necessitated employing two PROM's to achieve the desired programming. Subsequently, it was decided that the Intel 1702A EPROM's (Erasable PROMs--256 x 8 organization) were best suited for this digital compass prototype since it consumes less power than bipolar PROM's and is UV Erasable. A schematic (Figure 11) is included in this report which shows how to realize the Programming Logic by using just one 1702A PROM and other digital IC's resulting a reduction of circuit complexity and power consumption. Programming Tables 2 and 3 depict the bit pattern stored in PROM I and II respectively.

After the A/D converter completes a specified conversion, the digit-serial/bit-serial BCD data is loaded into the 16-Bit Serial-in/parallel-out shift register. This stored data is channeled to the simulated keyboard section via the four 8 to 1 data multiplexers whose select lines are controlled by PROM I outputs B1, B2 and B3. PROM I outputs B4 thru B7 also feed into the simulated keyboard hardware to program the various functions and constants. The simulated keyboard is composed of PROM II, the 9:1 multiplexer, and the 1:3 demultiplexer. PROM II outputs B4 thru B7 control the 9:1 multiplexer select lines while B1 thru B3 feed the 1:3 demultiplexer select lines.

A CMOS 4024 7-stage binary counter is used as the program counter (PC) where the $Q_1$ thru $Q_5$ outputs are connected to the address inputs $A_0$ thru $A_4$ of the PROM I respectively. This counter after being reset increments at the arrival of each clock pulse generated by the Programming Clock; possible states are $00000_2$ to $10010_2$.

Table 2. PROM I Data Listing.

| Address (Hex) | B8 | B7 | B6 | B5 | B4 | B3 | B2 | B1 | Comments | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | NOOP | | |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | D1 | MSD | Y Axis |
| 2 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | D2 | | |
| 3 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | D3 | | |
| 4 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | D4 | LSD | |
| 5 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | EN | (enter) | |
| 6 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | D1 | MSD | X Axis |
| 7 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | D2 | | |
| 8 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | D3 | | |
| 9 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | D4 | LSD | |
| A | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | ÷ | | |
| B | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | Arc | | |
| C | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | Tan | | |
| D | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | NOOP/CS | CS | |
| E | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 3 | |
| F | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 8 | 6 | |
| 10 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | |
| 11 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | + | + | |
| 12 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | NOOP | | |

NOTE: Addresses not listed are assumed to have $00_H$ as data.

Table 3. PROM II Data Listing.

| Address (Hex) | B8 | B7 | B6 | B5 | B4 | B3 | B2 | B1 | Comments |
|---|---|---|---|---|---|---|---|---|---|
| | Word Code Bits | | | | | | | | |
| 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| 2 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 2 |
| 3 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 3 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 4 |
| 5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 5 |
| 6 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 6 |
| 7 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 7 |
| 8 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 8 |
| 9 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 9 |
| A | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | en |
| B | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | ÷ |
| C | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | arc |
| D | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | tan |
| E | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | + |
| F | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NOOP |
| 10 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 3 |
| 18 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 6 |
| 1E | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | + |
| 1F | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | CS |

NOTE: Addresses not listed are assumed to have $00_H$ as data.

The function of the Programming Clock is to generate clock pulses that increment the PC (program counter). The PC should increment after each positive going transition of the calculator ready output; the occurrence of this edge indicates the calculator is able to accept new programming. Also the PC is incremented after the passage of 16 word scans without an intervening ready line positive edge. This is necessary primarily to begin a new bearing determination in both the automatic and manual operating modes. The 16 word scans are detected by a 7-bit binary counter whose clock input is being continuously fed by $D_9$ digit pulses of the calculator chip. Whenever the Ready line goes high or 16 consecutive word scans are counted (with the Ready line high) a 30 μs clock pulse is generated to increment the PC while clearing the scan counter.

To illustrate the functioning of the Programming Logic section, a partial schematic of the digital compass is shown in Figures 4, 5, and 6. Each diagram will demonstrate a specific program counter state with the logic levels being indicated at the appropriate signal lines.

In Figure 4, the PC state is $00010_2$ at which time the 2nd digit (D2) of the Y-axis A/D conversion is to be loaded into the calculator. PROM I outputs B4 thru B7 are all high enabling the 4 multiplexers' outputs to reach the PROM II $A_0$ thru $A_3$ address inputs. PROM I outputs B3, B2, and B1 are 0,0, and 1 selecting the $D_1$ input of the multiplexers. Notice that the 2nd digit D2 of the shift register feeds into the $D_1$ inputs of the multiplexers. Assuming D2 contained the number $3_{10}$, $0011_2$ appears on the multiplexer outputs and finally at the PROM II inputs. Looking ahead for the moment, to program the digit "3" into the calculator we must apply the calculator $D_3$ digit output pulses to the K4 input of the calculator. Referring back to Figure 4, we note that the select lines of the 9:1 multiplexer are $0010_2$, which channels the data present on the $D_2$ input ($D_3$ digit output pulses) to the multiplexer output. The $D_3$ digit pulses pass through an AND gate enabled by the ready line and is inputted to the 1:3 demultiplexer. The select lines of the demultiplexer are driven such that only the gate which feeds the $K_4$ input of the calculator is enabled. Thus we see that the $D_3$ digit output pulses are fed to the $K_4$ input resulting in the number "3" being loaded into the calculator.

