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BRUSHLESS DC MOTORS, VELOCITY AND POSITION CONTROL OF THE BRUSHLESS DC MOTOR

by

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Brushless DC Motors, Velocity and Position Control of the Brushless DC Motor

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

A velocity feedback controller for the brushless DC motor was designed using the Hall effect sensors. In addition, the position control of the brushless DC motor was developed using an optical encoder to sense angular position changes and a microprocessor to provide the desired position control. A Pittman 5111 wdg #1 brushless DC motor was used for this study. The design of the digital tachometer and pulse width modulator for velocity control and the design of the Z-80 based microprocessor controller and software design are described in detail.

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I. INTRODUCTION

In recent years, the brushless DC motor has found more applications because of its many advantages. It offers long operational life, it eliminates brushwear particles and arcing, and it is adaptable to spacecraft requirements.

As more specialized needs become obvious, the versatility of the brushless DC motor in applications to control systems was discovered and developed.

The brushless DC motor is mainly an inside out version of the conventional DC motor. The rotor consists of permanent magnets and the windings are in the stator. Besides this, the areas where the conventional DC motor and brushless DC motor differ are in the commutation processes and the amplifier design. The commutation of the conventional DC motor is done by a mechanical commutator and brushes. On the other hand, the commutation of the brushless DC motor is performed by semiconductor switching elements, usually transistors. The inductive switching energy is dissipated through a diode path which allows the current to decline in a controlled fashion.

The commutation sensor system for brushless DC motors is required to control the logic functions of the controller to maintain current to the proper coils in the stator. Hall effect sensors and optical incremental encoder sensors are the most commonly used methods for the angular position sensing system.

The Hall effect sensing system is based on sensors which are usually placed in the stator structure to sense the polarity and magnitude of the permanent magnet field in the air gap.

The optical increment encoder provides a pulse for each increment of angular resolution. It is most commonly a combination of light-emitting diode (LED), rotating disk, mask and phototransistor.

The Pittman 5111 Wdg #1 brushless DC motor and four-phase drives were used for this study. One motor had a Hall sensor and another motor had a Hall sensor and an optical incremental encoder as well.

The velocity control of the system was designed by using the fact that the Hall sensor gives two pulses per revolution for a four pole motor. By counting the intervals between each revolution, the digital speed can be obtained. With this idea in mind, a digital tachometer was designed. The speed command was given by dip switches and converted to the analog signal. The digital speed which was obtained from the digital tachometer was converted to an analog signal with a Digital to Analog Converter (DAC).

The Pittman four-phase drive accepts four inputs. Two of them are the logic signals from the Hall effect sensors. One of the inputs is the direction command. The other input is used for on-off control of the motor which is a convenient logic input to apply a pulse width modulation signal for speed and torque control. Keeping this feature in mind, the pulse width modulator was designed.

In recent years microprocessor systems have been useful tools with many applications. These involve the use of the brushless DC motor, and the microprocessor control of the brushless DC motor. Of its many features one of the most important is the ease with which a system can be modified to perform new functions. This can be easily done by writing a new software program. Assembly language or high level languages such as Forth, Basic, Fortran, C, Pascal and Ada can be used for programming and can be downloaded to the EPROM.

The microprocessor controller was designed by using a Z-80 control processor unit. Parallel interfacing was used to communicate with the outside world (the CRT terminal and pulse width modulator). Position commands were given from the CRT terminal and the updated position of the motor was observed from the terminal also.

In Chapter Two the brushless DC motor is compared with conventional DC motors and drive circuits. The third chapter's emphasis is on the velocity control of the brushless DC motor and the building of the digital tachometer and pulse width modulator. In Chapter Four testing and data collection of the velocity control system are studied. The position control of the system with the microprocessor controller is discussed in Chapter Five. In Chapter Six testing and data collection of the position control system are studied.

II. CONSTRUCTION AND OPERATION OF BRUSHLESS DC MOTORS

A. CONSTRUCTION OF BRUSHLESS DC MOTORS

Brushless DC motors, unlike conventional DC motors have a permanent-magnet rotor and a multi-coil stator. It can be said that the basic brushless DC motor is essentially an "inside out" version of the conventional DC motor. A cut-away of a conventional DC motor is shown in Figure 2.1 and an equivalent version of a brushless DC motor is shown in Figure 2.2. Here we can see the permanent magnet rotor and a multi-coil stator.

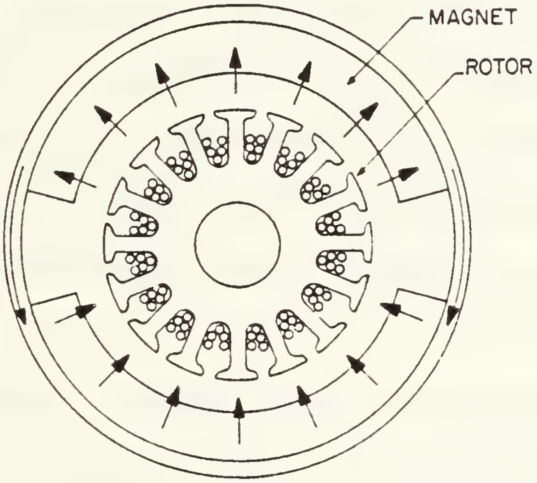


Figure 2.1. Cut-Away View of Conventional DC Motor Assembly.

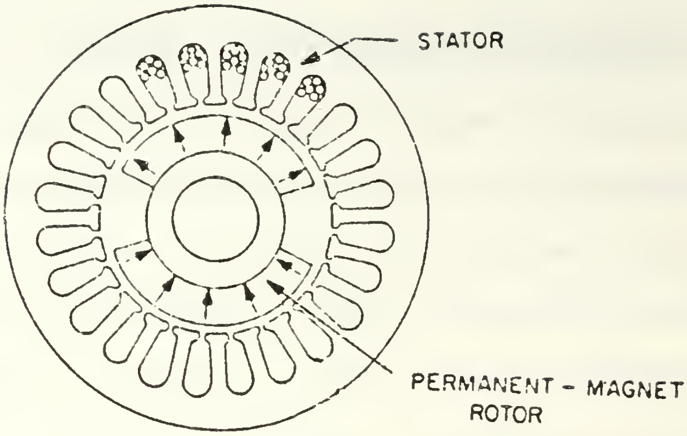


Figure 2.2. Cut-Away View of Brushless DC Motor Assembly.

A significant difference can be seen in the winding and magnet locations. The conventional DC motor has the active conductors in the slots of the rotor, and in contrast, the brushless DC motor has the active conductors in slots of the stator. Since the windings are closer to the environment the removal of the heat produced in the active windings is easier in the brushless DC motor. The result is that the brushless DC motor is a more stable mechanical device from a thermal point of view.

Another basic difference from the conventional DC motor is the commutation process. The commutation of the conventional DC motor is done by a mechanical commutator and brushes. The brushless DC motor, on the other hand, is commutated electronically.

B. ELECTRONIC COMMUTATION AND DRIVE

In order to see the similarities and differences between conventional and brushless DC motor systems, two sketches are shown in Figures 2.3 and 2.4. In Figure 2.3 we have the elements of DC motor and control. The connections between the rotor windings and the commutator are shown. In Figure 2.4 the commutation control stage is different from the conventional DC motor. Slots, windings, magnetic poles, and the electronic commutator work in such a way that the direction of the rotation is controlled by the polarity of the DC power supply. By an electronic commutator, the current is switched from one coil group to the adjacent one with a four section stator winding. Switching takes place from one coil to the next four times per revolution for a two pole motor. Since the switching transistors are already in place in electronic commutation, pulse width modulation can be applied to the logic circuit. The shaft position sensor creates pulses to generate logic signals which control the commutation of the windings.

One of the simple, three-phase brushless DC motor circuits is shown in Figure 2.5. This is a "half-wave" control circuit with a conduction angle of 120^o. As is shown, each winding is used one third of the time and the logic control of the system is not complicated. The speed and torque output of the motor can be controlled by varying the power supply voltage V_s. In the lower part of the diagram the same system can be seen in reversed torque. The torque reversal in a conventional DC motor is achieved by reversing the power supply voltage. In the brushless DC motor the same thing can be done by shifting all the logic functions by 180°. This example illustrates one of the basic differences between conventional and brushless DC motors.

In the illustration of Figure 2.5, the inductive transient current in each winding is ignored. Due to the voltage produced by the stored

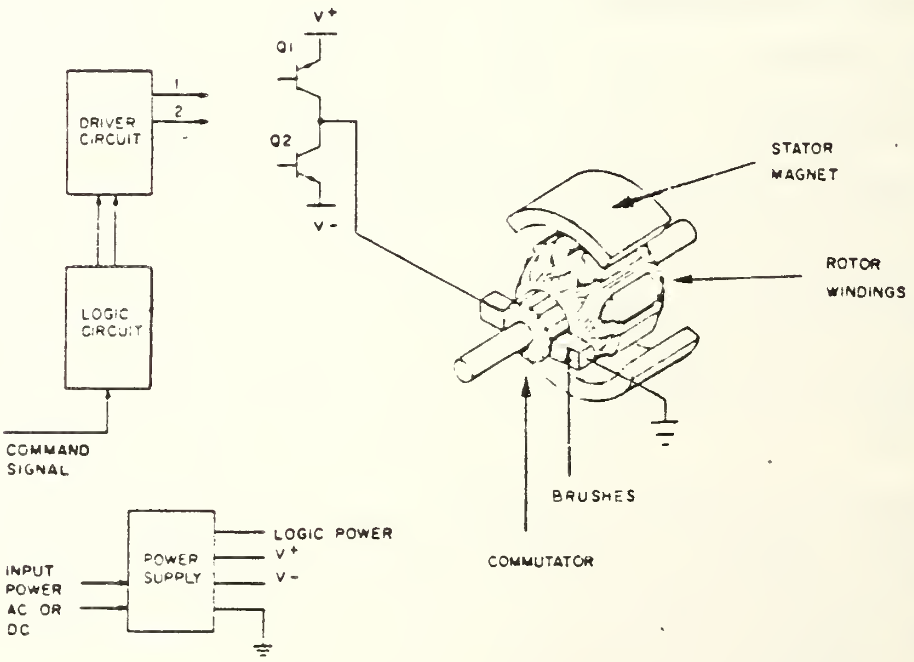


Figure 2.3. Essential Parts of a Conventional DC Motor .

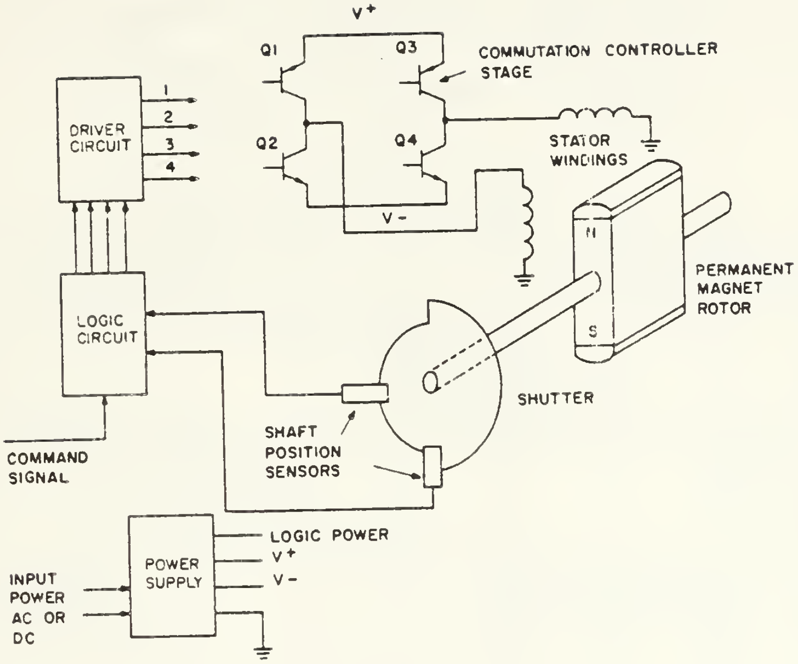


Figure 2.4. Essential Parts of a Brushless DC Motor.

energy in each winding, the circuit creates a reverse breakdown voltage on each transistor. Since stored energy is low in the low-power systems, such break-down conditions can be tolerated. However, if any significant amounts of current and voltage are handled in such a system, breakdown conditions would cause damage to the semiconductor junctions. Therefore other methods are used to maintain proper commutation of the inductive energy in each winding. Figure 2.6 shows a two-phase brushless DC motor using two power supplies $+V_S$ and $-V_S$. We now have four power transistors and four

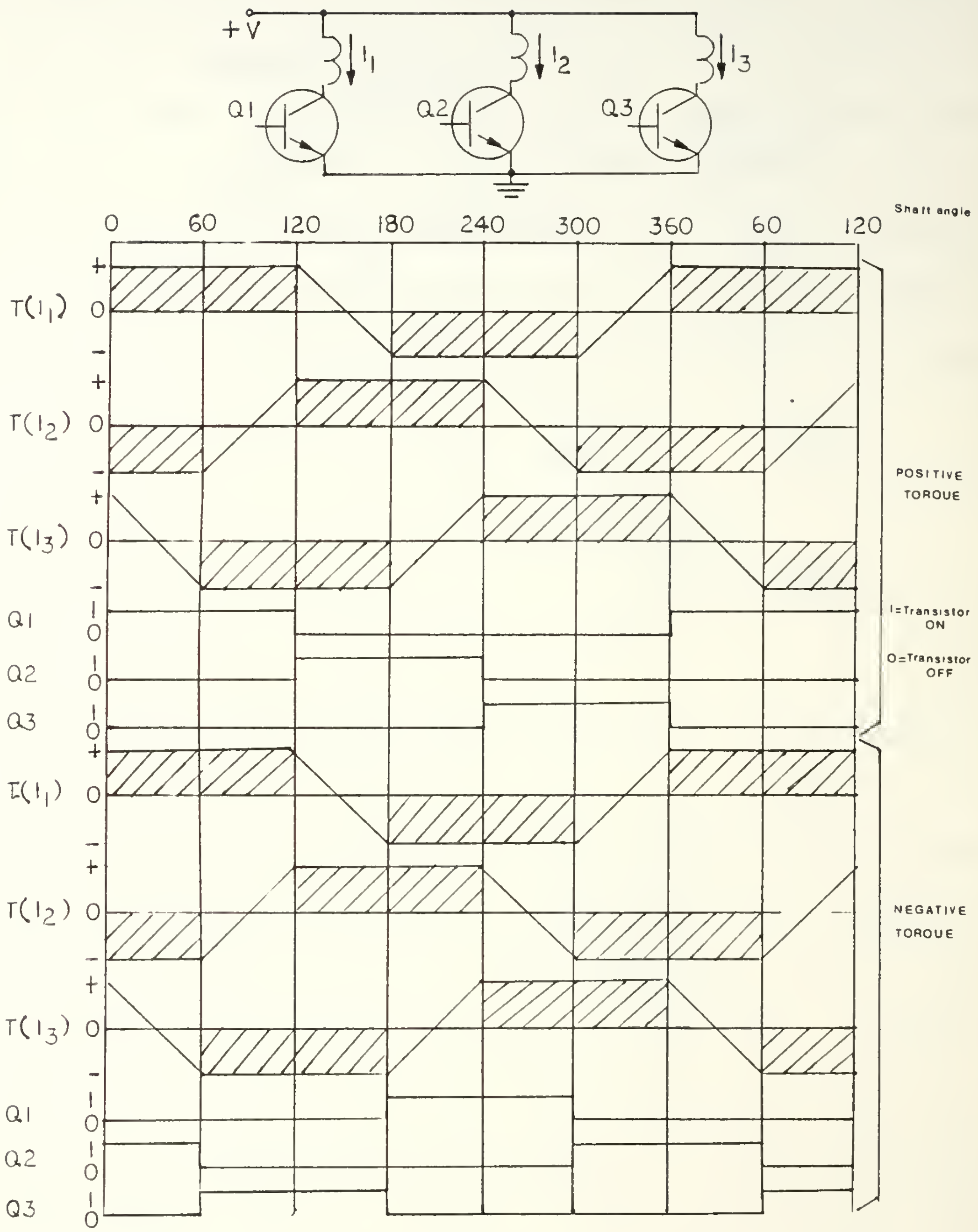


Figure 2.5. A Three-Phase, Half Wave Brushless Motor Controller.

diodes. Each half of the circuit controls it's own winding, and the two operate independently of each other.

The diagram shows the current response with respect to rotor position and current versus time at a given shaft velocity.

It can be seen that the current I_{Q1} has an exponential initial increase to a steady state value which is maintained until the 90° position has been reached. Then Q1 is switched to the off condition. The stored energy is dispelled through the power supply by using diode D3, and an exponential decline is shown in I_{D3}, when the current rise is now progressing in Q2. Thus there is a continuous torque production maintained in the motor as one stage is turned off and the next is turned on.