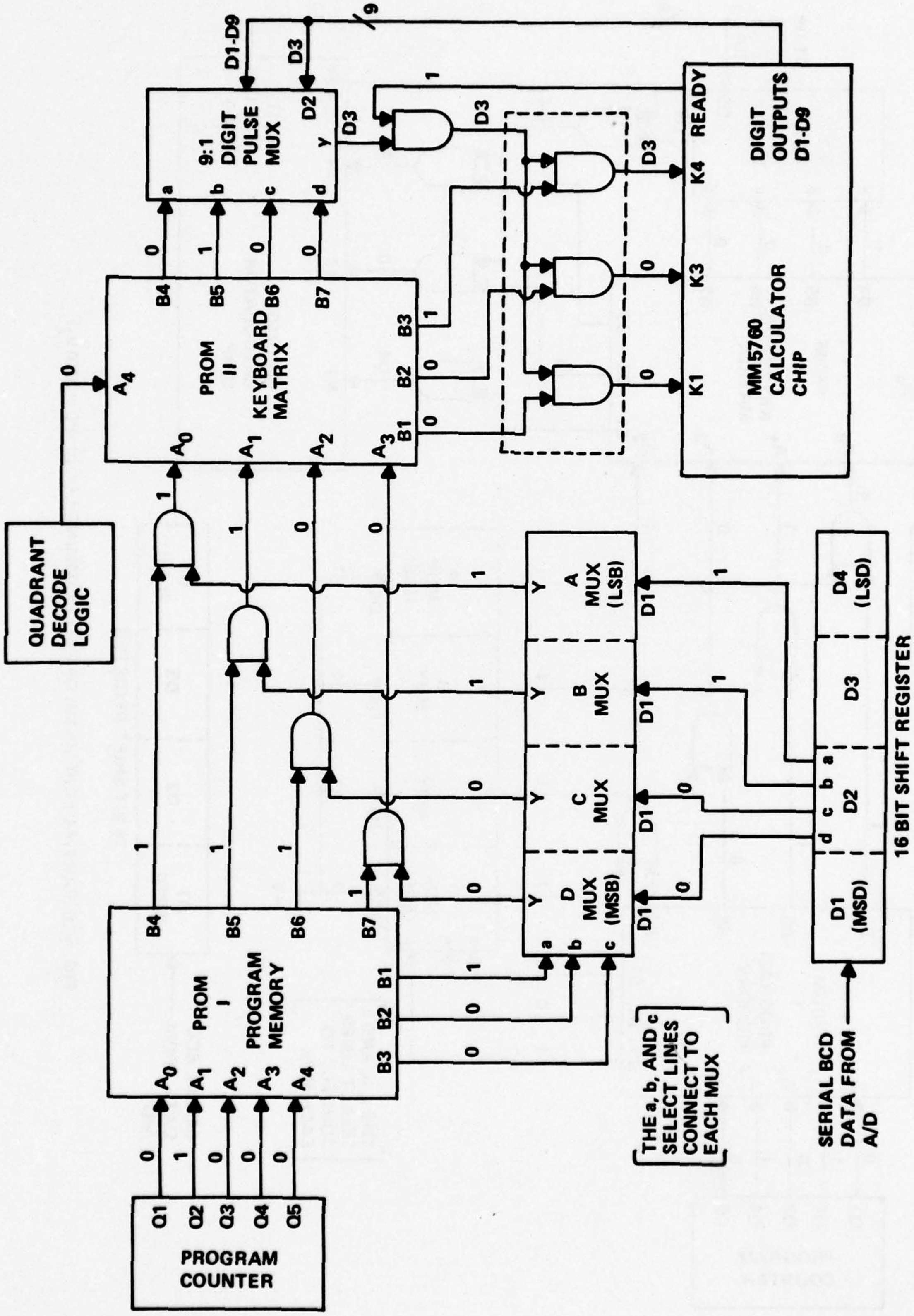



FIG. 4(U) PARTIAL SCHEMATIC OF PROGRAMMING LOGIC (PC = $00010_2$)

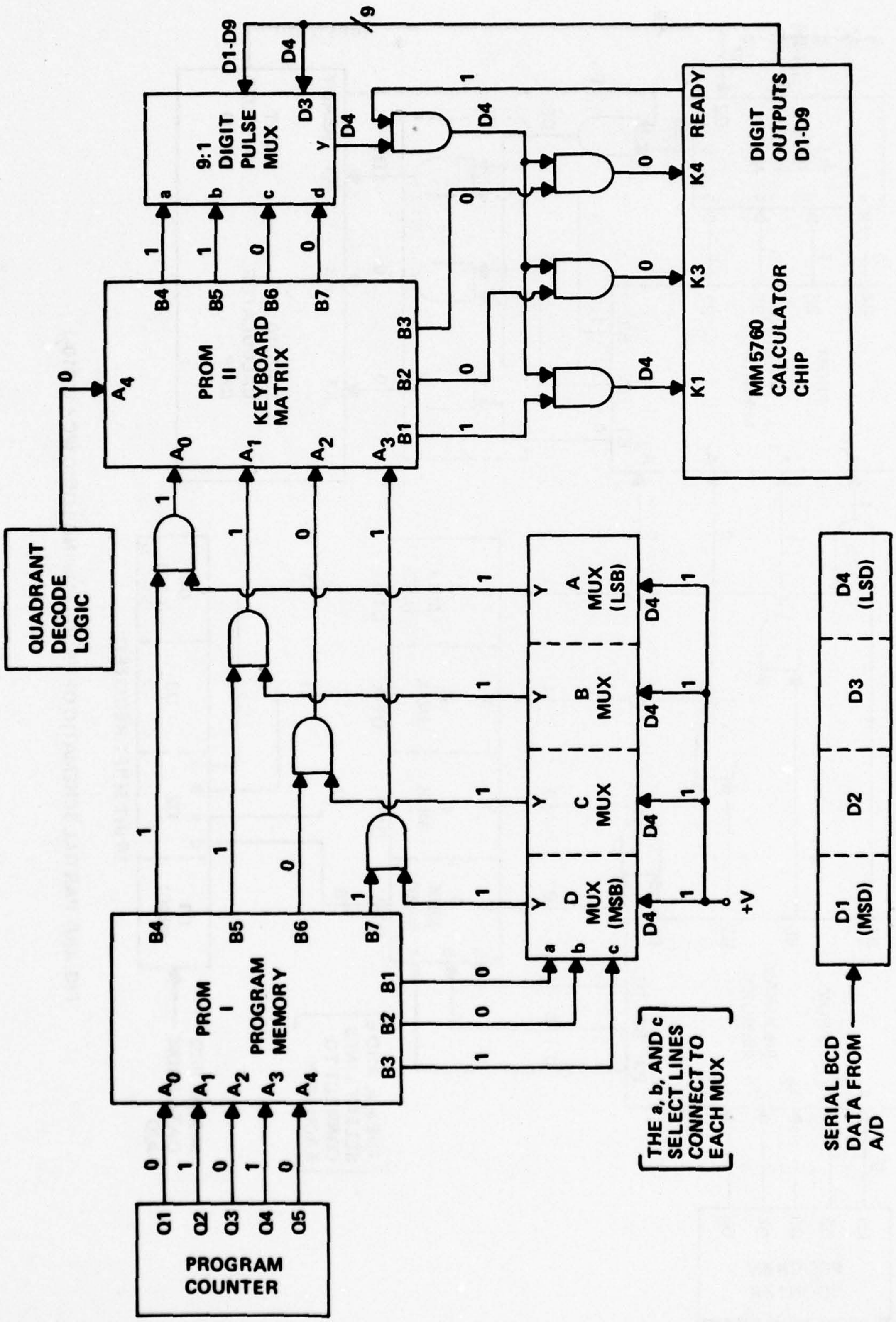



FIG. 5(U) PARTIAL SCHEMATIC OF PROGRAMMING LOGIC (PC = $01010_2$)

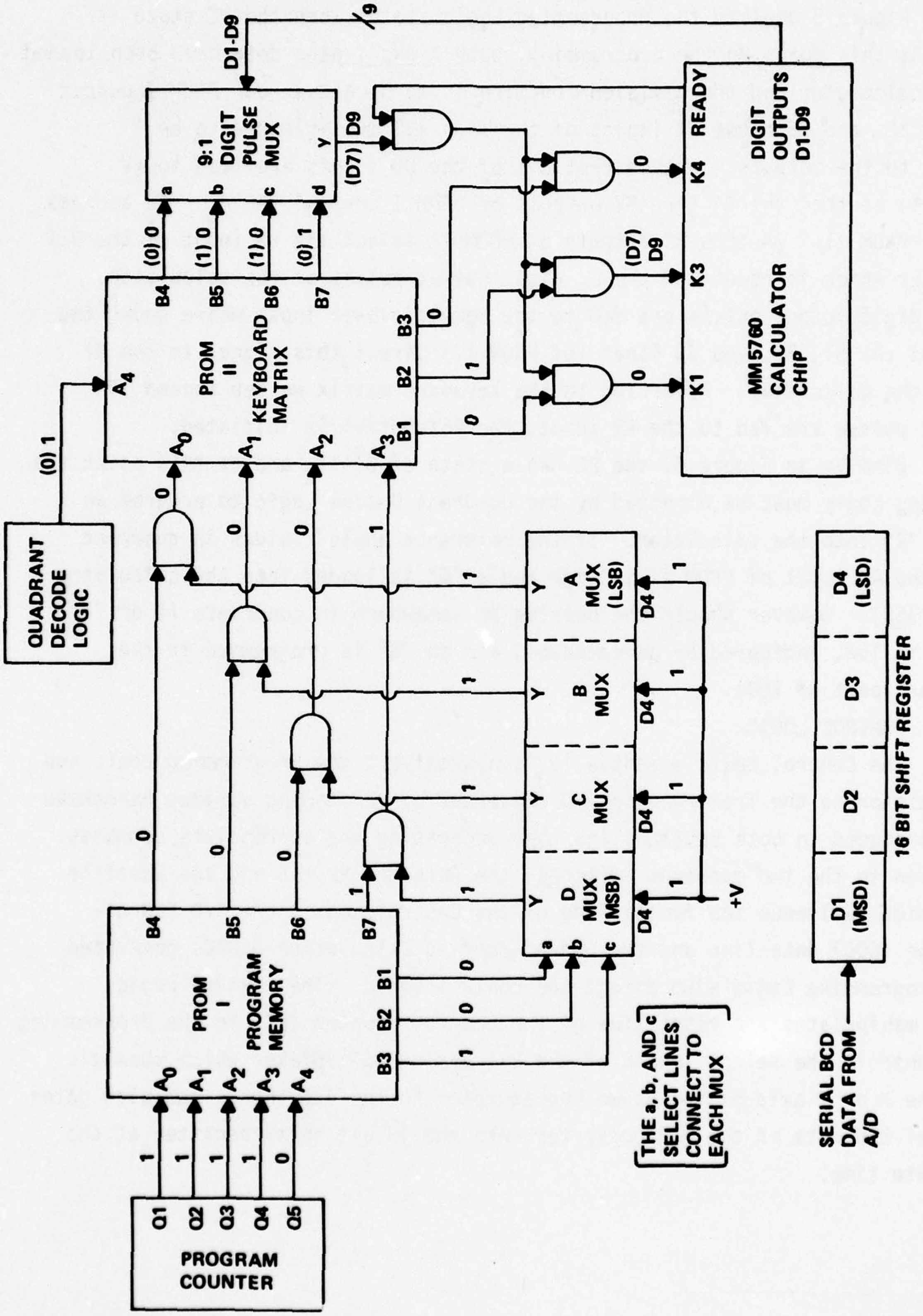



FIG. 6(U) PARTIAL SCHEMATIC OF PROGRAMMING LOGIC ($PC = 01111_2$) (U)

Figure 5 depicts the Programming Logic status when the PC state is $01010_2$. At this point in the programming, both X and Y axes data have been loaded into the calculator and the division function is to be actuated. PROM I output lines B1, B2, and B3 cause D4 inputs of the four 4:1 multiplexers to be channeled to the outputs. Notice that all of the D4 inputs are tied to +V (logical 1) so that the B4 thru B7 outputs of PROM I control the $A_0$ - $A_3$ address inputs of PROM II. B4 thru B7 outputs of PROM II select the D3 input of the 9:1 multiplexer which is receiving the $D_4$ digit output pulses of the calculator. These $D_4$ digit output pulses are fed to the demultiplexer input where under the control of the B1, B2, and B3 lines (of PROM II) direct this signal to the K1 input of the calculator. Referring to the keyboard matrix we see indeed if D4 output pulses are fed to the K1 input, the ÷ function is initiated.

Finally in Figure 6, the PC has a state of $01111_2$ and at this point the Programming Logic must be directed by the Quadrant Decode Logic to program an "8" or a "6" into the calculator. If the reference angle resides in quadrant IV then the $A_4$ input of PROM II is high and a "6" is loaded into the calculator (part of 3$\underline{6}$0). However should the bearing be somewhere in quadrants II or III, $A_4$ input is low, indicated by parentheses, and an "8" is programmed in the calculator (part of 1$\underline{8}$0).

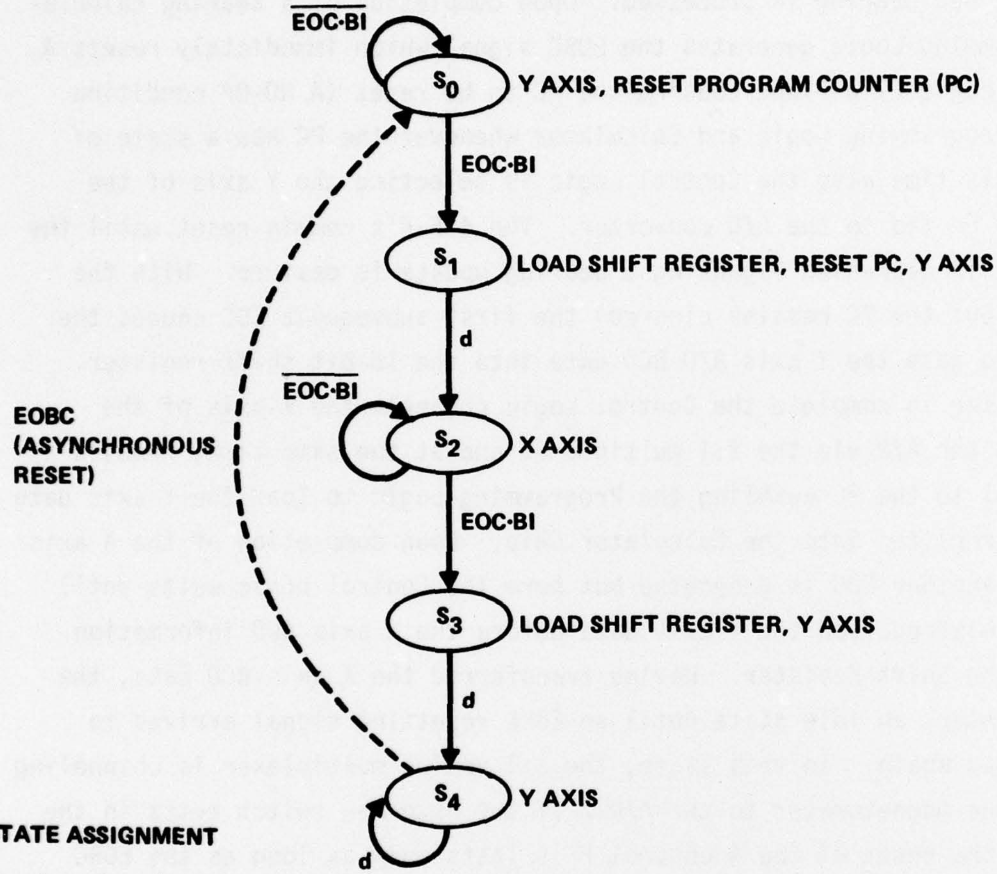
f. CONTROL LOGIC.

The Control Logic essentially "synchronizes" the Programming Logic and the Calculator to the free-running A/D converter by monitoring various handshake signals produced in both sections and then generating the appropriate commands. In addition to the two operator switches, the Auto-Man Switch and the Initiate Switch which influence the functioning of the Control Logic, the A/D End-of-Conversion (EOC) data line and the End-of-Bearing Calculation (EOBC) generated by the Programming Logic also direct the Control Logic. The Control Logic, in turn, manipulates the reset line of the program counter (PC) in the Programming Logic, controls the select inputs of the 2:1 Analog Multiplexer which channels either the X or Y axis of the Brown Magnetometer to the A/D input, and also gates the serial BCD data of the A/D converter into the 16 bit shift register at the appropriate time.