C. FOUR-PHASE DELTA BRUSHLESS DC MOTOR

A four-phase Delta motor from the Pittman Corporation (see Appendix A) is used for the following experiments. A four pole structure is used for this motor.

There are several reasons to fabricate the rotor as a four pole structure:

i) Mechanical arc lengths of 60° per magnet segment yield a higher material utilization than 120° arc used for a two pole structure and therefore lower cost.

ii) High performance magnetic materials do not accept radial magnet paths and thus are not as efficient magnetically if made in long arc lengths.

iii) The four-pole structure doubles the number of commutation cycles per mechanical revolution of the shaft.

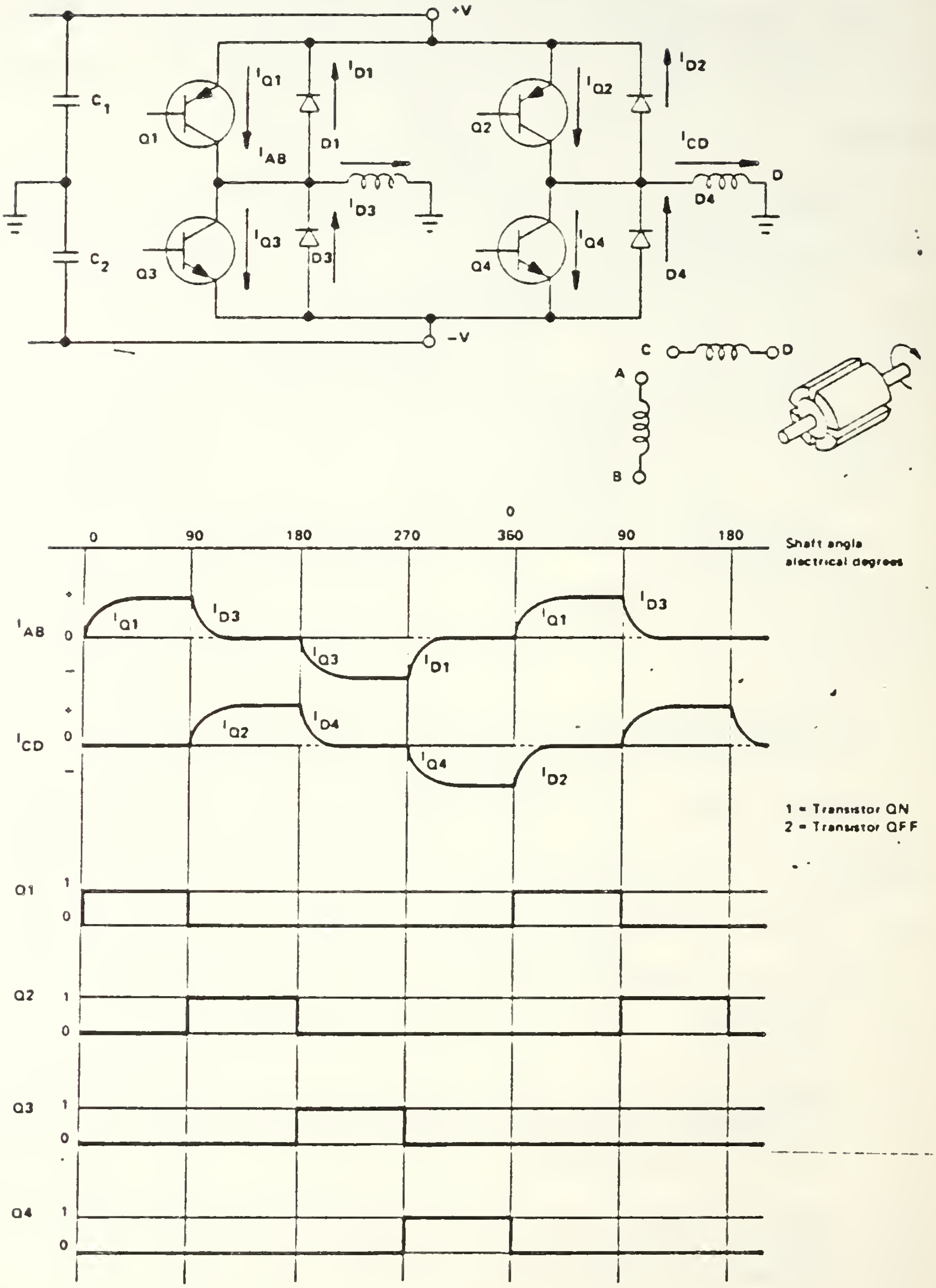


Figure 2.6. Two-Phase Brushless DC Motor.

A four-phase commutation circuit is shown in Figure 2.7.

The logic outputs from the sensors are connected to a BCD to decimal decoder by using the "A" and "B" inputs. The "C" input is used to control the rotation of the motor. "D" input is used for on-off control of the decoder. The "D" input of the decoder in the motor drive is a convenient logic input to apply a pulse width modulation signal for speed and/or torque control. More details will be discussed in the later sections. The flux rotation is provided by the "on", "off" position of the transistors. When a transistor is on, it creates current on the related windings. The current passing through the transistor will create flux on the related windings. The driver controls the stator excitation. For the clock-wise (CW) direction of the flux rotation, transistors Q1 and Q_3' are on. This means that D phase will have positive voltage and B phase will have negative voltage. In the next step, Q2 and Q4' transistors will be on. This will create positive voltage at the C phase and negative voltage at the A phase. This will continue in the order: transistors Q3 and Q1' on and transistors Q4 and Q2' on. To reverse the flux direction, the operating program will be transistors Q1 and Q3' on, transistors Q4 and Q2' on, transistors Q3 and Q1' on, transistors Q2 and Q4' on. Shaft angle position, phase voltage, and corresponding sensor signals are shown in Figure 2.8.

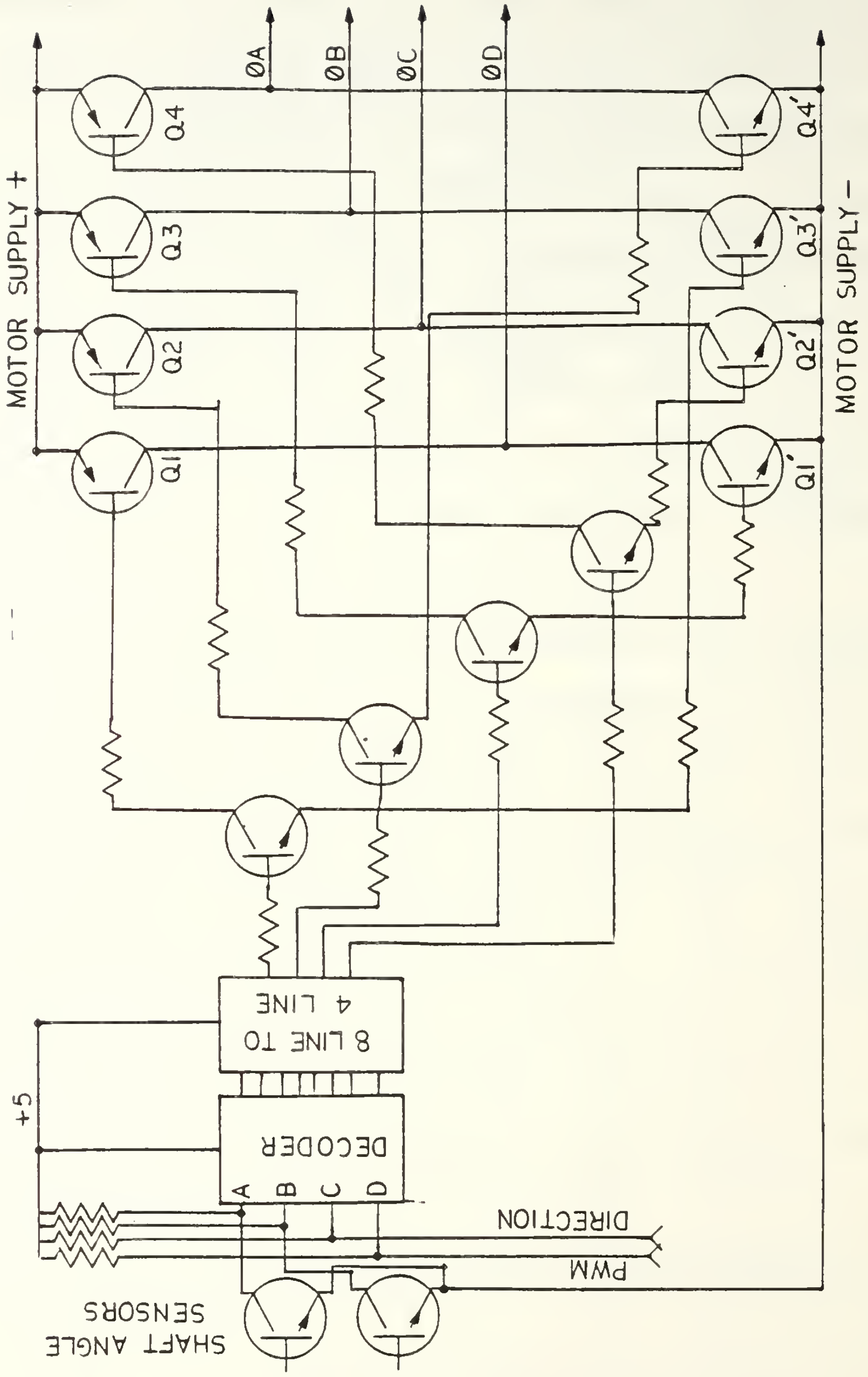


Figure 2.7. Four-Phase Commutation Circuit.

CW TORQUE

ELECTRICAL ANGULAR POSITION	SENSOR 1	SENSOR 2	PHASE A		B		C		D	
			TRAN ON	VOL	TRAN ON	VOL	TRAN ON	VOL	TRAN ON	VOL
0°	0	1	Q4	+			Q2′	—		
90°	0	0			Q3	+			Q1′	—
180°	1	0	Q4′	—			Q2	+		
270°	1	1			Q3′	—			Q1	+

CCW TORQUE

0°	0	1	Q4′	—			Q2	+		
270°	1	1			Q3	+			Q1′	—
180°	1	0	Q4	+			Q2′	—		
90°	0	0			Q3′	—			Q1	+

Figure 2.8. Four-Phase Logic Control.

D. ADVANTAGES AND DISADVANTAGES OF THE BRUSHLESS DC MOTOR

1. Advantages

Brushless DC motors are more expensive for the same horsepower rating than conventional DC motors, but they have some advantages over DC commutator-brush motors:

a) The motor has a long life because it does not have brushes.

b) Due to the elimination of brush arcing, there is a reduction in electromagnetic interference.

c) There is a reduction in acoustic noise.

d) Little or no maintenance is required.

e) The motor permits a small signal control of speed and on-off operation since the power circuitry is included as part of the brushless DC motor.

f) When they are properly sealed, they are capable of operation in fluids or vapors.

2. Disadvantages

The following are important disadvantages of the brushless DC motor:

a) The total size of the motor is bigger overall because of the additional space required for the electronic devices.

b) Overall cost is higher compared to conventional commutator types of the same horsepower.

c) Choice is somewhat limited at present in "stock" sizes and horsepower rating, necessitating "special" orders for particular applications.

Even though the brushless DC motor has some disadvantages, developing electronic technologies and applications in space and the military make it preferable to conventional DC motors.

III. VELOCITY CONTROL OF THE BRUSHLESS DC MOTOR

A. General

Before studying the speed control of the brushless DC motor, it will be helpful to study the components of the system. The block diagram of the velocity control circuit is shown in Figure 3.1.

The Hall effect sensing system is based on sensors which are located adjacent to the end of the stator winding to sense the polarity and magnitude of the permanent magnet field in the gap. The position of the Hall sensors are shown in Figure 3.2. The Hall effect device is made of two sensors which are placed 90 electrical degrees apart to sense the rotational position of the rotor relative to the stator coil groups. The flux in the gap between the rotor and stator and the output of each sensor is shown in Figure 3.3. As can be seen in Figure 3.3, the output of each Hall sensor switches from logic high to logic low when the sensed rotor flux passes through zero. The output is high for a north magnetic pole and low for a south pole (or vice versa if Hall sensors are reverse mounted). [Ref 4]

The two rotor position signals are decoded by digital logic gates in the motor drive to give a four phase output which controls 8 power transistors in such a way that sequential switching from one stator coil to the next occurs at intervals of 90° mechanical rotor rotation. Both the outputs of the

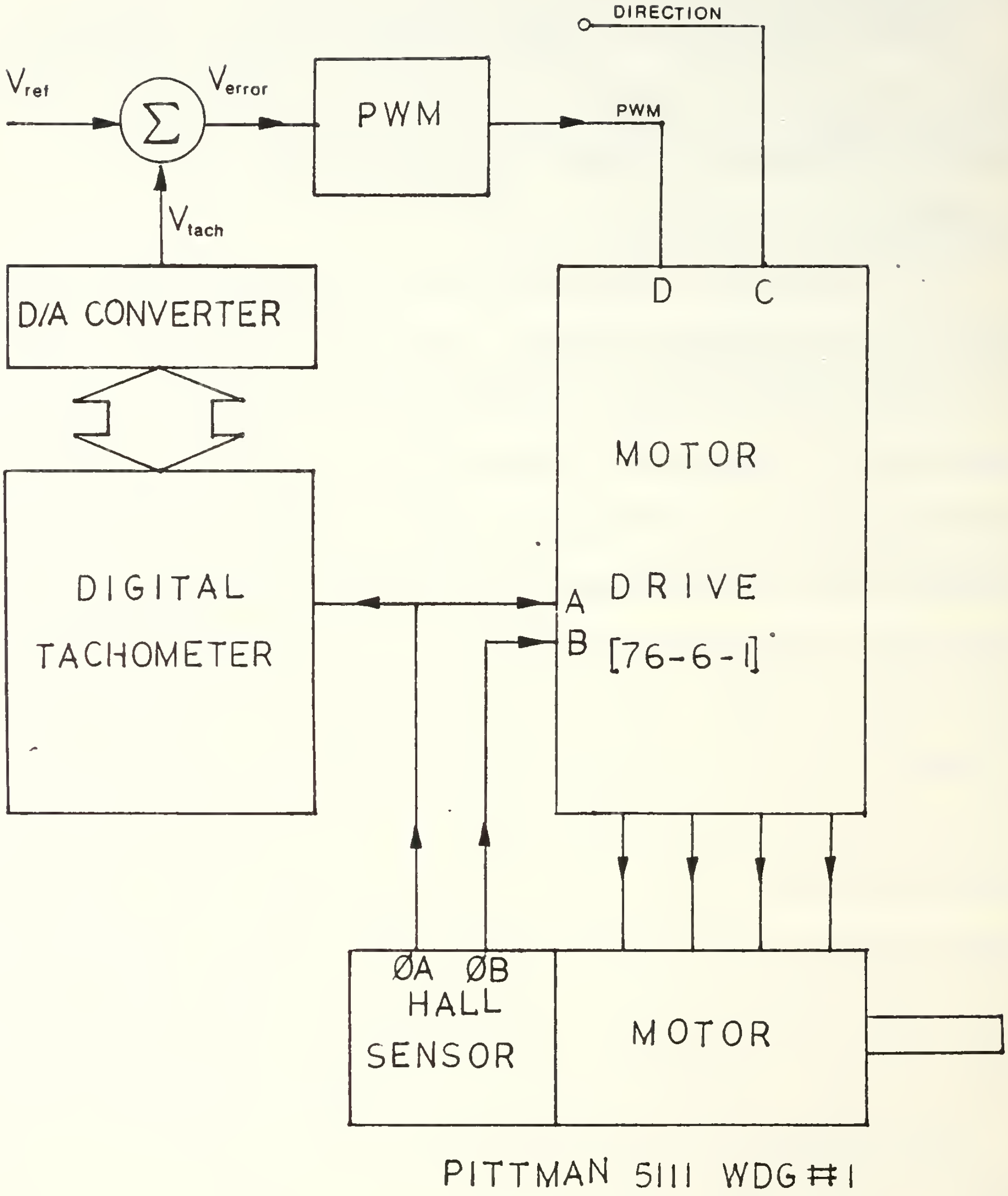


Figure 3.1. Block Diagram of the Velocity Control System.

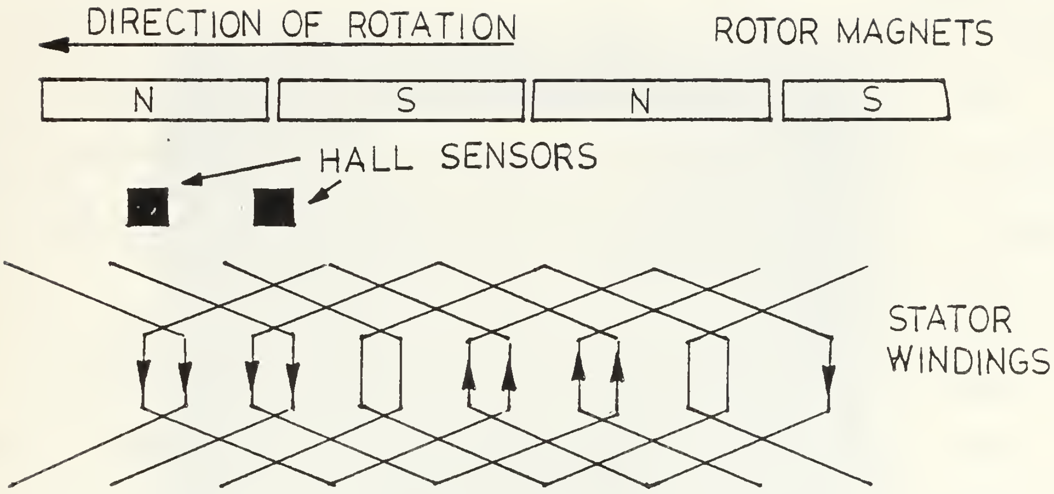


Figure 3.2. Position of the Hall Effect Sensors.

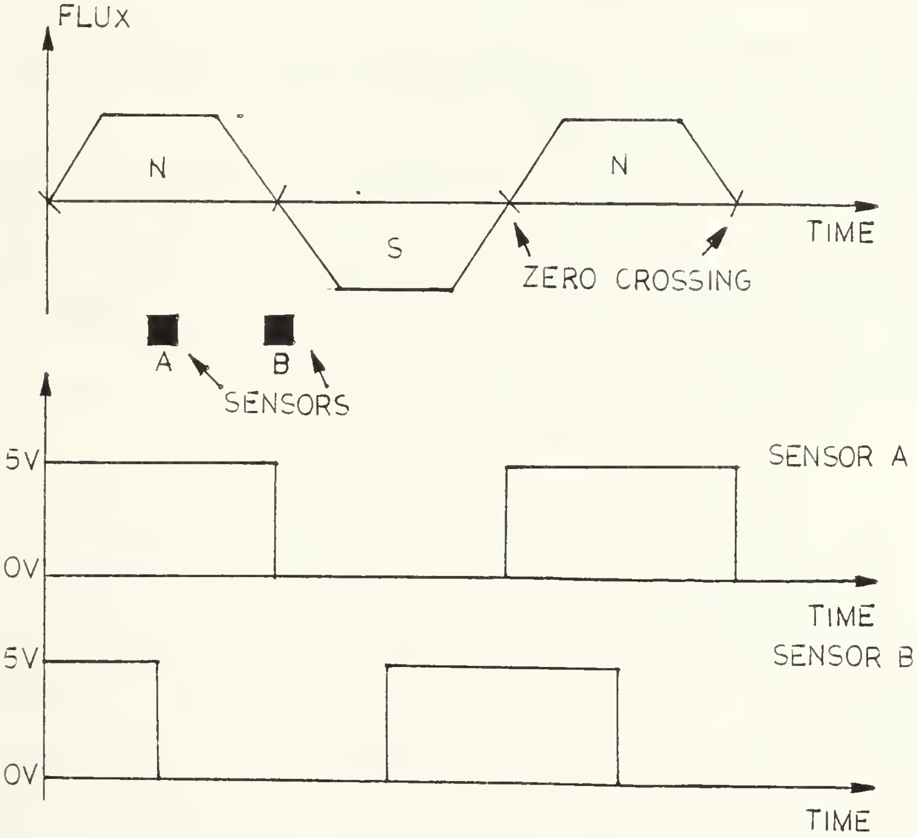


Figure 3.3. Flux in the Air Gap and Output Voltage Wave Forms for Hall Effect Sensors.

The Hall sensor will produce square waves related to the speed. Following from this concept a digital tachometer will be built and discussed in the next section.

The "D" input of the decoder in the motor drive is a convenient logic input to apply a pulse width modulation signal for speed and/or torque control. More details will be discussed in later sections.

B. DESIGN OF THE DIGITAL TACHOMETER FOR SPEED CONTROL

The speed of the brushless DC motor can be observed from the output of the Hall sensors. Hall sensors produce 2 square waves for each rotation. If elapsed time for each revolution can be measured, the speed of the motor can be found. One channel of the Hall sensor output of the brushless DC motor is shown in Figure 3.4.

The arrows indicate the beginning and end of the period of revolution. The relation between the period of the revolution and the speed of the motor can be shown with the following example:

Period = 1 Revolution = 50 10^{-3} sec

speed = 20 revolutions per second (RPS).

This is equal to 1200 revolutions per minute (RPM).

By starting from this approach, a digital tachometer was designed by the author. The main idea was to measure the period of revolution by using counters and inverting to the voltage value by using a Digital to Analog converter (DAC).

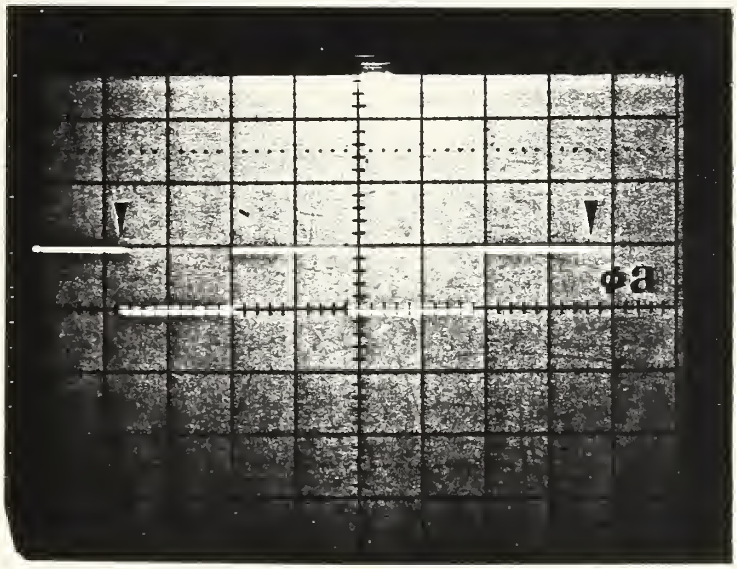


Figure 3.4. One Channel Output of Hall Sensor.

A circuit diagram of the digital tachometer is shown in Fig. 3.5.

A 7474 Dual-D-Type positive-edge-triggered flip flop was used to obtain 1 pulse per revolution by dividing the Hall sensor signal by two. The output of the flip-flop is shown in Figure 3.6.

74LS161 synchronous 4-bit counters were used to count for each period. Clock pulses were used for the counters. For this design the 16 bit procedure was found to be the most appropriate from a hardware point of view. When the motor was running at a slow RPM, the period of the revolution was high and the counter registered high. From an overflow point of view, the maximum count on the counter should not

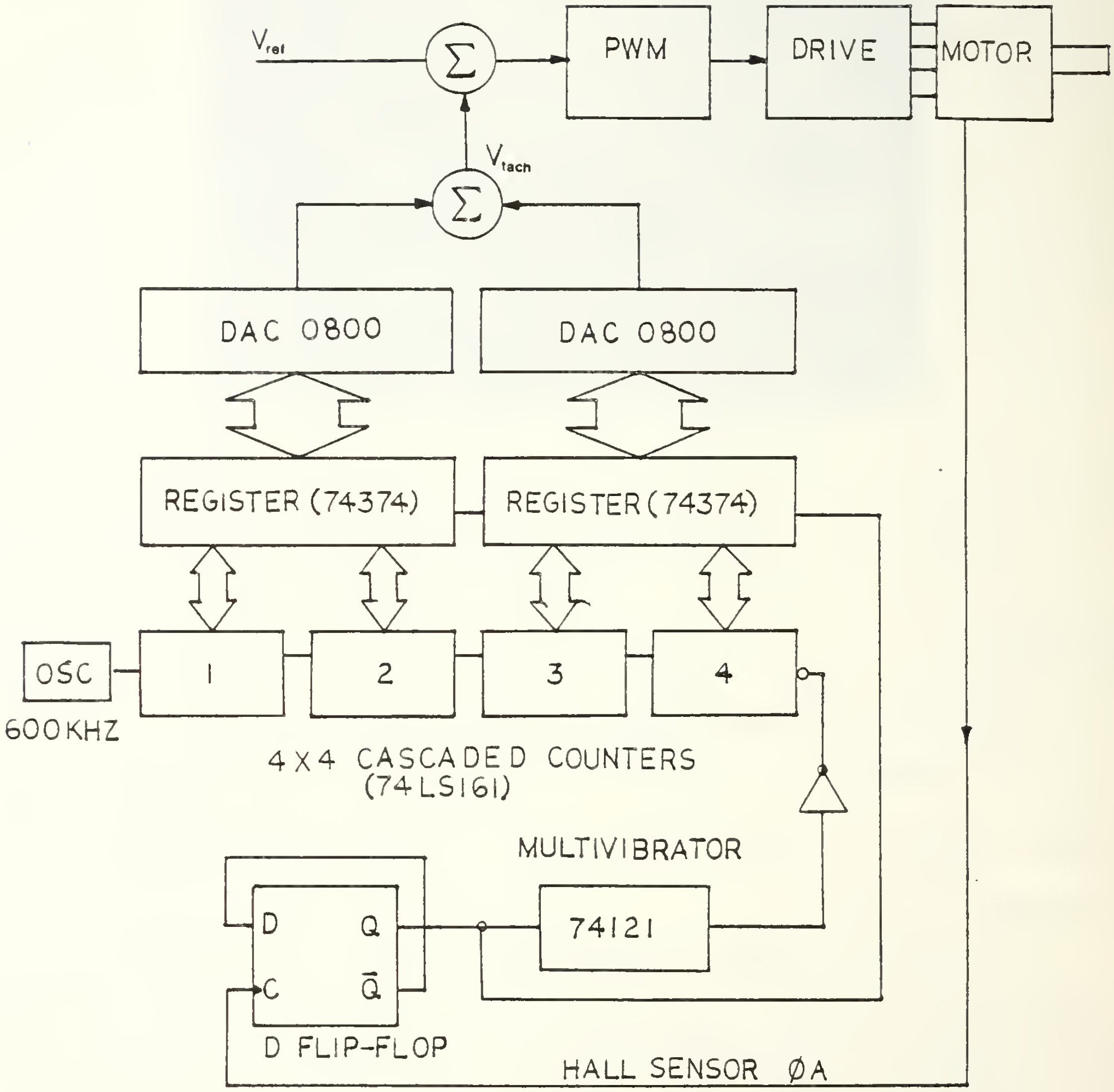


Figure 3.5. Circuit Diagram of Digital Tachometer.

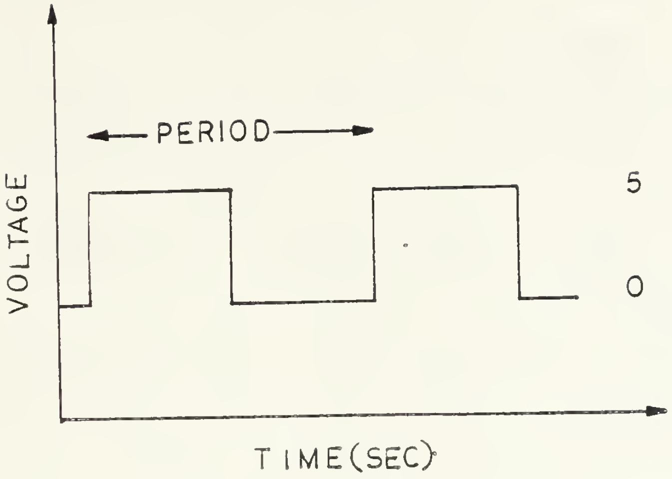


Figure 3.6. Output of the Flip Flop.

have exceeded 65536. Keeping in mind that when the motor runs under 600 RPM the counter overflows, this criteria became the minimum speed restriction for the motor. A 74121 monostable multivibrator was used to get short, clear pulses for the counters. The output of the multivibrator (one shot) is shown in Figure 3.7.

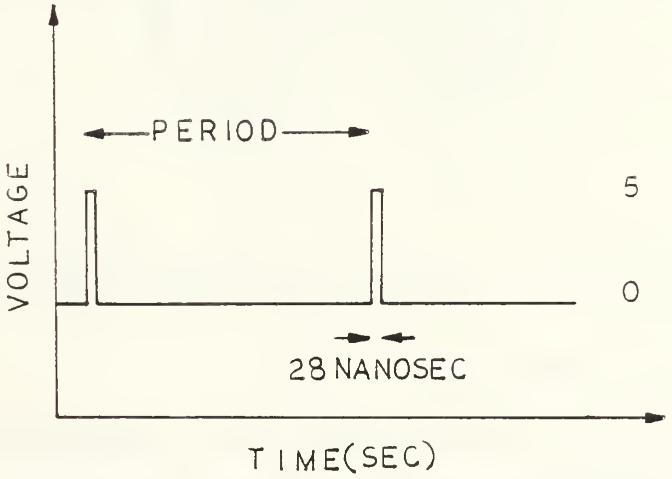


Figure 3.7. Output of the Multivibrator.

The 74374 Register stored the counts for each period until the new count came.

Two 8-bit DAC Digital to Analog converters were used to convert the counts to the voltage as it related to the speed. The logic of the Digital to Analog conversion is shown in Figure 3.8.

The voltage related with speed is between 0 and 10 volts. When the speed is 40 rpm the output of the DAC will be 0 volts; when the speed is 24,000 rpm the output of the DAC will be 10 volts. The lowest speed is equal to 0, the highest speed is equal to 10 volts.

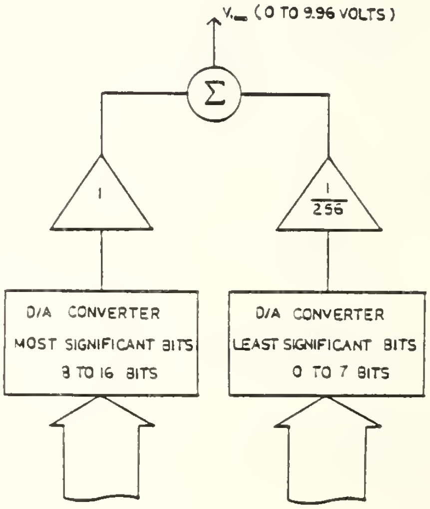


Figure 3.8. Digital to Analog Conversion.

C. PULSE WIDTH MODULATOR

The "D" input to the decoder is a convenient logic input to which the pulse-width modulated logic signal can be applied. It should be recognized that the low mechanical time constant of these motors could cause instantaneous speed variation at slow speeds when a low duty cycle is used in the pulse width modulation. The pulse-width modulator is shown in Figure 3.9. A pulse width modulated signal was obtained by mixing a low frequency input error signal with a high frequency triangular "dither" signal. Twenty kilohertz was the frequency chosen for the dither signal. The sum of the error and triangular signal e(t) is shown in Figure 3.10A

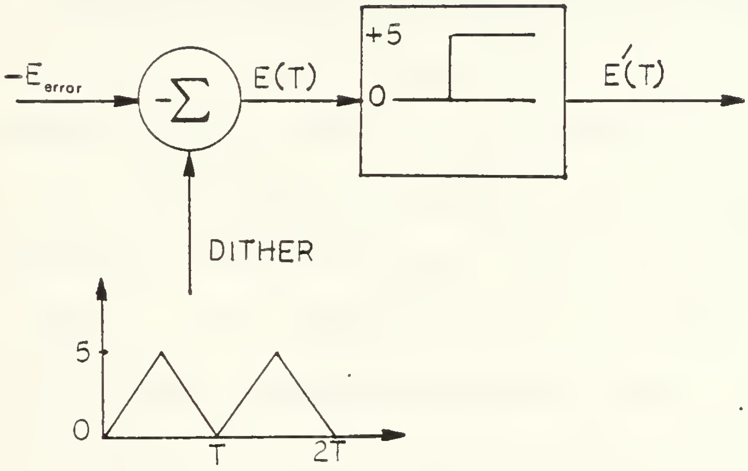


Figure 3.9. Pulse Width Modulator.