A typical sequence of events is now presented assuming the Auto-Man Switch is in the Man (Manual) position. Recall that this will cause the most recent bearing calculation to remain displayed until the Initiate Switch is depressed and a new bearing is processed. Upon completion of a bearing calculation the Programming Logic generates the EOBC signal which immediately resets 4 of the Control Logic Flip-Flops causing the PC to be reset (A NO-OP condition exists in the Programming Logic and Calculator whenever the PC has a state of $00000_2$). At this time also the Control Logic is selecting the Y axis of the magnetometer to be fed to the A/D converter. The 4 F-F's remain reset until the Initiate Switch is depressed signaling a bearing update is desired. With the reset removed (but the PC remains cleared) the first subsequent EOC causes the Control Logic to gate the Y axis A/D BCD data into the 16-bit shift register. Once that transfer is complete the Control Logic channels the X axis of the magnetometer to the A/D via the 2:1 multiplexer and at the same time, removes the reset signal to the PC enabling the Programming Logic to load the Y axis data from the shift register into the Calculator Chip. Upon completion of the X axis A/D conversion another EOC is generated but here the Control Logic waits until the calculator has received the Y axis' data before the X axis BCD information is gated into the Shift Register. Having transferred the X axis BCD data, the Control Logic enters an idle state until an EOBC resetting signal arrives to begin the process again. In this state, the 2:1 analog multiplexer is channeling the Y axis of the magnetometer to the A/D. If the Auto-Man switch rests in the Auto position, the reset of the 4 control FF's lasts only as long as the EOBC persists (about 1 μs) meaning that the bearing update process begins immediately after an EOC pulse occurs not requiring a depression of the Initiate Switch. Thus in the Auto Mode, bearing determination is completed as frequently as possible where the speed of the A/D and calculator chip are the limiting factors. The state diagram and state assignment of the Control Logic is shown in Figure 7.

g. DISPLAY PROCESSING LOGIC.

In order to provide an acceptable machine-man interface, the Display Processing Logic manipulates the bearing information outputted by the calculator chip in two important ways. Assuming the Digital Compass was in the Auto Mode of operation and the calculator chip directly was driving the LED 4 digit ReadOut (R/O), most of the time either the display would be blank or portraying useless




**STATE ASSIGNMENT**

| | Y2 | Y1 | Y0 |
|---|---|---|---|
| $S_0$ | 0 | 0 | 0 |
| $S_1$ | 0 | 0 | 1 |
| $S_2$ | 0 | 1 | 1 |
| $S_3$ | 1 | 0 | 1 |
| $S_4$ | 1 | 0 | 0 |

NOTES:
1. THE OPERATION OCCURRING IN EACH STATE IS LISTED TO THE RIGHT.
2. X AXIS/Y AXIS RELATES WHICH MAGNETOMETER AXIS IS CHANNELED TO THE A/D
3. EOC·BI IS ASSERTED JUST AFTER THE COMPLETION OF AN A/D CONVERSION AND THE CALCULATOR IS WAITING FOR DATA
4. d ≡ DON'T CARE

**FIG. 7(U) STATE DIAGRAM OF CONTROL LOGIC**

intermediate results. Thus a memory chip was added to store the bearing data at the end of each sampling providing a non-blinking R/O presentation. Secondly, a desirable feature missing from this calculator chip is a selectable fixed decimal display function. The output of the calculator is in a floating point, left-justified format and if we would look at the left-most 4 digits, the number of decimal places in the result will vary (the desired resolution is tenths of degrees). For example, should the bearing be less than 100°, then possible outputs could be 15.64°, 4.218°, and .6319°. Consequently, hardware is included in the Display Processing Logic to provide a "fixed 1" right-justified display format regardless of the bearing; the same examples above become 15.6°, 4.2°, and .6° respectively.

More specifically the display storage hardware consists primarily of a 4 word x 8 bit CMOS Read/Write Memory IC. Calculator digit pulse outputs $D_5$, $D_6$, $D_7$ and $D_8$ are binary encoded and drive the two address inputs of the RAM chip. The multiplexed segment outputs of the calculator chip are fed to the data inputs of the RAM while the RAM Data outputs directly control the Inverting Segment Drivers of the R/O. During the first complete word scan after an EOBC pulse, the Write line is activated under the direction of the 3-state control hardware and the segment information present during $D_5$, $D_6$, $D_7$ and $D_8$ is stored into locations $11_2$, $10_2$, $01_2$, and $00_2$ respectively in the memory. After this "write" scan, the Digit pulses remain unchanged and thus the RAM is continuously accessing the segment information in an identical sequence as when it was stored. In summary instead of the calculator driving the R/O directly, a 4 x 8 RAM is inserted between the calculator and the segment drivers to provide a 4 digit non-blinking bearing display.

The hardware that addresses the problem of deriving a fixed-1 decimal, right-justified 4 digit display from a left-justified floating point calculator format is now briefly discussed. Since the segment memory mentioned above is outputting data that is synchronized with the calculator digit outputs, we must generate the digit select signals which are modified (delayed as needed) to be in synchronism with same segment information. In Figure 8, the timing relationships between the calculator digit pulses and the common anode (digit select) R/O signals are shown for the four possible bearing results. Notice that to adjust