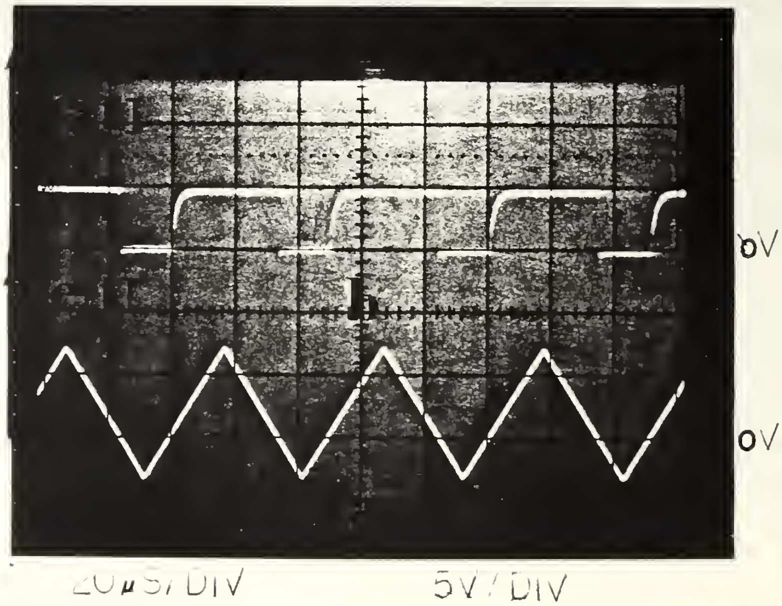


Figure 3.10. Error and Dither Signal.

An e(t) signal was fed to the "zero crossing circuit." The zero crossing circuit converts the resulting sum into a two level signal e'(t) as shown in Figure 3.10B. The signal shifts between the two digital levels 0 volts and 5 volts. Input, e_o, is assumed to be a DC level or slowly changing signal. Added to the triangular signal d(t), which oscillates between -10 volts and 0 volts, and has a period, T. This signal was added to e_o to produce e(t). This result was then fed to a zero crossing detector, which in this case is shown to switch from plus 5 volts (logic 1) to 0 volts (logic 0).

A circuit diagram of the pulse width modulator is shown in Figure 3.11. A circuit diagram of the digital tachometer and pulse width modulator is shown in Figure 3.12. The artwork of the circuit is shown in Appendix C.

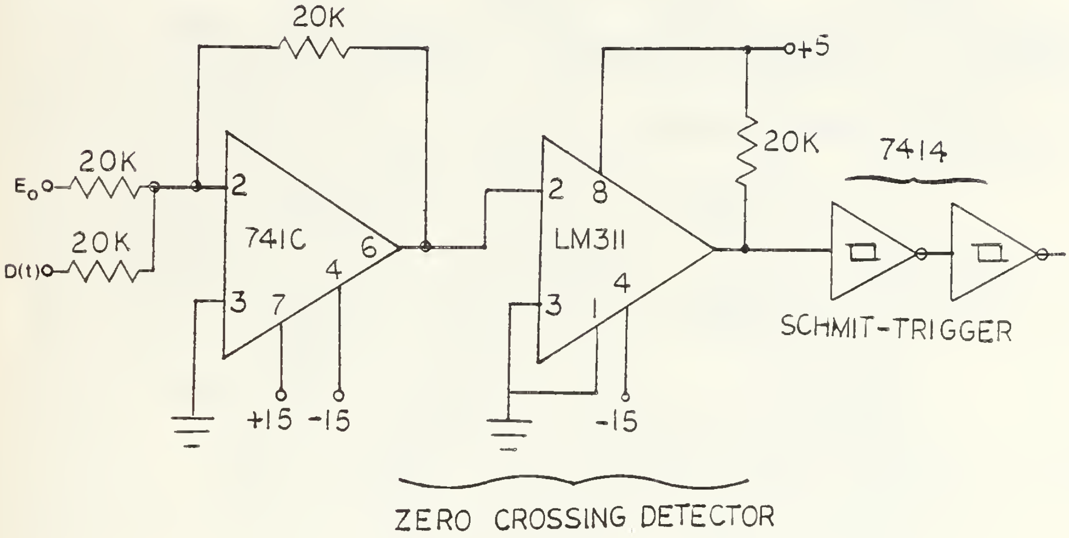


Figure 3.11. Circuit Diagram of the Pulse Width Modulator.

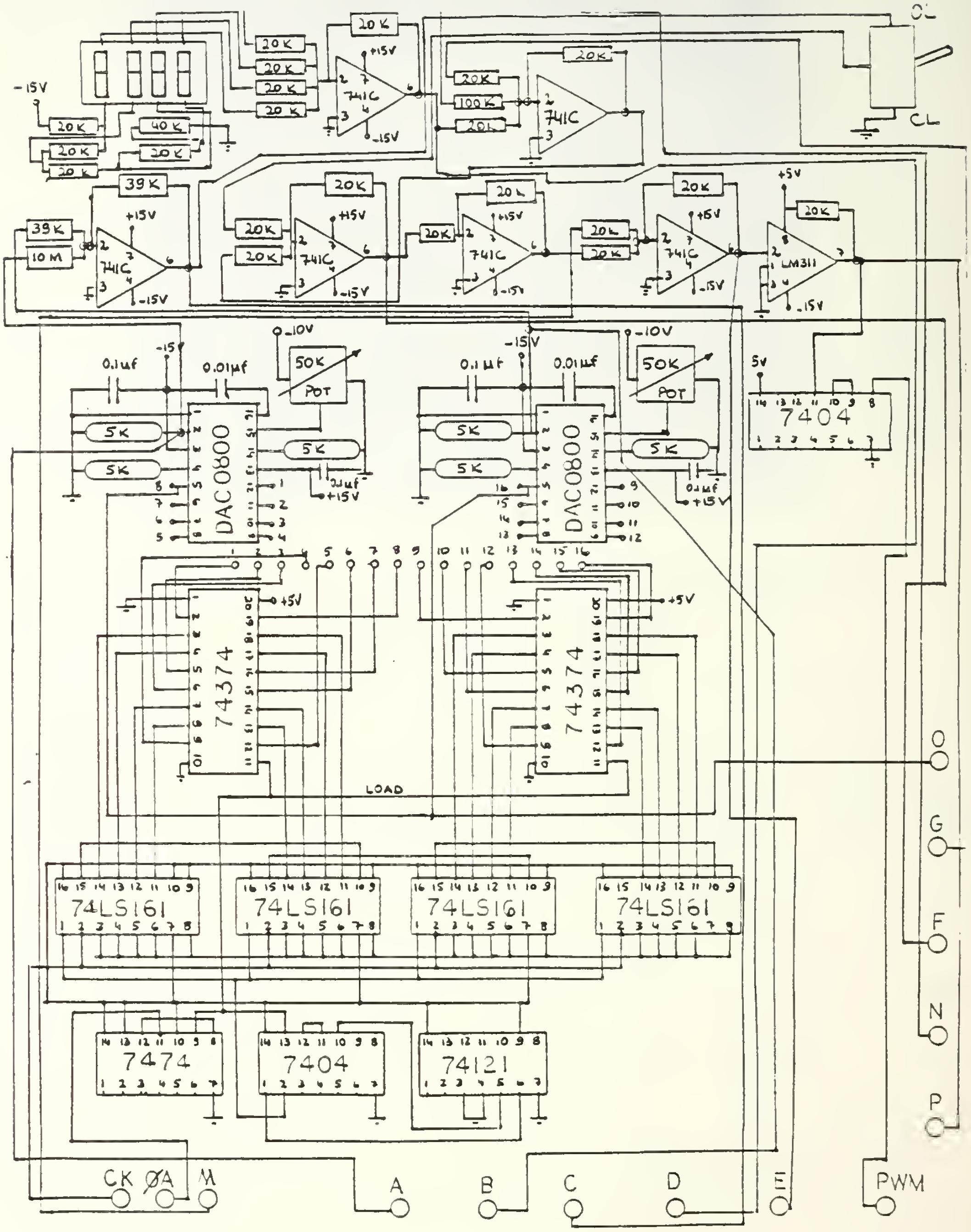


Figure 3.12. Circuit Diagram of the Digital Tachometer and Pulse Width Modulator.

IV. SYSTEM TESTING AND DATA COLLECTION FOR VELOCITY CONTROL

A. GENERAL

After building the velocity control system for the brushless DC motor some experiments were done to get data on how the system works. The instruments used for these experiments are shown below:

1. Power supply unit PS 150E
2. Hewlett-Packard 6216A power supply
3. Wavetek model 145 pulse/function generator
4. Textronix 2213 oscilloscope
5. Textronix 464 storage oscilloscope
6. Hewlett-Packard 3582A spectrum analyzer
7. Hewlett-Packard 85 plotter
8. Hewlett-Packard 124A camera.

The power requirements for the system were +15V, -15V, +5V, -10V, -15V.

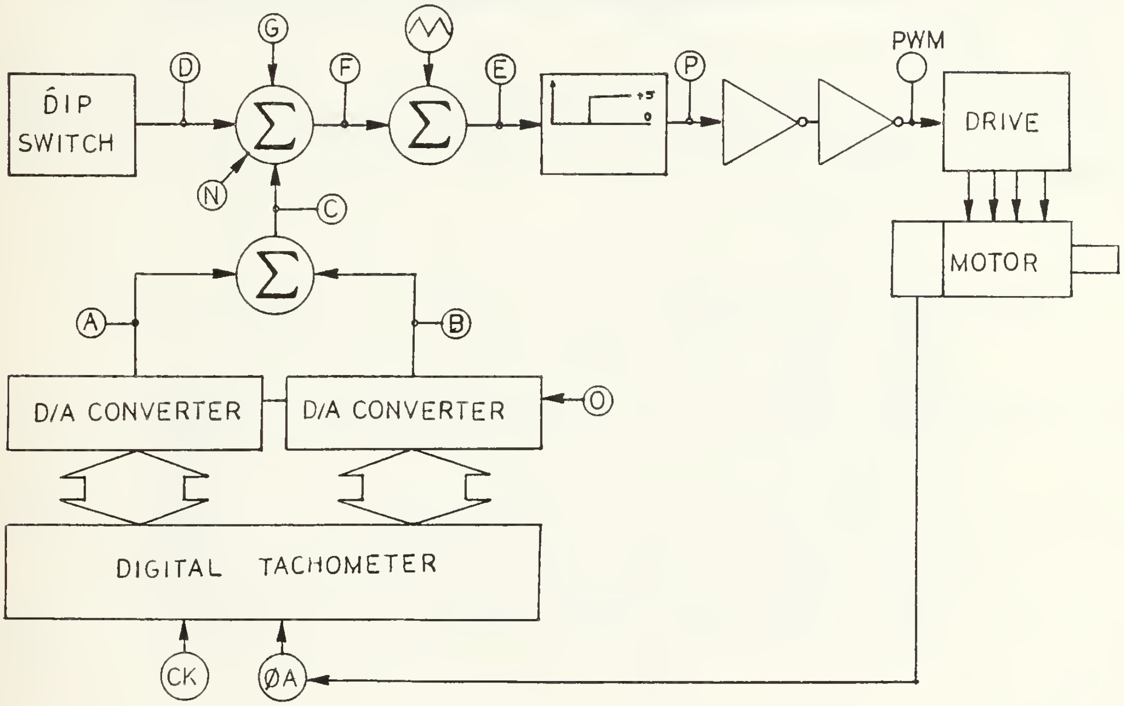


Figure 4.1. Block Diagram of the Velocity Control System.

For simplicity, test points were defined by letters. A block diagram (and test points) of the system is shown in Figure 4.1.

These test points are the same on the circuit board. For velocity command, a four position dip switch was used. Fifteen different speeds are produced depending on the relevant motor power supply.

The calibration of the system is important to getting accurate data. For calibration purposes, many adjustable resistors were used in the system. The calibration of the system is explained in Appendix B.

B. OPEN LOOP VELOCITY CONTROL

For open loop studies, the feedback switch is turned to the open loop (OL) position. The power supply was set to 15V. The Speed command was given by a dip switch. The position of the dip switch and the equivalent RPM values are as shown below:

Dip switch position	Speed (RPM)
0001	3000
0010	3260
0011	3410
0100	3570
0101	3660
0110	3750
0111	3800
1000	3845

The 3750 RPM speed (Dip switch = 0110) was chosen for the first experiment. The two channel Hall sensor output of the motor is shown in Figure 4.2. From the Hall sensor output the speed of the motor can be calculated.

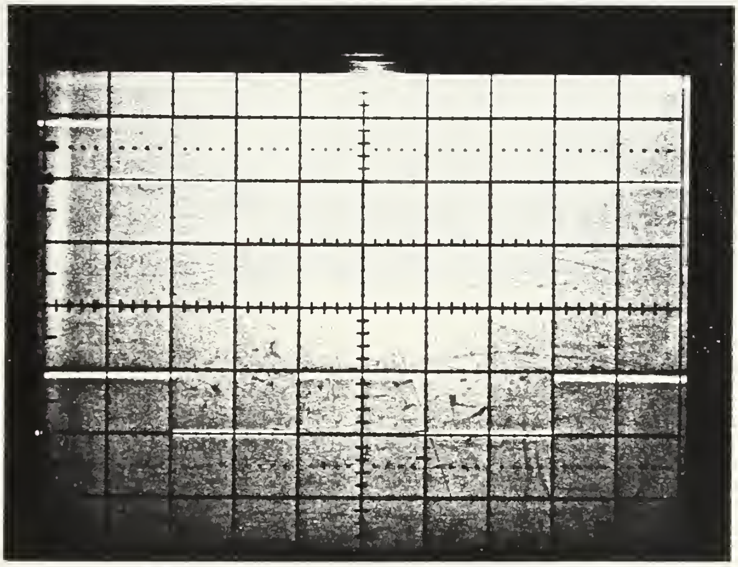


Figure 4.2. Hall Sensor Output of the Motor for 3750 RPM.

Since the Hall sensor sends 2 pulses per revolution, Figure 4.2 shows that

$$1 \text{ rev} = 8 \times 210^{-3} = 16 \text{ msec.}$$

$$= 1/16 \text{ msec} \times 60 = 3750 \text{ RPM.}$$

The pulse width modulated signal (test point P) is shown in Figure 4.3.

When the shaft of the motor is held, the motor slows down and no change of the pulse width modulated signal can be seen. Another experiment was done by changing the power supply of the motor. The speed of the motor was changed.

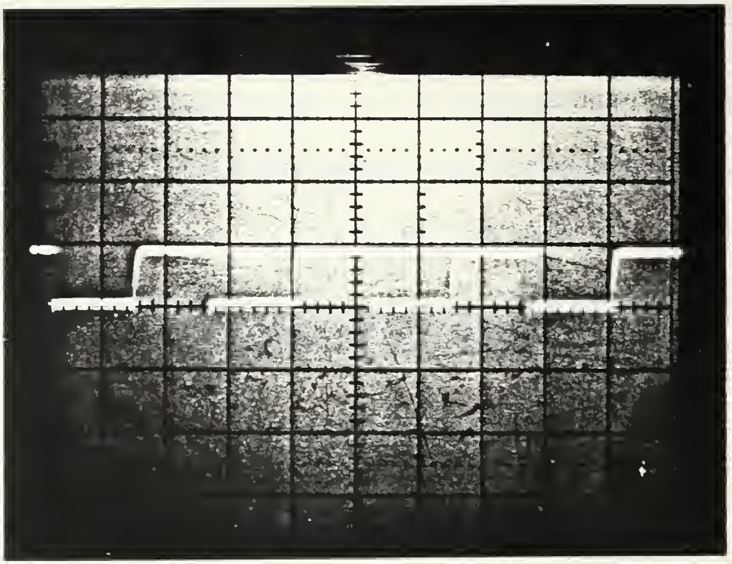


Figure 4.3. Pulse Width Modulated Signal.

Both these observations show that this is an open loop system. In the second experiment 3260 RPM speed (dip switch = 0010) was chosen. The Hall sensor and PWM signals are shown in Figure 4.4 and Figure 4.5 respectively.

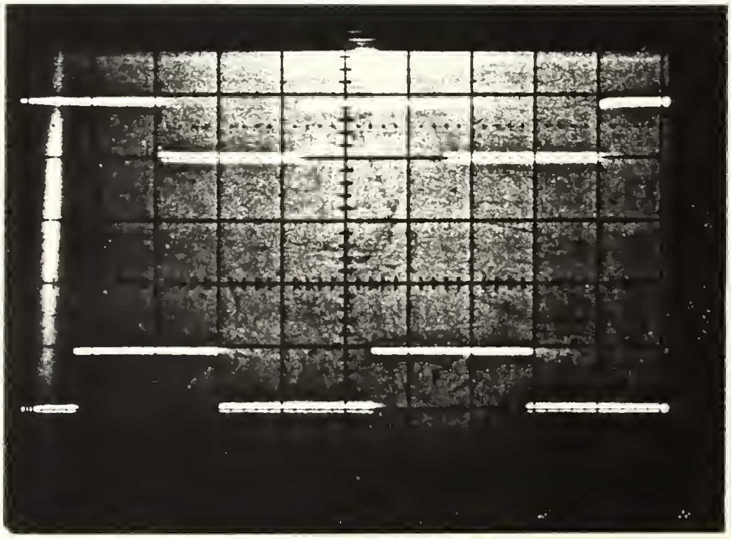


Figure 4.4. Hall Sensor Output of the Motor.