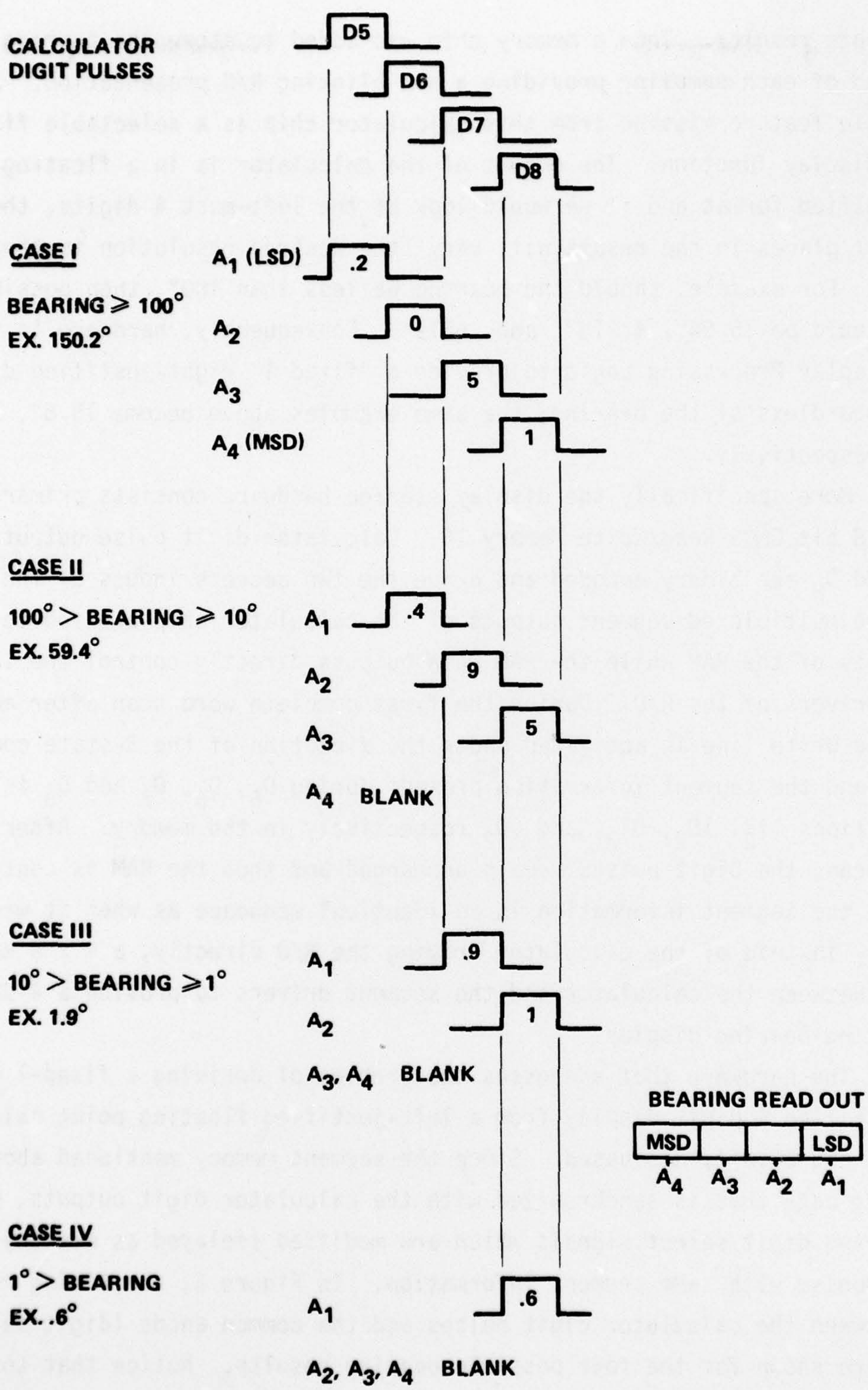



FIG. 8(U) TIMING RELATIONSHIP BETWEEN CALCULATOR AND R/O COMMON ANODE PULSES (U) the display to be right-justified and with one decimal place, the common anode pulses may be delayed by as much as 3 digit times; the total number of delays reveals the number of digits blanked beginning with the MSD. By monitoring the position of the decimal point in the calculator R/O it can be determined how many delays are necessary.

A 4-bit serial-in/serial-out shift register is used to store the decimal point position relative to $D_6$, $D_7$, $D_8$ and $D_9$ just after the completion of a bearing calculation during the "write" scan. After this, the shift register is configured to function in a circular shift fashion where the clock pulses are derived from the leading edge of $D_5$, $D_6$, $D_7$ and $D_8$. A second 4-bit shift register (serial-in/parallel-out) was added to actually control the four anode drivers. Here the output of the first shift register becomes the data input to the second with the clock inputs of both being tied together. The first output stage of the second shift register produces the LSD common anode pulse (A1) while the fourth stage generates the anode pulse (A4) for the MSD. Again referring to the timing diagram in Figure 8, the anode signals A1 through A4 are depicted in relation to the calculator digit pulses $D_5$ through $D_8$. Actually the decimal point in the LED R/O is not driven by the calculator decimal point output but is hard-wired to glow with each A1 pulse.

h. DIGIT/SEGMENT DRIVERS AND R/O.

The display elements selected for the Digital Compass were .3" common anode, 7 segment LED R/O's. The four digits were wired for multiplex operation to realize hardware minimization but necessitating the use of high current drivers. Since typical duty cycles approach 1/9, peak currents are quite high. Therefore, the four anode pulses A1 thru A4 generated by the 4-bit shift register are heavily buffered by the Anode Drivers before reaching the LED R/O's. Also the segment outputs of the CMOS RAM are inverted and buffered in order to adequately drive the multiplexed R/O segments.

## IV. DISCUSSION

The digital compass circuitry described in the preceeding sections was fabricated and this prototype is shown in photographs of Figures 9 and 10. Just to the left of the R/O is located the Power Switch which can energize the circuitry via internal batteries or an external AC power supply (not shown). The Auto-Man switch is positioned to the right of the display while the Initiate push button is found on the far side of the compass housing. The circuit board which can be seen in Figure 10 contains the calculator chip, display RAM, and the Programming Logic; beneath it is a second circuit board holding most of the Control logic, A/D, and Display Processing logic. Finally, the magnetometer is mounted to the bottom of the compass housing below the second circuit board. Non-magnetic materials and hardware were used to fabricate the unit and it was attempted to demagnetize the batteries installed in an effort to minimize earth's magnetic field distortion near the sensor.

The specifications of the digital compass are summarized below:

1. power consumption - 2.6 watts 70% of which is used by the LED R/O
2. maximum bearing processing time - 1.5 sec
3. chip count - 40 (5 - LSI)
4. weight - 3.9 lbs (1.75 Kg) w/o batteries
5. dimensions - 7.5" (19cm) wide, 11" (28cm) deep and 4 ½" (11.5cm) high

As for accuracy, bearing is correct to about ±1 degree even though tenths-of-degrees are indicated on the display; tenths were included to simplify interfacing to the calculator output. It appears that the major source of error is due to the nonorthogonality of the sense windings in the magnetometer sensor.

Taking advantage of hindsight, several improvements to the digital compass are in order should other units be constructed. First, as stated before, the PROM's used in the programming logic are the 1702A's (256x8) whereas the circuit was designed for two 32 word x 8 bit PROM's. By utilizing more of the memory space in the 1702A, the programming logic is realizable with just a single 1702A and this implementation in depicted in Figure 11. This modification effects a decrease of 5 in the overall chip count including 1 LSI chip. To further reduce energy consumption Liquid Crystal Displays (LCD) could be used instead of the power-hungry LED's; for low ambient light conditions a small light would be necessary since the LCD's do not emit light themselves.