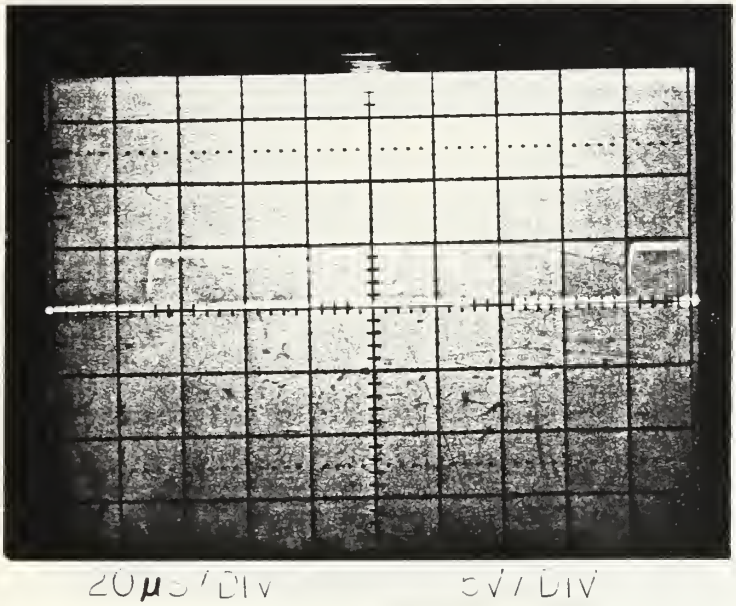


Figure 4.5. Pulse Width Modulated Signal for 3260 RPM.

C. CLOSED LOOP VELOCITY CONTROL

For the closed loop system, the feedback switch was turned on to the closed loop position (CL). The power supply was set to 30 V. The position of the dip switch and equivalent RPM values are as shown below.

Dip switch position	Speed (RPM)
0100	1275
0101	1500
0110	1580
0111	1875

Due to hardware restrictions, a 16 bit system was used. That brought some unwanted results in low speed experiments. For that reason -2 V steady state error was added to the Dither signal. The Dither signal is shown in Figure 4.6.

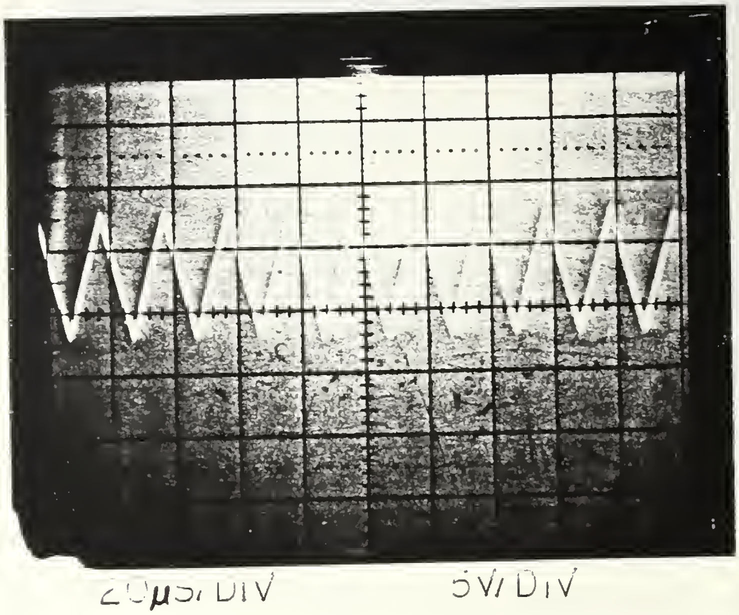


Figure 4.6. The Dither Signal.

For the first experiment on closed loop velocity control the speed of 1275 RPM was chosen. The dip switch was set to 0100. The Hall sensor output of the motor is shown in Figure 4.7. From this picture the speed of the motor can be calculated in the same fashion as the previous section. Its speed is 1275 RPM. The PWM signal is shown in Figure 4.8. When the shaft of the motor was held slightly the PWM signal was changed to keep up with the given speed command (see Figure 4.9). This is one of the expected results of a closed loop system. Another experiment was done by changing the power supply of the motor. No change in the speed was observed. This is another expected result of a closed loop system.

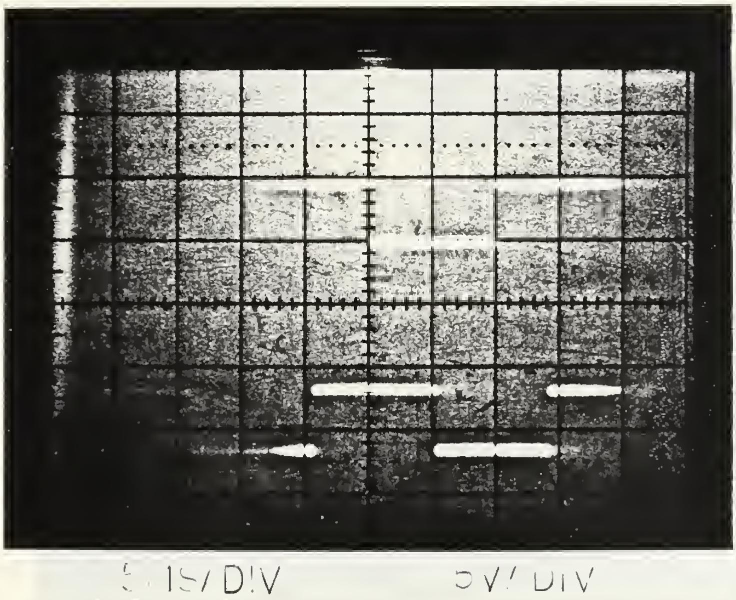


Figure 4.7. Hall Sensor Output of the Motor for 1275 RPM.

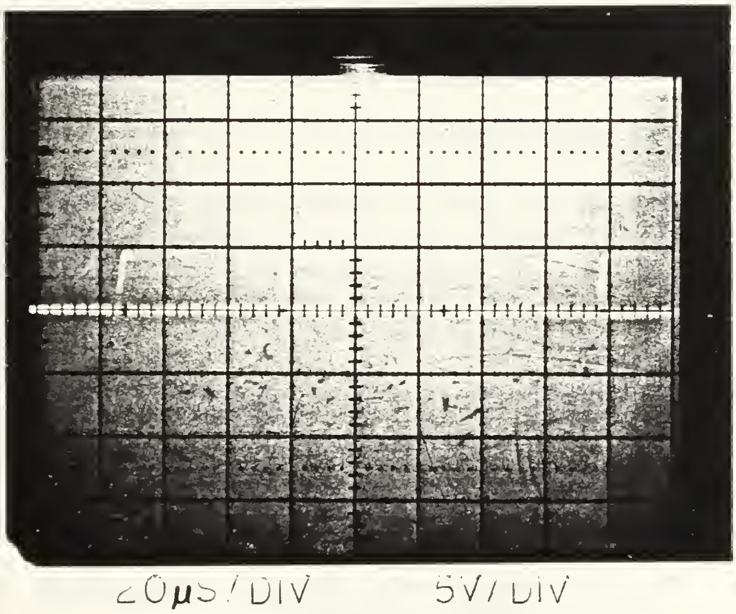


Figure 4.8. Pulse Width Modulated Signal for 1275 RPM.

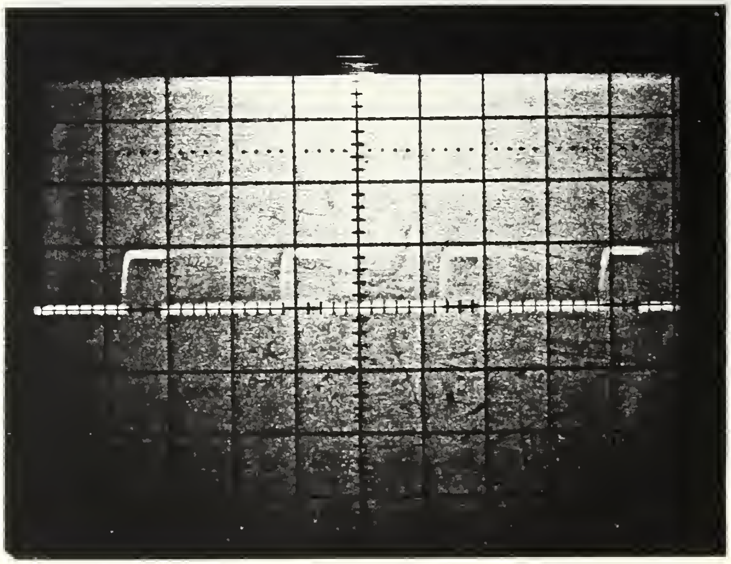


Figure 4.9. Pulse Width Modulated Signal with External Force on the Motor Shaft.

D. TRANSFER FUNCTION MEASUREMENT AND SIMULATION STUDIES

The transfer function of the motor can be found by using a spectrum analyzer. A Hewlett-Packard 3582A spectrum analyzer was used for this experiment.

A block diagram of the closed loop velocity system and its connections to the HP spectrum analyzer are shown in Figure 4.10.

Random noise was used in the system and was fed to the summing junction (test point N). When the forward gain of the noise was 1.0, the speed of the system was changed due to the noise. This unwanted result was eliminated by choosing the noise gain equal to 0.2. The frequency response of the system found by the HP spectrum analyzer as shown in Figure 4.11a and Figure 4.11b.

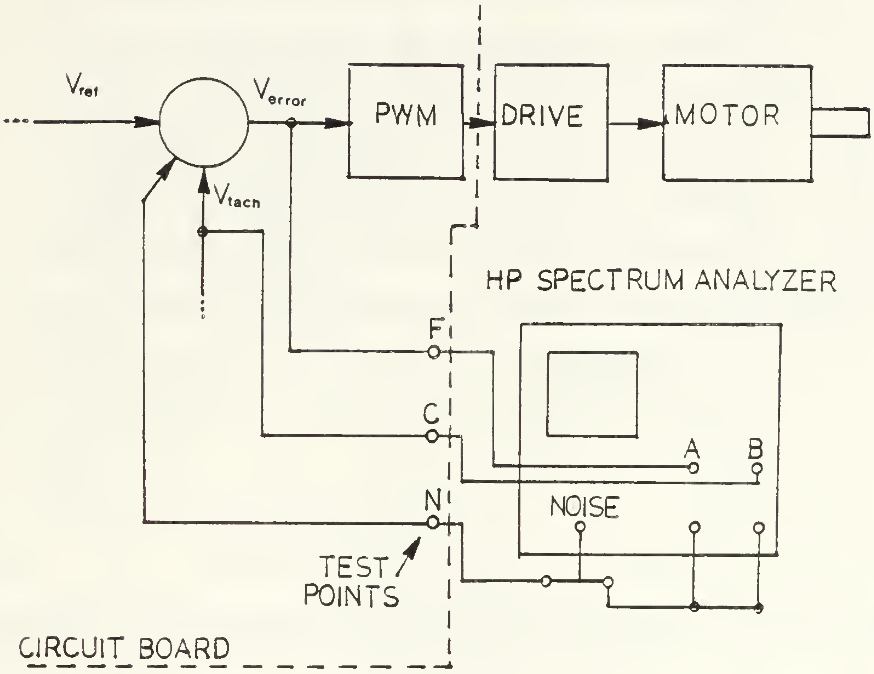
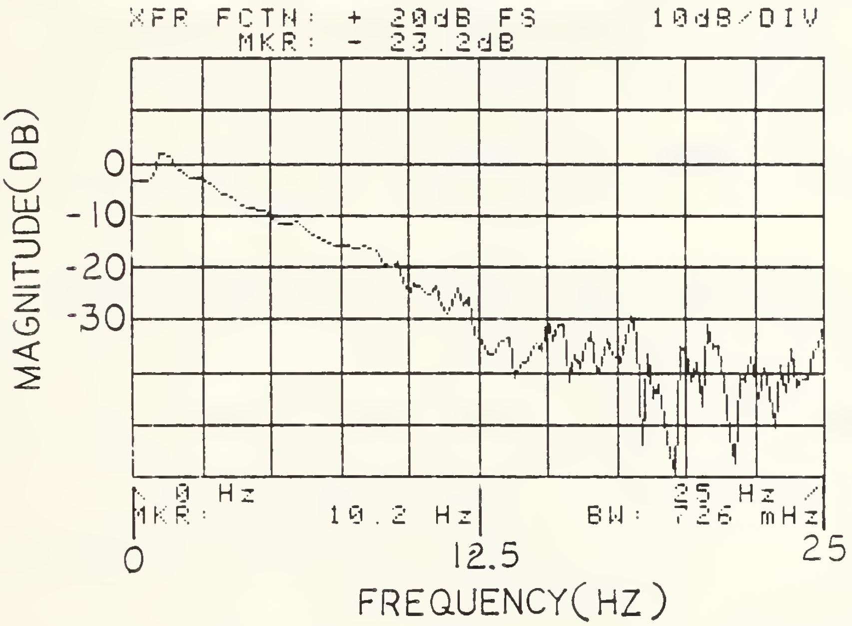


Figure 4.10. Closed Loop System with Spectrum Analyzer.



4.11a. Open Loop Frequency response of the system with magnitude curve.

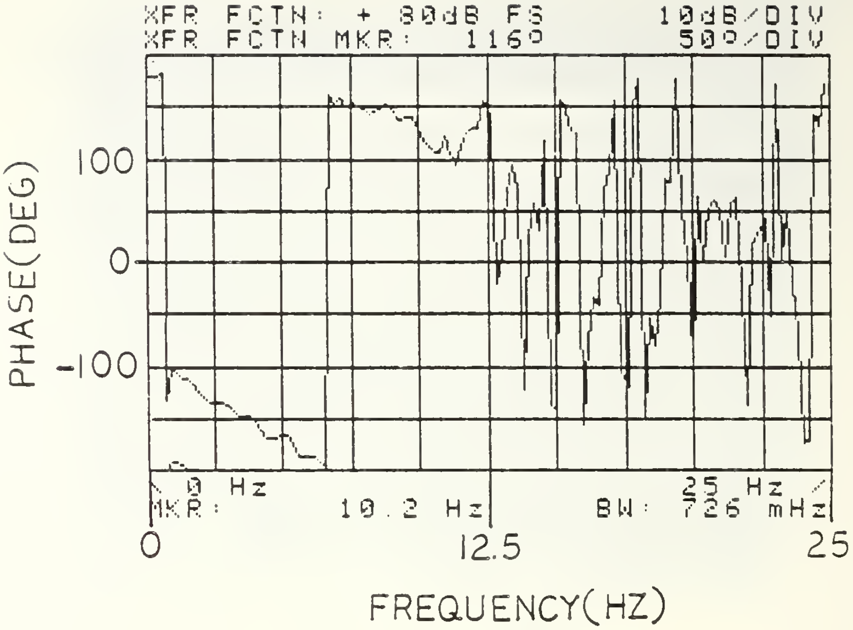


Figure 4.11b. Open Loop Frequency Response of the System with Phase Curve.

In the velocity control system there are a number of various digital components, such as flip-flops, counters and D/A converters. The counters which were used in the system are synchronous devices, this means they use clock pulses.

The following events take place in the system.

1. Wait for a clock pulse.
2. Determine the speed for one revolution of the motor.
3. Perform digital to analog conversion.
4. Send the updated control variable to the motor.
5. Go to step 1.

Because the computation of the speed and sending the control variable takes some time, there is a time delay between steps two and four. The D/A converter holds the signal over one revolution of the motor. This implies that the sampling interval is equal to one revolution of the motor. During the transfer function measurements, the speed chosen was 1360 RPM. With simple calculation, one revolution of the motor can be found to be 44 milliseconds. The Nyquist frequency is thus /0.044 = 71.2 rad/sec or 11.3 hz.

At frequencies which are greater than the Nyquist frequency, the ambiguities of the transfer function for both the gain and phase curves can be seen in Figure 4.11a and 4.11b. For that reason, this part of the experimental data was not included in the calculations.

The frequency, magnitude and phase of the transfer function which was found from Figure 4.11a and b are shown in Table 1. The Bode plot which was drawn by using the data in Table 1 is shown in Figure 4.12.

The transient response of the closed loop and open loop system were found from a strip chart recorder and are shown in Figure 4.15 and Figure 4.16. On the other hand, the transient response of the system can also be observed from the storage oscilloscope.

A Textronix 464 storage oscilloscope was used to get the transient response of the system. The step input (from

1035 rpm to 1305 rpm) was applied to the system as a step input. The closed loop transient response of the system is shown in Figure 4.17. This transient response correlates with the transient response which was found from the strip chart (see Figure 4.16).