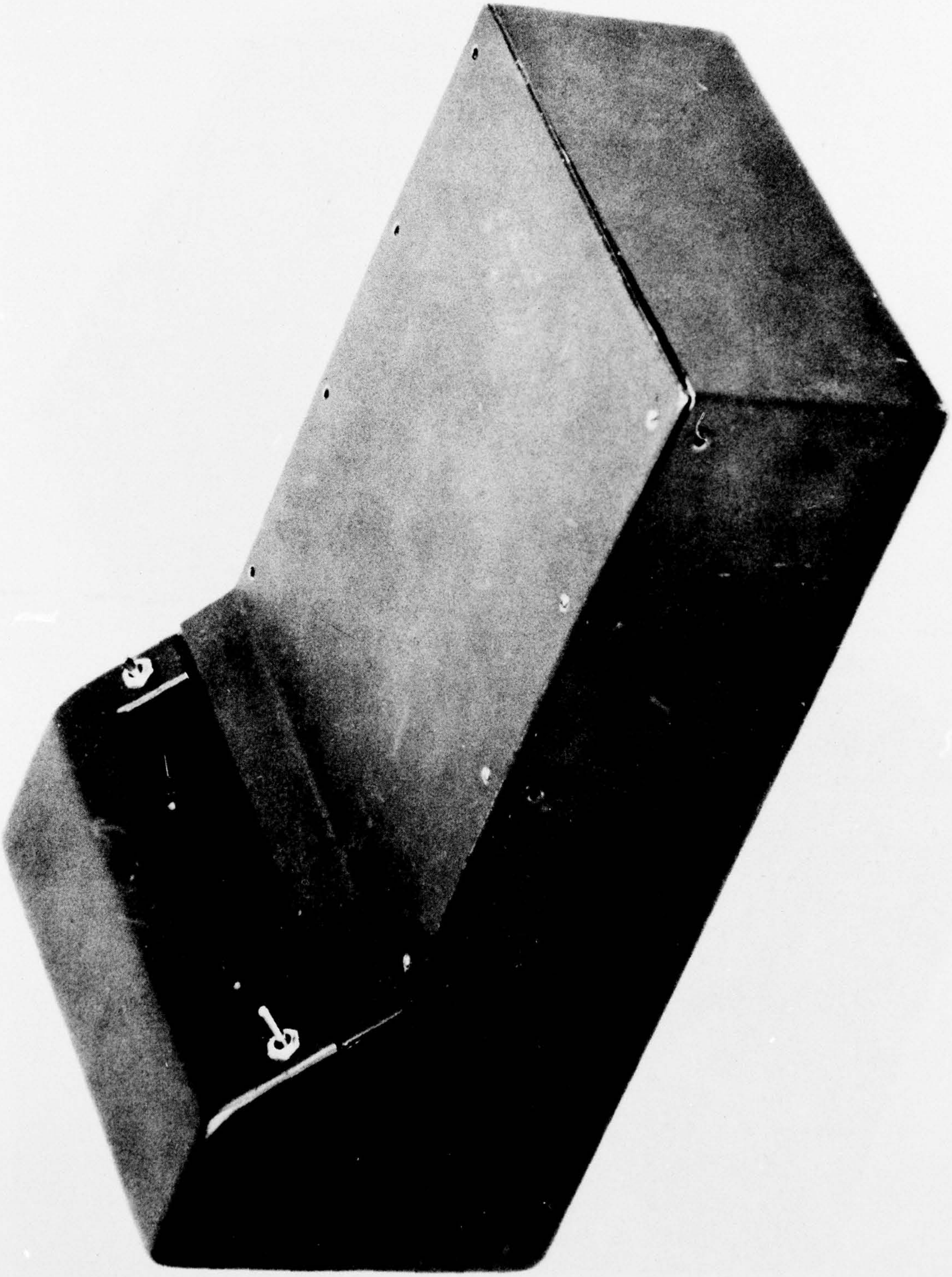


FIG. 9(U) DIGITAL COMPASS PROTOTYPE (U)

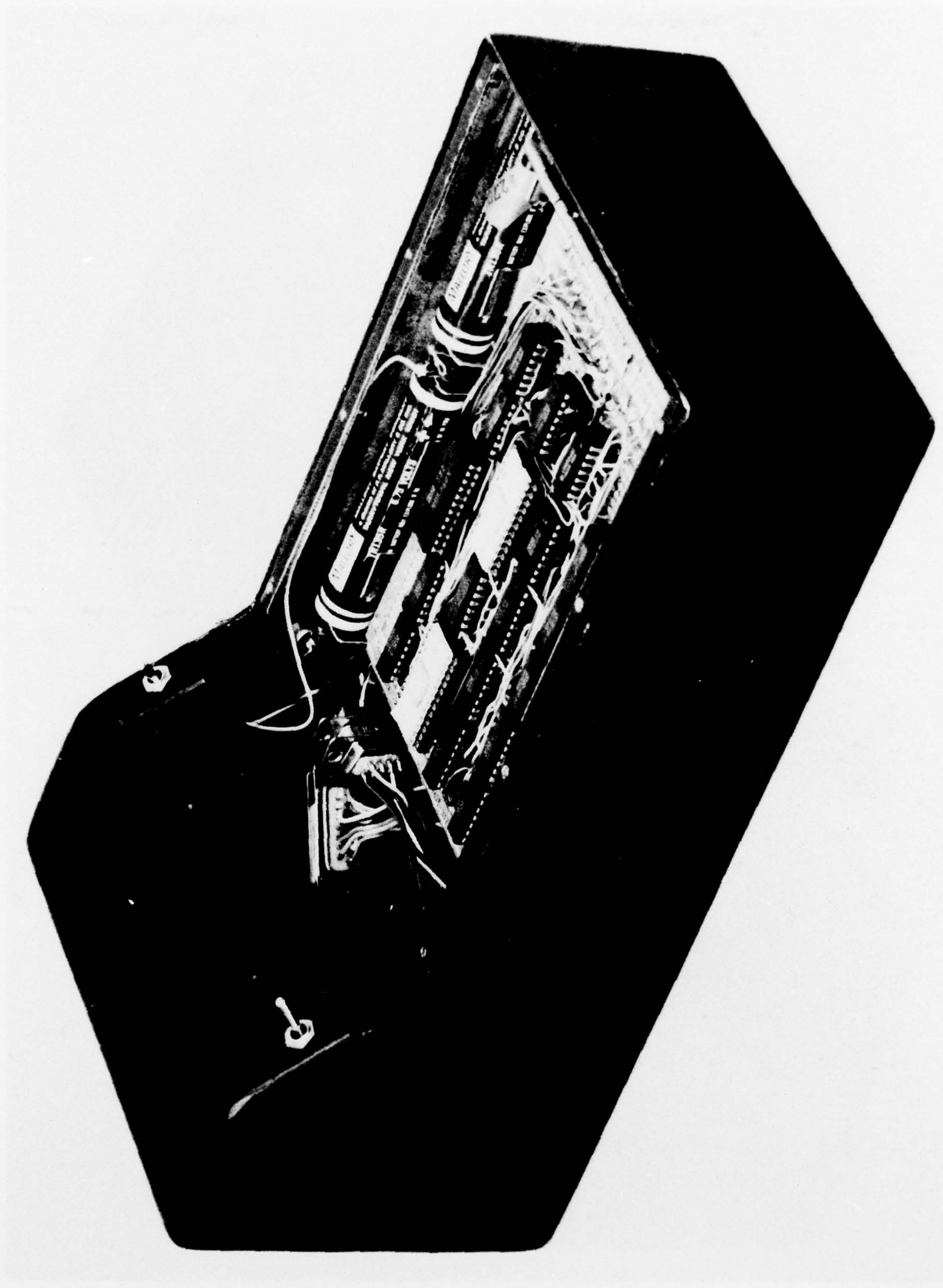


FIG. 10(U) DIGITAL COMPASS PROTOTYPE (COVER REMOVED) (U)