As can be seen, the system is type 0 [Ref. 1] and has one pole at w = 7.0 rad/sec and one pole at w = 27 rad/sec. The open loop transfer function of the system is shown below.

$$G(s) = \frac{1.35}{(s/7.0+1)(s/27.0+1)}$$

TABLE 4.1
FREQUENCY RESPONSE WITH MAGNITUDE AND PHASE

w(rad/sec)	Magnitude(db)	Phase(degrees)
4	2.5	-91
5	2.6	-91
6.2	2.6	-94
8.7	0.7	-107
10	-0.9	-111
15	-3.8	-123
20	-6.8	-138
25	-9.2	-153
30	-11.7	-164
35	-13.5	-176
40	-14.8	-195
45	-17.1	-207
50	-18.3	-212
55	-19.6	-230
60	-22.2	-241
65	-24.9	-246
70	-28.9	-250

This transfer function was used for computer simulation of the system. The open loop frequency response of the system is shown in Figure 4.13 and the transient response of the system is shown in Figure 4.14.

The time constant of the system was found from the open loop transient response (see Figure 4.15). The time it takes to get 63% of velocity gives the time constant of the of the system. From Figure 4.15 the time constant was found to be 140 milliseconds. On the other hand, the time constant of the system can be found from the transfer function which was determined using the data from the HP spectrum analyzer. The low frequency pole of the system as determined from Figure 4.12 was 7.0 rad/sec, then the time constant

$$\tau = \frac{1}{7.0} = 142 \text{ milliseconds}$$

This time constant correlates with the time constant which was found from the strip chart recorder. This indicates that the frequency response of the system which was found from the HP spectrum analyzer was accurate.

The time constant of the closed loop system can be calculated from the closed loop transient response of the system which was shown in Figure 4.16. From the figure, the settling time of the system was found to be 320 milliseconds. Thus the time constant of the closed loop system was 320 milliseconds/4 = 80 milliseconds. It can be seen that the time constant of the closed loop system was faster than the open loop system. This was the expected result.

Another important subject arises from the usage of a D/A converter in the system. Since the D/A converter creates a delay related to the sampling rate, this will cause phase lag in the system. This phase difference can be seen by comparing the measured open loop frequency response with that calculated from the transfer function. The calculated phase does not include time delay, which the measured phase does. It is seen that the measured phase lag exceeds the calculated lag by 15° at the corner frequency $w = 7.0$ rad/sec. Thus the time delay is approximately

$$T_D = \frac{\phi}{w} = 37.4 \text{ milliseconds}$$

The time constant of the motor which was given by the factory specifications was 14.4 milliseconds. It is obvious that the time constant of the motor is faster than the system time constant. This difference is caused by the time delay of the pulse width modulator and the D/A converter.

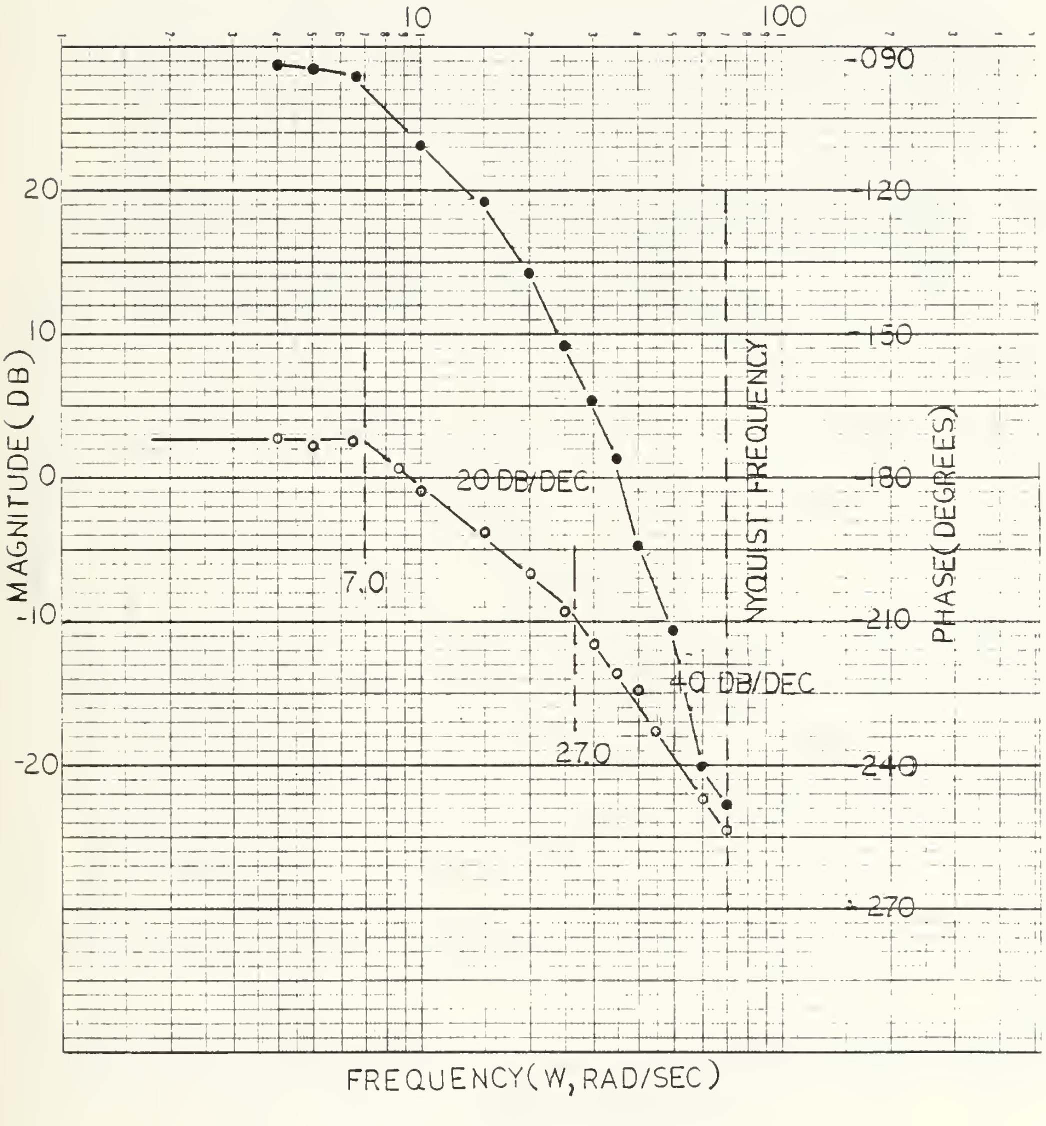


Figure 4.12. Bode Plot of the System.

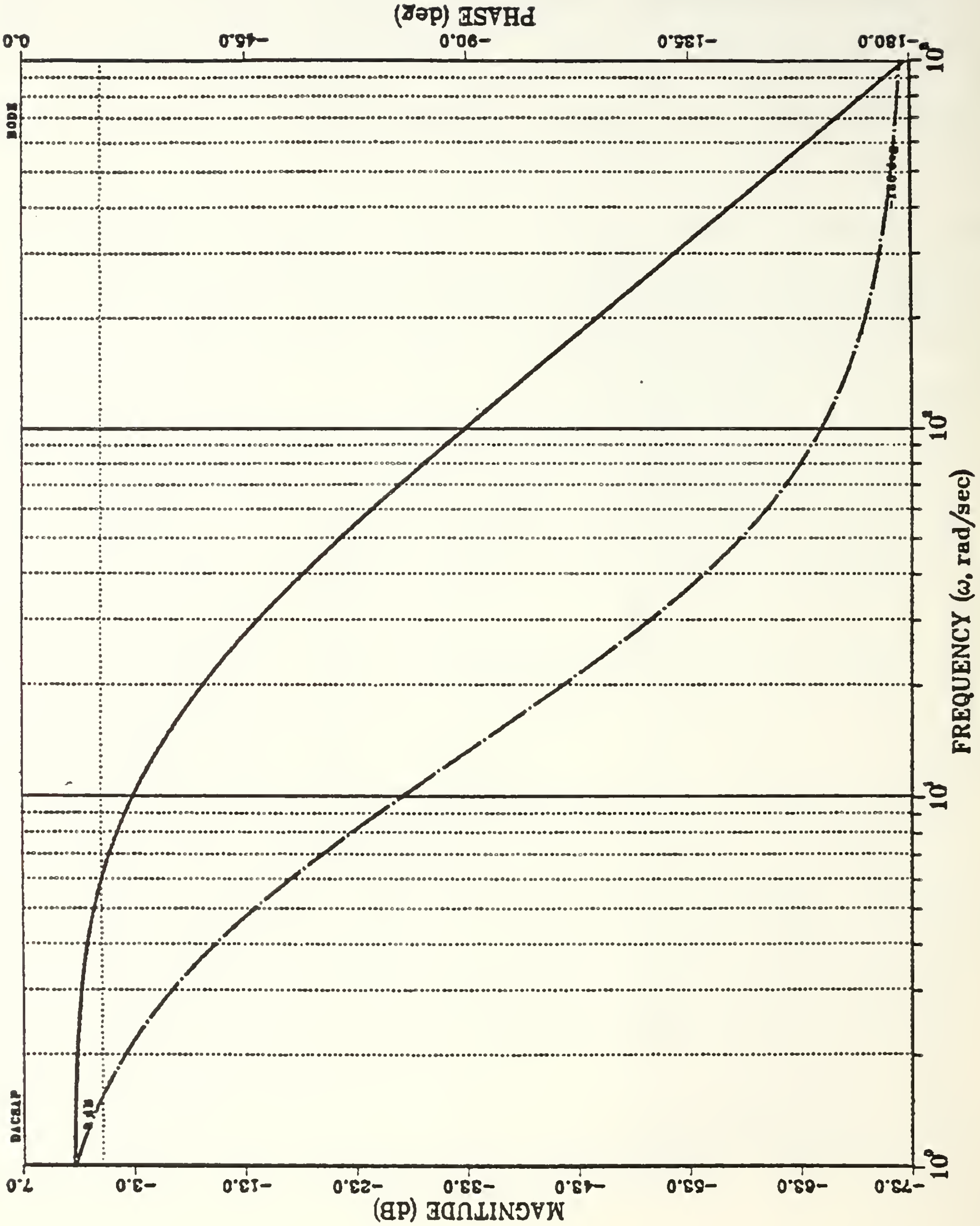


Figure 4.13. Frequency Response of the System from Computer Simulation.

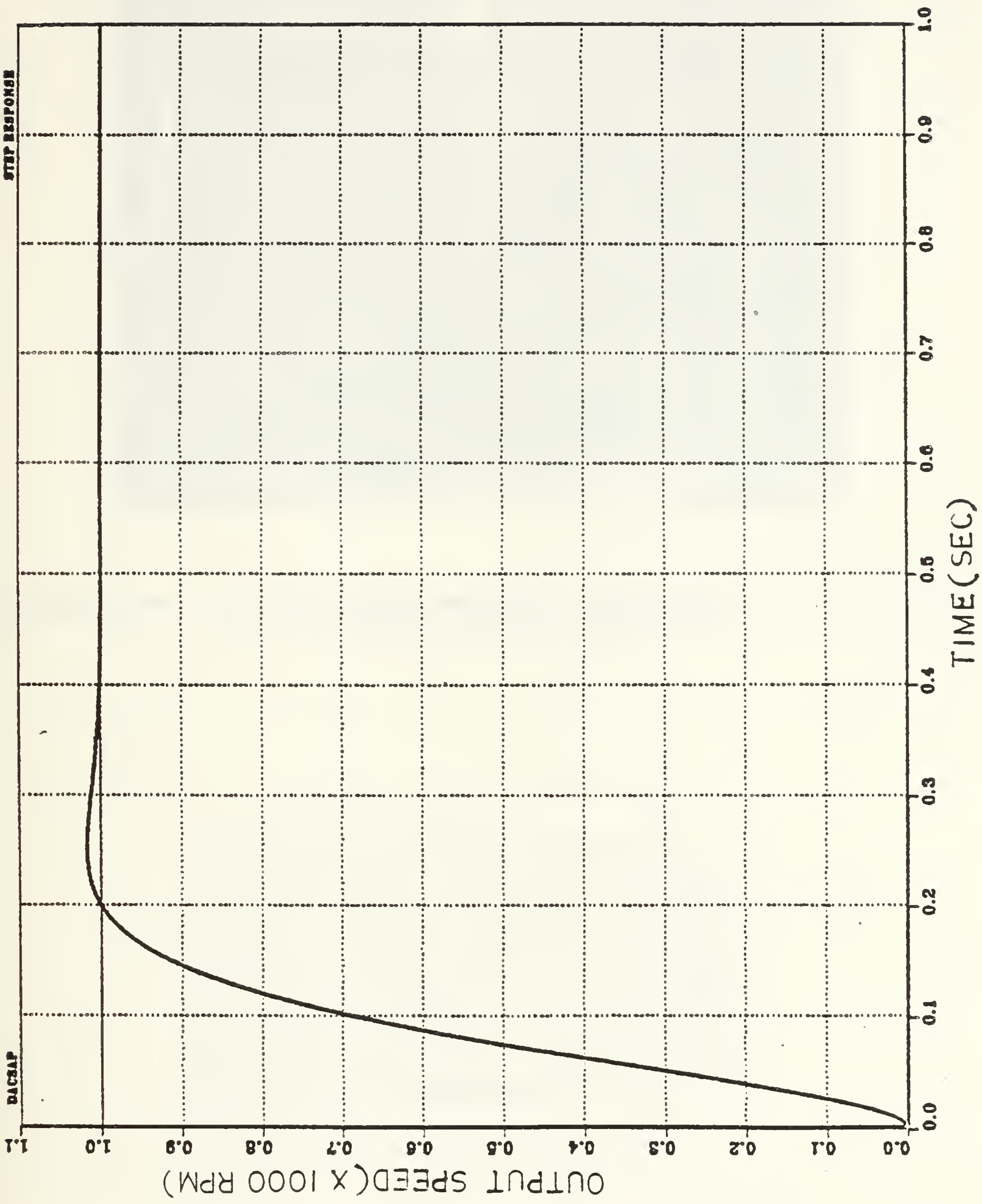


Figure 4.14. Transient Response of the System from Computer Simulation.

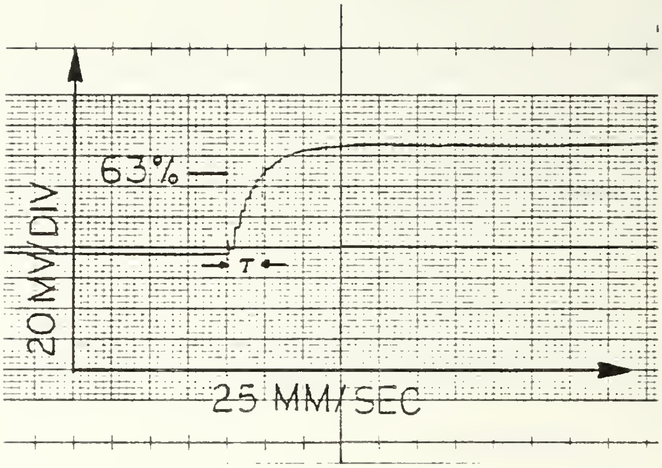


Figure 4.15. Open Loop Transient Response of the System from the Strip Chart.

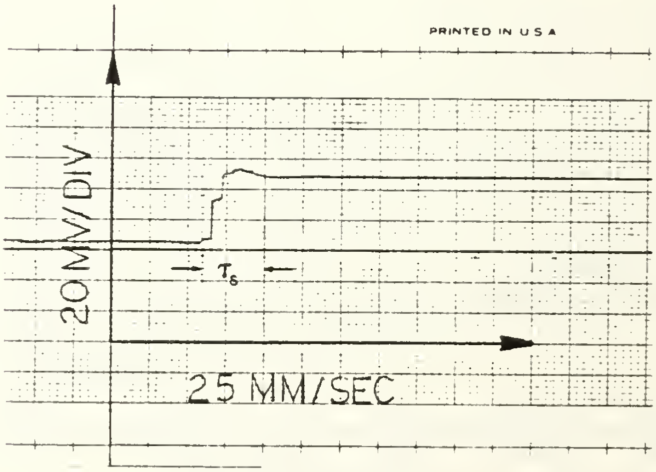


Figure 4.16. Closed Loop Transient Response of the System from the Strip Chart.