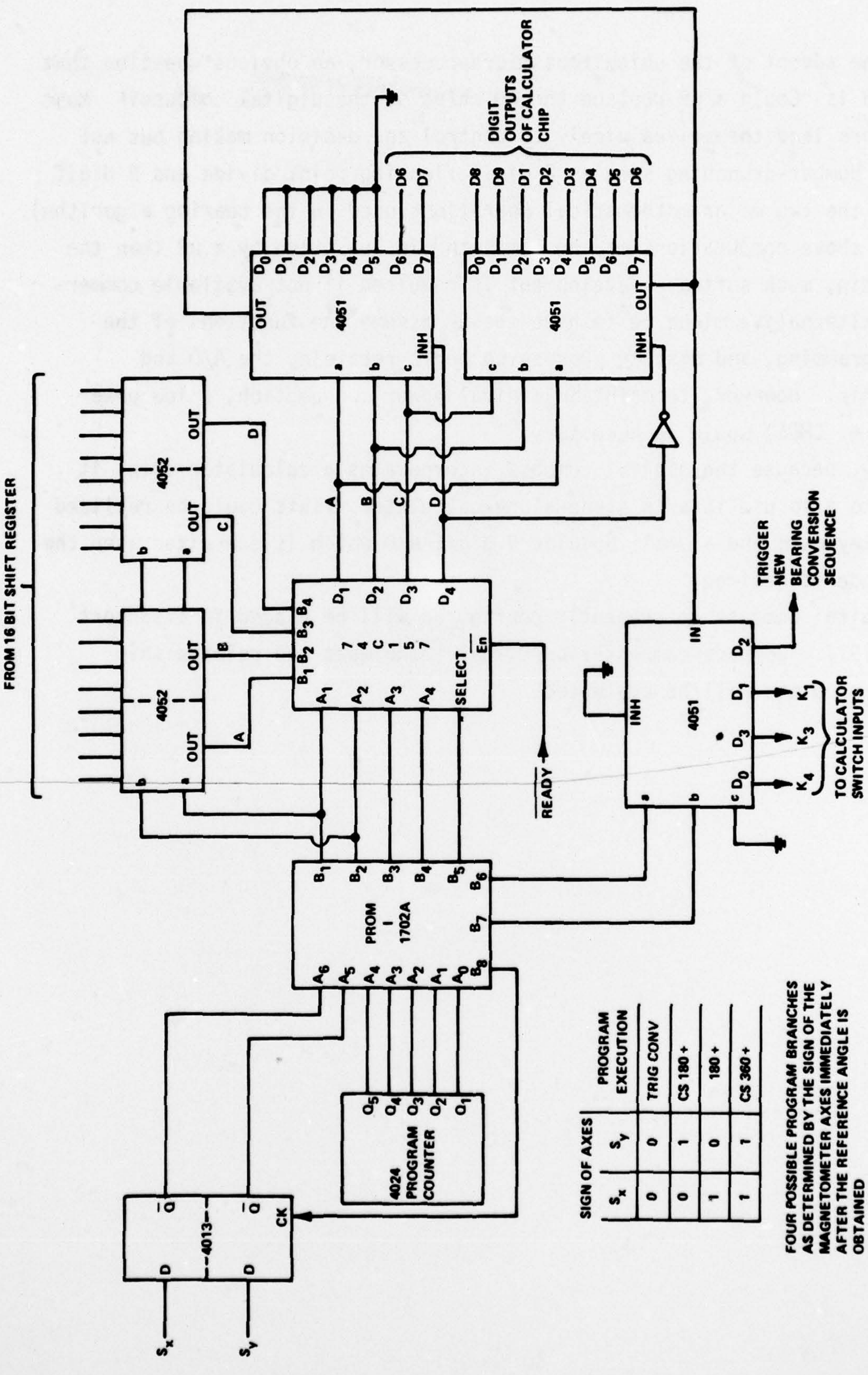
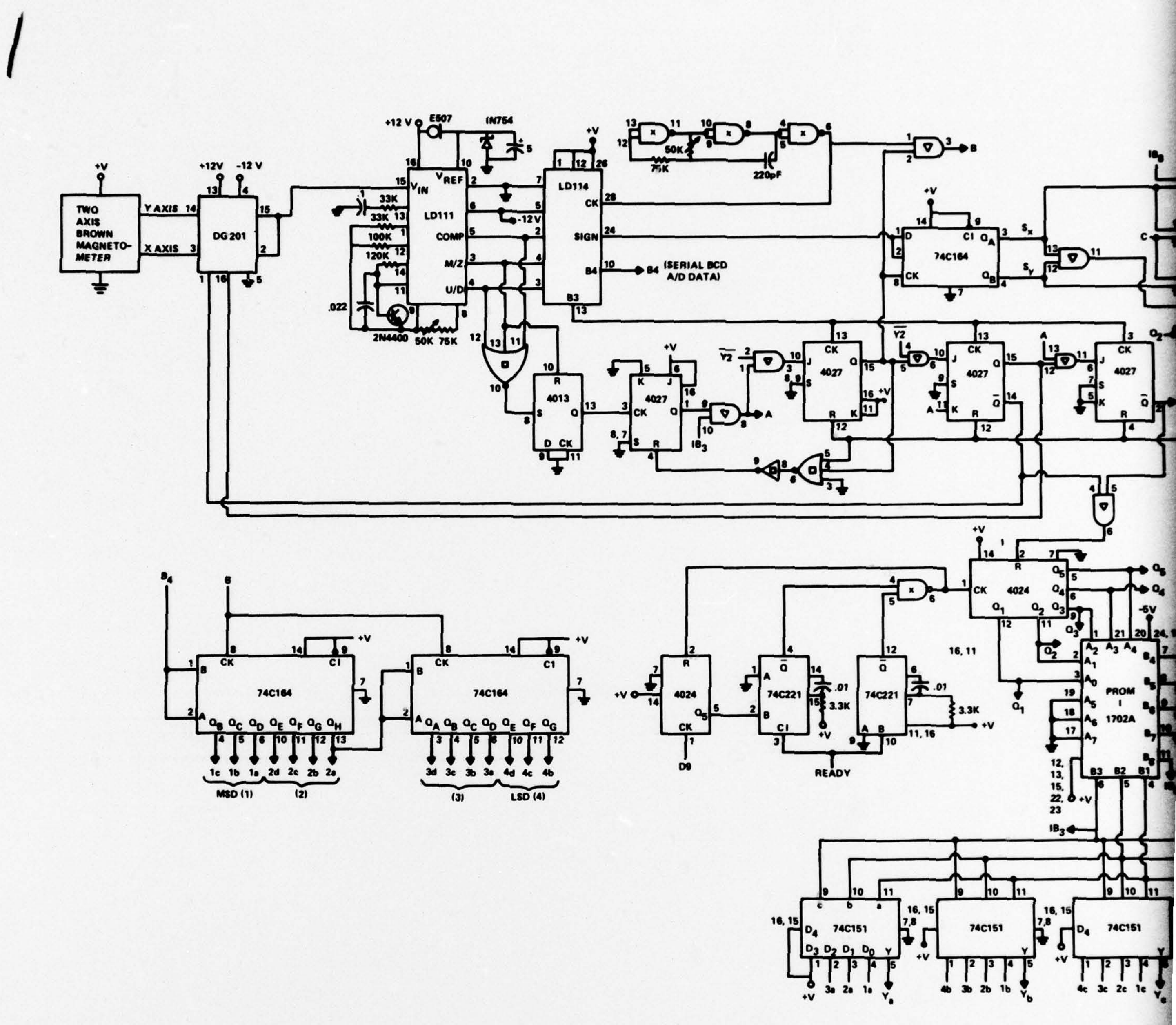



FIG. 11(U) PROGRAMMING LOGIC SIMPLIFICATION (USING ONLY 1 PROM)

With the advent of the ubiquitous microprocessor, an obvious question that comes to mind is "Could a μP replace the 40 chips of the digital compass?" Most microprocessors lend themselves nicely to control and decision making but not very well to number-crunching such as 8 digit floating point divide and 8 digit arc tangent (the two major mathematical operations used in the bearing algorithm). Although the above computations may be completed in less time by a μP than the calculator chip, much software development is required if not available commercially. An alternative might be to have the μP assume the functions of the control, programming, and display processing Logic retaining the A/D and calculator chip. However, to maintain minimal power consumption, a low power μP system (i.e. CMOS) would be necessary.

Finally, because the digital compass incorporates a calculator chip, it is possible to also use it as a stand-alone calculator. This could be realized by adding a keyboard and a small modular 9 digit R/O which is energized when the calculator mode is desired.