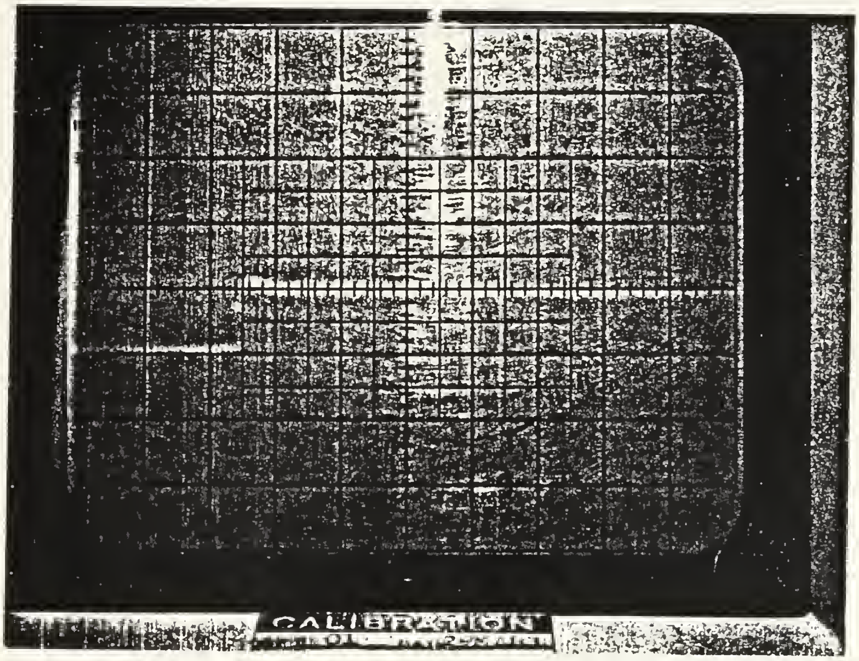


Figure 4.17. Closed Loop Transient Response of the System from Storage Oscilloscope.

V. POSITION CONTROL OF THE DC MOTOR WITH MICROPROCESSOR CONTROL

A. GENERAL

Microprocessor control of brushless DC motors has many advantages over an analog control. One of the advantages is that since it can be built with a couple of integrated circuits, it is smaller and lighter than an analog controller. It is also easy to debug the system.

There are some advantages and disadvantages to consider in software design and its implementation as well. Some of the advantages are:

1) By changing the software program, the function of the system can be changed.
2) By modifying the input/output devices, this system can be used for other control systems.
3) By standardizing the hardware, system design emphasis can be increased on software programs and subroutines.
4) Since the system is constructed of standardized units, it is easy to debug the system.

B. MICROPROCESSOR CONTROL OF DC MOTORS

There are two approaches to microprocessor control. One approach is the "direct" approach, another is the "indirect" approach. In the direct approach the data obtained from the system are fed into a microprocessor to compute the new value of control. In the "indirect" method of microprocessor control, the motor has an analog servo controller and microprocessor is used to turn the servo on and off. [Ref. 2] In this thesis the "direct" approach is used.

The block diagram of the microprocessor-controlled position control system is shown in Figure 5.1 [Ref 3]. The position and direction commands are given from the cathode ray tube (CRT) terminal. Another input to the microprocessor controller is the actual direction of the motor which is determined by using two channels of the optical encoder. The direction sensing system is shown in Figure 5.2.

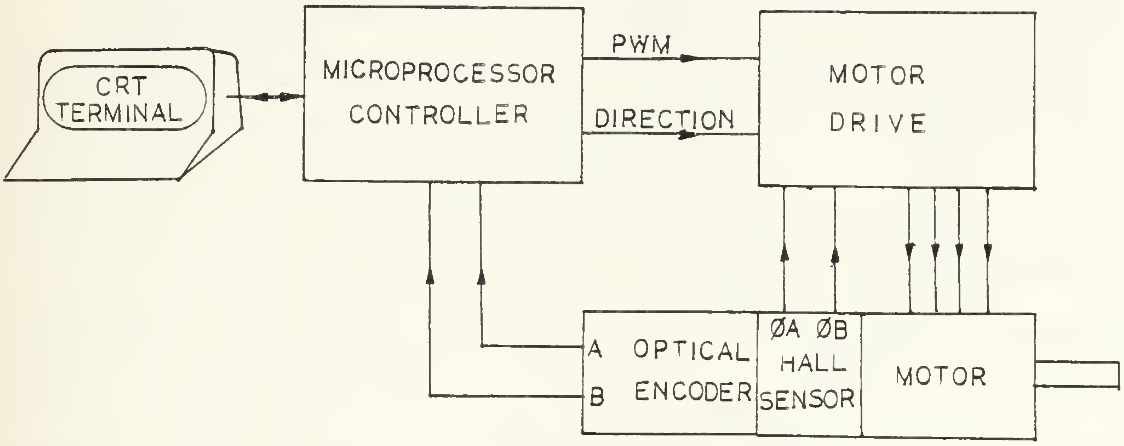


Figure 5.1. Position Control System.

C. INCREMENTAL OPTICAL ENCODER

The incremental optical encoders are used for position confirmation and for feedback signal generation. Incremental optical encoders provide a pulse for each increment of resolution. An incremental encoder has four main parts: a light source, a rotation disk, a stationary mask, and a sensor as shown in Figure 5.3. [Ref. 2] A Hewlett-Packard Heds-6000 series incremental optical encoder was used for the system.

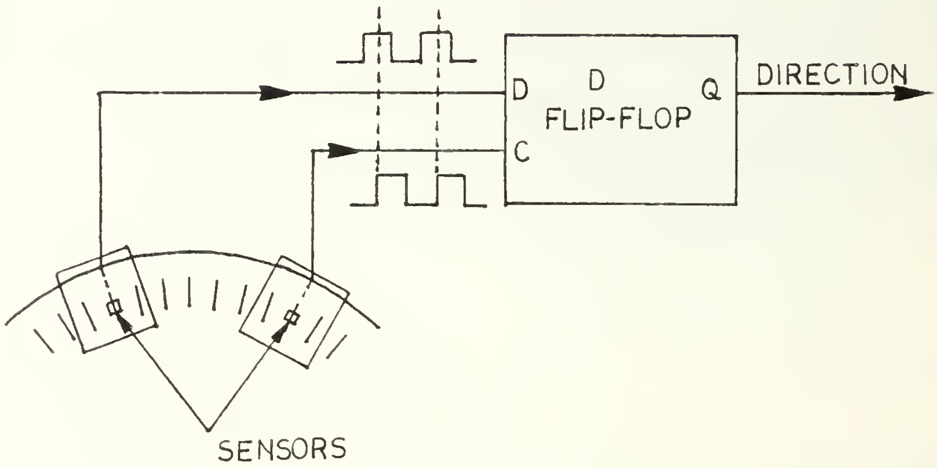


Figure 5.2. Direction Sensor.

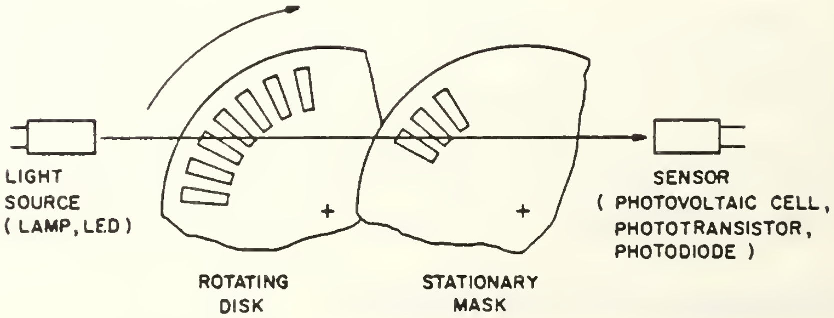


Figure 5.3. Incremental Optical Encoder.

The Heds-6000 series is a high resolution incremental optical encoder. It consists of three parts: the encoder body, a metal code wheel, and emitter and plate.

The incremental shaft encoder operates by translating the rotation of a shaft into interruptions of a light beam which provides output as electrical pulses.

The standard code wheel is a metal disc which has N=1000 equally spaced slits around its circumference. An aperture with a matching pattern is positioned on the stationary phase plate. The light beam is transmitted only when the slits in the code wheel and the aperture line up. Therefore, during a complete shaft revolution, there will be N=1000 alternating light and dark periods. A molded lens beneath the phase plate aperture collects the modulated light into a silicon detector.

The encoder body contains the phase plate and the detection elements for three channels. The first channel gives N=1000 pulses for each revolution. The second channel has a similar configuration but the location of its aperture pair provides an output which is in quadrature to the first channel. The phase difference is 90° electrical. The direction of rotation is determined by observing the leading form of the channel B. The outputs are TTL logic level signals.

The index channel is similar in optical and electrical configuration to the A,B channel described above. An index pulse of typically one cycle width is generated for each rotation of the code wheel.

For counter clockwise and clockwise rotation of the code wheel, channel A, channel B, and index channel outputs are shown in Figure 5.4a and Figure 5.4b respectively. Encoding characteristics, recommended operating conditions and definitions are shown in Appendix E.

D. MICROCOMPUTER SYSTEM

The general block diagram of the microcomputer system is shown in Figure 5.5. The microprocessor unit (MPU), Z-80, implements the function of the central-processing unit (CPU) within one chip. It includes an arithmetic-logical unit (ALU), plus internal registers, and a control unit (CU), in charge of sequencing the system. The Z-80 creates three busses: an 8-bit bidirectional data bus, a 16 bit unidirectional address bus and a control bus.

The data bus carries the data being exchanged by the different elements of the system. Mainly, it will carry data from the memory to the Z-80 or from the Z-80 to an input/output chip. The input/output chip is the component in charge of communication with an external device.

The address bus carries an address generated by the Z-80 which will select one of the chips attached to the system. For this system a 74LS138 decoder was used.

This address specifies the source or the destination of the data which will transit along the data bus.

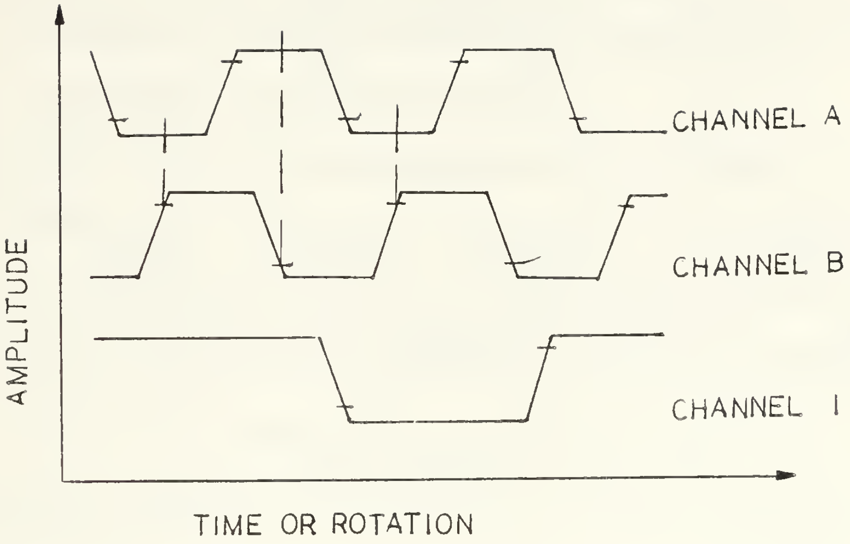


Figure 5.4a. Encoder Channel Outputs for CW Rotation.

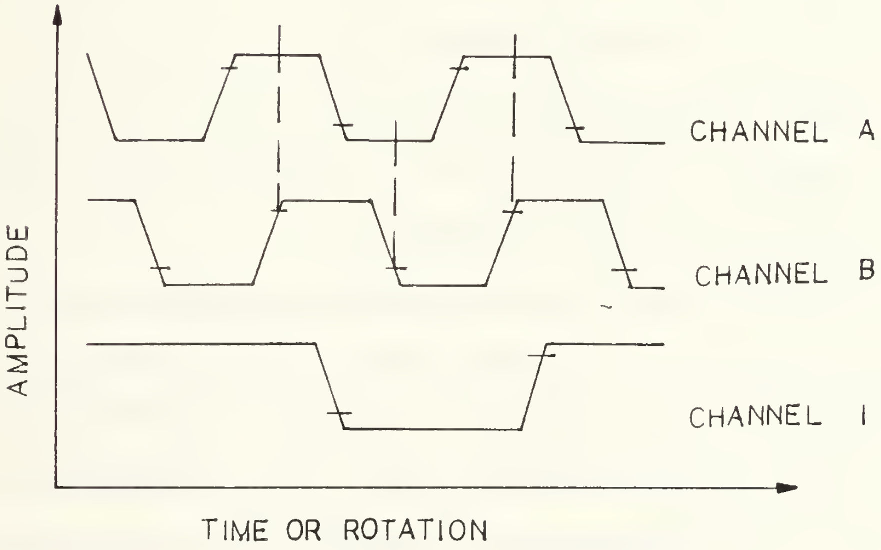


Figure 5.4b. Encoder Channel Outputs for CCW Rotation.

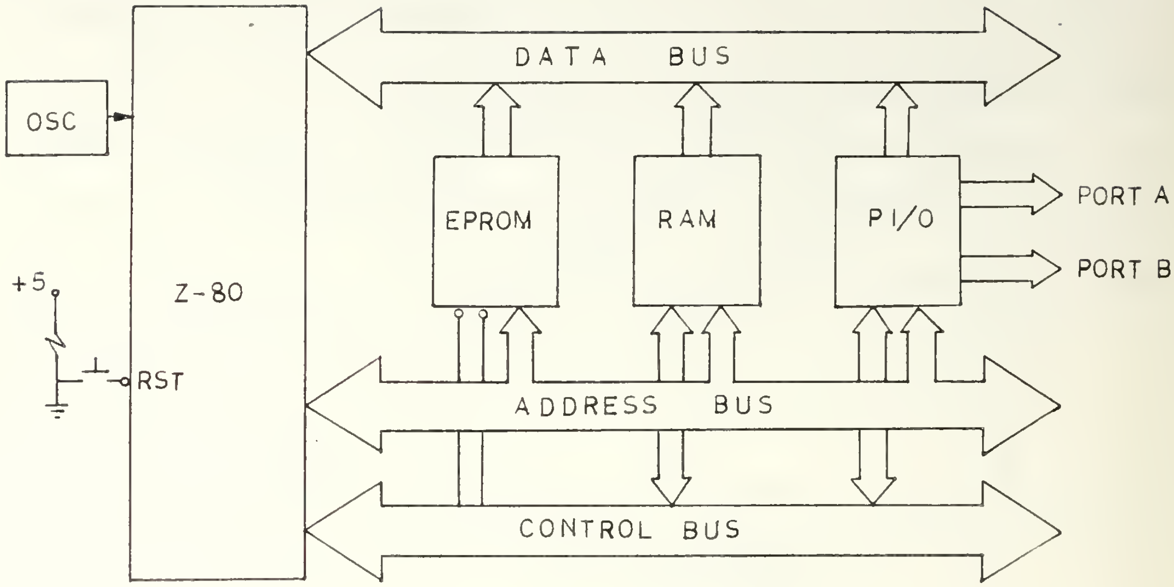


Figure 5.5. Microcomputer System.

The control bus carries the various synchronization signals required by the system.

The Z-80 requires a precise timing reference which is supplied by a 4.915 MHz crystal.

The RAM (random-access memory) is the read/write memory for the system. MOSTEK MK 4118 (P/N) series, 1KX8 static RAM was used for the microcomputer.

The system contained two interface chips so that it could communicate with the external world. The MC 68661B, Enhanced Programmable Communications Interface (EPCI) was used to communicate with the CRT terminal. The details on the EPCI programming are explained in Appendix F. An Intel M8255A

Programmable Peripheral Interface (PPI) was used to interface with the motor. The M8255A PPI has three ports which can be used for input or output purposes. The operating modes of the chip are explained in Appendix G.

The 2716 16K(2Kx8) UV Erasable Prom (EPROM) was used to load the program for the system. The function of the system can be changed entirely by writing the new program and loading the EPROM. The circuit diagram of the microcomputer is shown in Figure 5.6.

E. SOFTWARE DESIGN

1. General

The software was designed in such a fashion that a position command to the motor is given from the CRT terminal. The direction of the motor is calculated by the program which chooses the CW or CCW direction for the shortest path to its destination.

The system software was written in Assembly language (Appendix H) at a Zenith Z-100 microcomputer, using a Z-80 instruction sets [Ref 3]. The program was assembled and the hex files downloaded to the EPROM by using a SYS19 routine.

The main program consists of:

1) an initialization routine for the ports and a CRT interfacing,
2) calibration routine for a D/A converter, and
3) position control routine and subroutines.

2. Main program components.

The initialization routine sends a control word to the parallel ports of the computer, setting them to the output mode. There are two options given to the user. First is the calibration of the D/A converter (Appendix D) and second is the position control of the system. After the calibration of the system, the position command to the motor can be given from the CRT terminal. For simplicity, the position of the motor should be given as a count of pulses. Since the incremental optical encoder gives 1000 pulses per revolution, 1 pulse represents 0.36^{o}. If the command is 100 counts, it will represent 36^{o}.

The direction of the motor is determined in the following fashion. If the position command is greater than 180^{o} (500 counts) the direction of the motor will be counterclockwise (CCW).