The Digital Compass as presently configured will be placed in a support ship in Aug 1977. Compass compensation/Gimbal techniques and related ship installation problems will be evaluated.


TWO AXIS BROWN MAGNETO-METER
Y AXIS
X AXIS
DG 201
LD111
LD114
(SERIAL BCD A/D DATA)
2N4400
1N754
4013
4027
4024
74C164
74C221
74C151
PROM I 1702A
READY
MSD (1)
LSD (4)

7

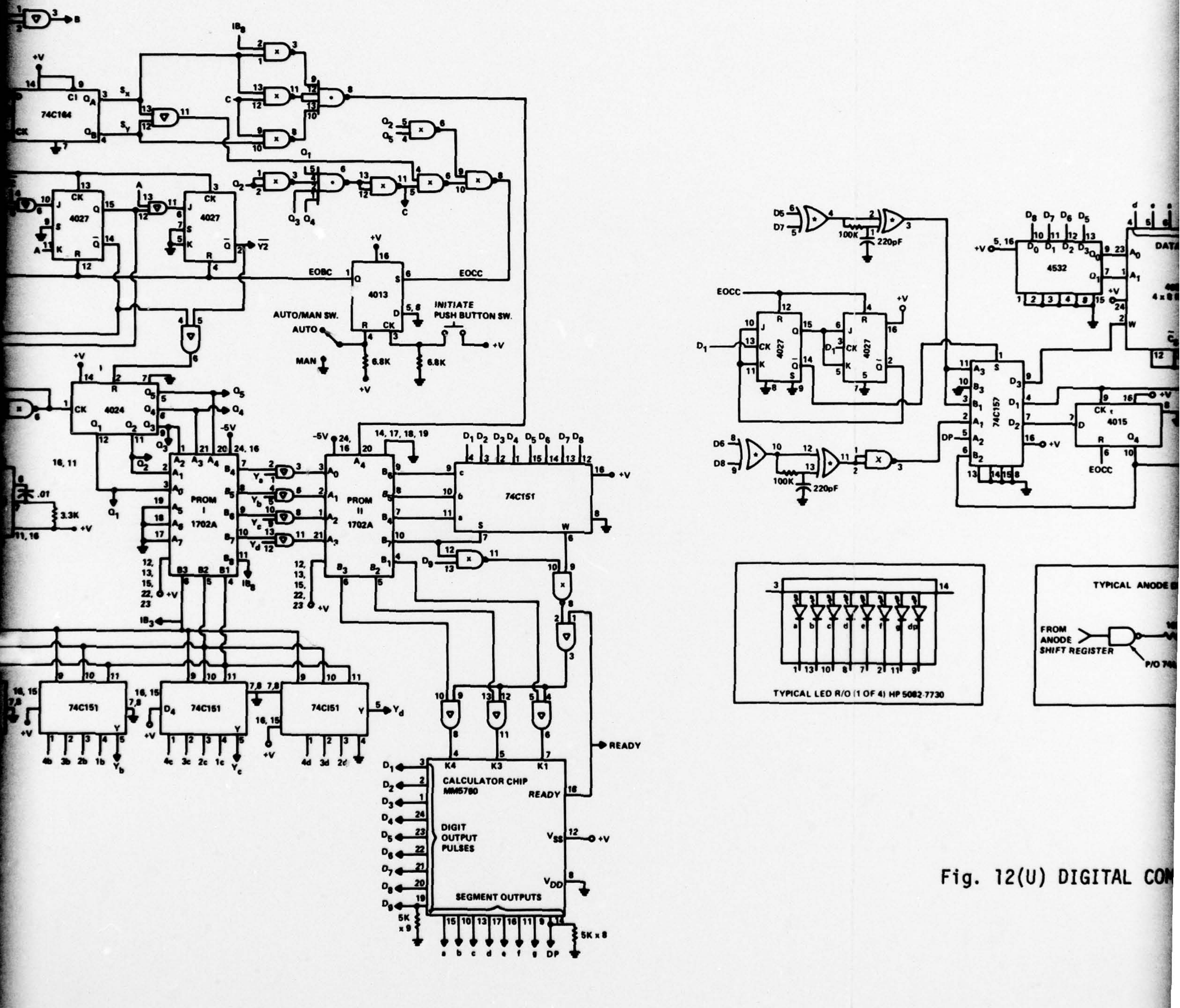
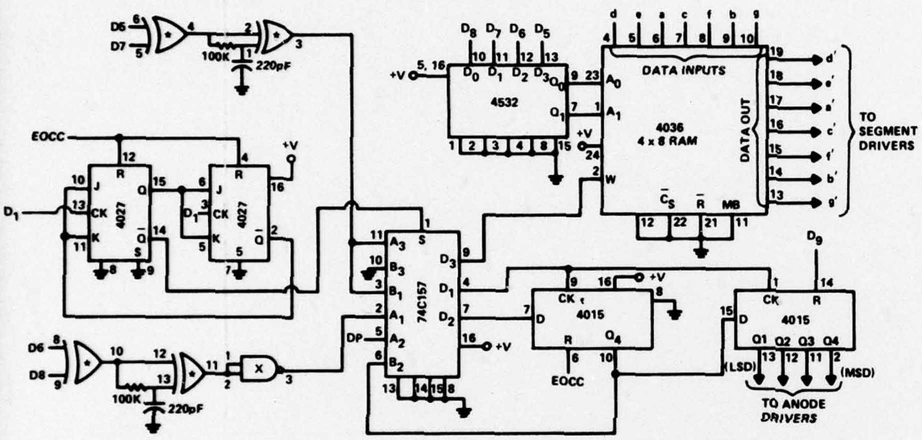



Fig. 12(U) DIGITAL CON

3



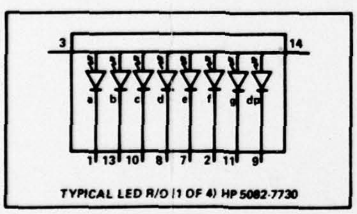

PWR SUPPLY REQUIREMENTS

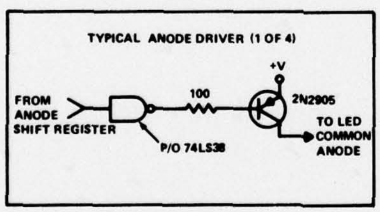
| VOLTAGE | CURRENT |
|---|---|
| +5.5V (+V) | 400 MA |
| + 12V | 6 MA |
| - 5V | 22 MA |
| - 12V | 19 MA |

INTEGRATED CIRCUIT SYMBOLS AND RESPECTIVE PWR SUPPLY PINOUTS

| SYMBOL | | +V | GND |
|---|---|---|---|
| x | 74C00 | 14 | 7 |
| □ | 4001 | 14 | 7 |
| ▽ | 74C08 | 14 | 7 |
| • | 74C20 | 14 | 7 |
| * | 4030 | 14 | 7 |

CAPACITANCE IN μF
RESISTANCE IN OHMS



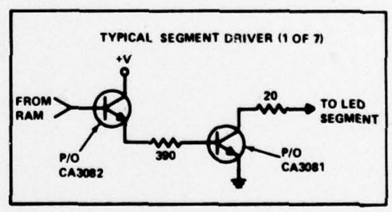




Fig. 12(U) DIGITAL COMPASS SCHEMATIC DIAGRAM (U)

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