The program takes 300 states to calculate the position of the motor and determine the new control command. The actual time the program takes to execute can be found by multiplying the number of states by the clock period. A 4.915 MHz clock was used for this microcomputer, so the period of the pulse is:

$$1/4.915\ \ 10^{6} = 0.2035 \text{ microsecond.}$$

Each state would correspond to 0.2035 microseconds of real time. By adding up the total number of states that the program requires to execute and multiplying this by the clock period, it can be determined how long this program will take to execute.

300 states x 0.2035 microseconds = 60.6 microsecond.

On the other hand, the period of the pulses that are sent from the incremental optical encoder should be longer than 60.6 microseconds. Otherwise, the microcomputer will miss the pulses and go to the wrong position.

At maximum, 810 rpm was found to be a sufficient speed for the brushless DC motor. The motor will make one rotation in 74 milliseconds and each encoder pulse period will be 74 microseconds long. This corresponds to 4 volt power supply for the motor. When the position error is maximum, the motor speed will be 810 rpm and it will decrease with a decreasing error signal. When the error signal is between 0^{o}-5^{o}, the speed of the motor will be 600 rpm. The torque at this speed was found sufficient to overcome friction in the motor.

The flow chart of the system is shown in Figure 5.7.

3. Description of the subroutines

To make the program useful and understandable some subroutines were written.

The Getchar subroutine gets the character from CRT terminal and stores it in register.

The Echo subroutine sends message string to the CRT terminal.

The Recall subroutine sends characters to the CRT terminal.

The *Wait* subroutine waits for the next positive rising edge of the encoder pulse.

The *CPY88* subroutine calculates 8x8 bit multiplication.

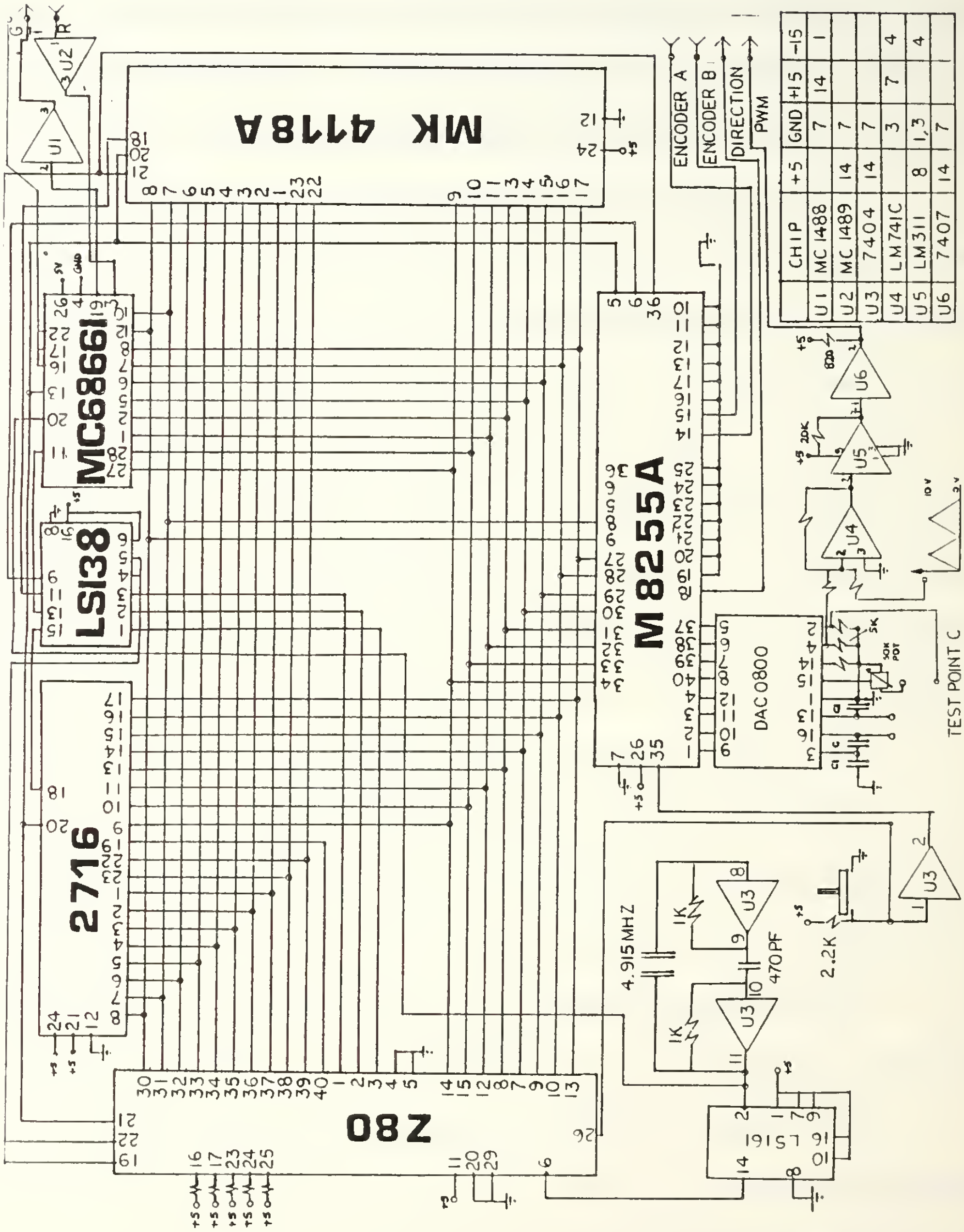


Figure 5.6. Circuit Diagram of the Microprocessor.

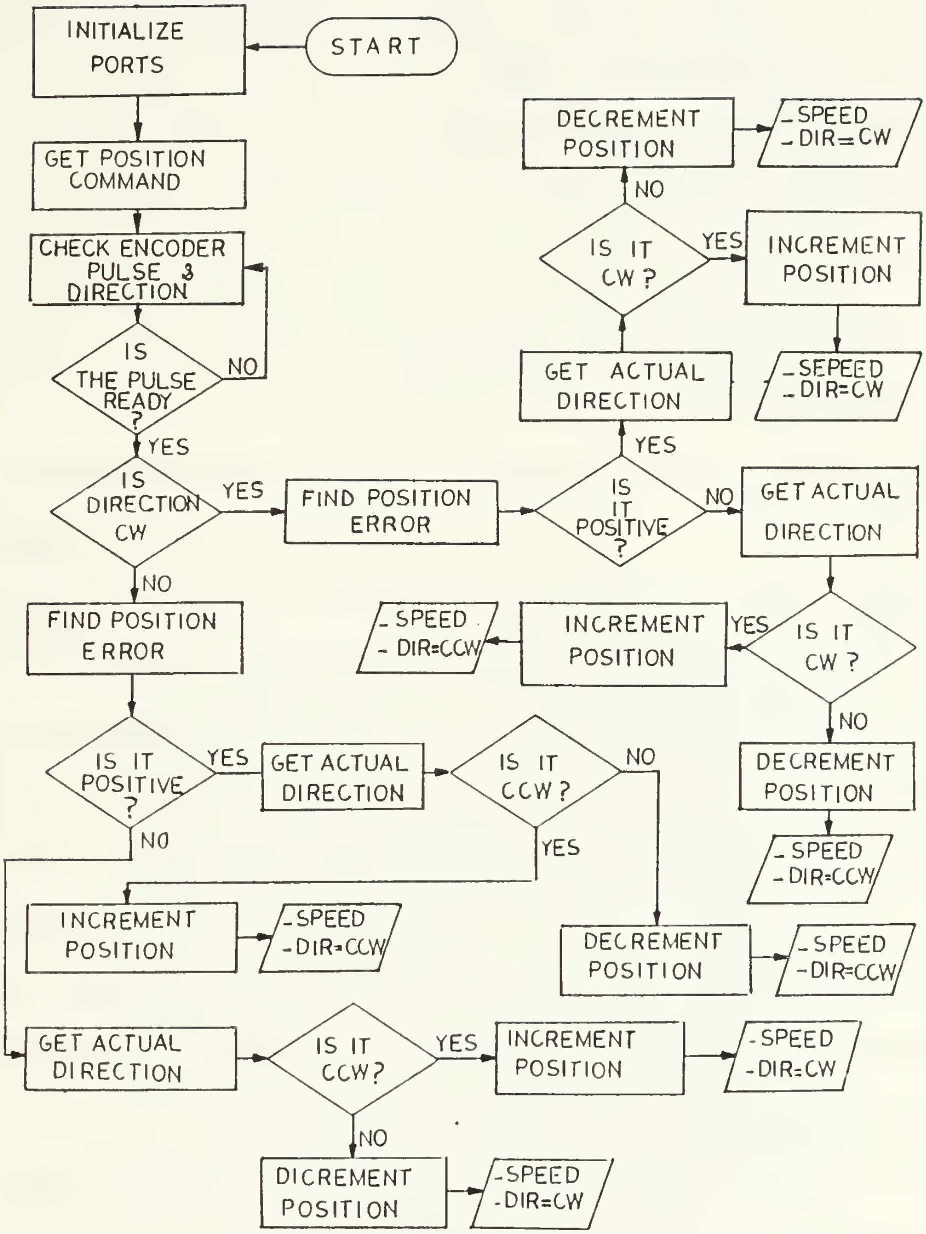


Figure 5.7. Flow Chart of the Main Program.

VI. SYSTEM TESTING AND DATA COLLECTION FOR POSITION CONTROL SYSTEM

A. GENERAL

A microprocessor controller using the Z-80 was built for the position control system. During the testing the following equipment was used:

1. Power supply unit PS 150E
2. Hewlett-Packard 1216A power supply.
3. Wavetek model 145 pulse/function generator.
4. Power supply model 3650.5.
5. Hewlett-Packard 124A camera.

The power requirements for the microprocessor were +15V, -15V, -10V, +15V and 3-30V. The power requirement for motor drive as well as the incremental optical encoder was +5V. A four volt power supply was used for the motor.

The sequence for turning on the power supplies for the system is important. First, the power supply of the microprocessor and motor drive should be turned on. The power supply of the motor should be turned on at the very last. The microprocessor system draws a total of 450 milliampers. The maximum current limit of 500 milliampers should be set before adjusting the five volt power supply.

To start the microprocessor the reset button should be set. The dial which was mounted on the shaft to observe the angular position of the motor can be adjusted to 0° as an initial position.

B. SYSTEM CALIBRATION

The calibration of the system should be done before using the system. For this purpose a calibration program was written. After resetting the system, two options appear on the CRT terminal. (See Figure 6.1)

After entering "1" for system calibration, a set of instructions appear on the CRT Terminal. (See Figure 6.2)

The voltage on test point "C" should be adjusted to -4.96 volts.

C. CLOSED LOOP POSITION CONTROL

After choosing the position control option from the menu, a set of instructions appear on the CRT terminal. (See Figure 6.3)

Since the optical incremental encoder has a resolution of 1000, each pulse of the encoder represents 0.36°. The position command should be given as counts. The relation between counts and angular positions is given in Table 2. A dial was used to easily observe the angular position of the motor.

The block diagram of the position control system is shown in Figure 6.4. The blow up picture of the curve following block is shown in Figure 6.5. When the position error is maximum the velocity will be 810 rpm. When the position error is between minus 5° and plus 5° the velocity will be 600 rpm. When the position error is minus, tne direction of the motor is changed from the CW direction to the CCW direction or from CCW direction to the CW direction, depending on the initial direction of the motor.

The software program was written in such a way that when the position error is zero the motor will not shop. When the position error is 0.36° the direction of the motor is changed to the other direction and position error is -0.36° the motor is reversed again. This algorithm will create a dither signal between $\mp 0.36^{\circ}$ at the position. This dither behavior will hold the motor shaft at the given position within $\mp 0.36^{\circ}$.

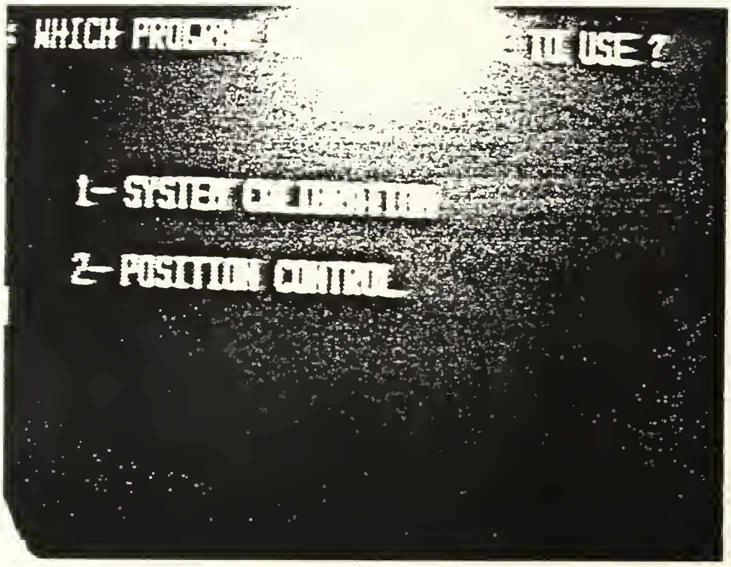
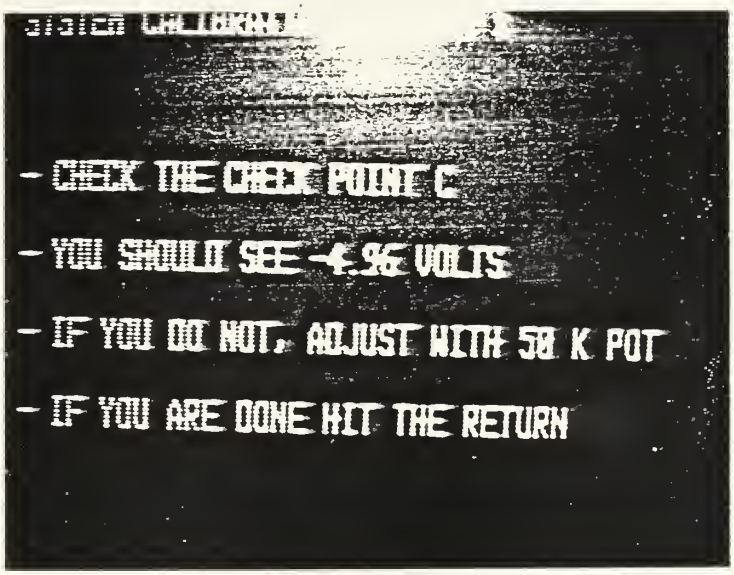
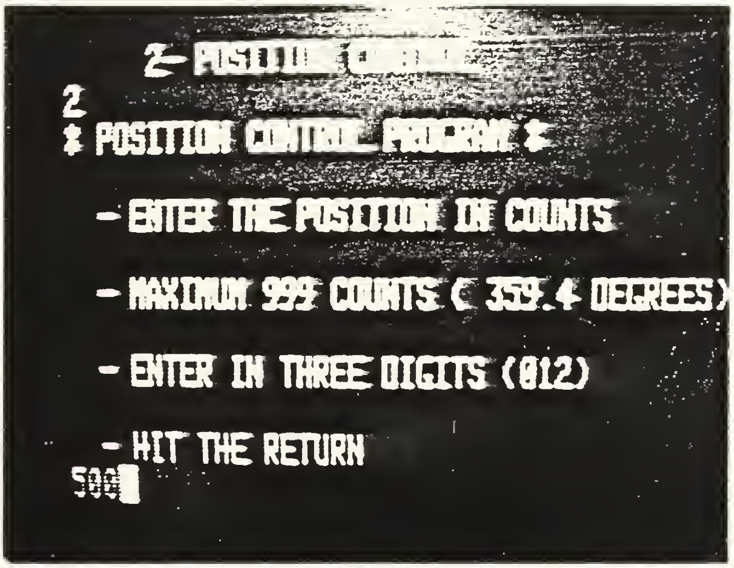


Figure 6.1. CRT Terminal Menu for Program Options.



```
SYSTEM CALIBRA

- CHECK THE CHECK POINT C

- YOU SHOULD SEE -4.96 VOLTS

- IF YOU DO NOT, ADJUST WITH 50 K POT

- IF YOU ARE DONE HIT THE RETURN
```

Figure 6.2. CRT Terminal Menu for Calibration of System.



```
      2- POSITION [illegible]
  2
  * POSITION CONTROL PROGRAM *

    - ENTER THE POSITION IN COUNTS

    - MAXIMUM 999 COUNTS ( 359.4 DEGREES)

    - ENTER IN THREE DIGITS (012)

    - HIT THE RETURN
  500
```

Figure 6.3. CRT Terminal Menu for Position Control.

TABLE 6.1
COUNTS AND ANGULAR POSITIONS

Counts	Angular Position (degrees)
000	0
142	15
083	30
125	45
167	60
208	75
250	90
375	135
500	180
625	225
750	270
875	315
997	359

The software program was written in such a fashion that when the position command was bigger than 180°, the program would chose the shortest path for its destination.

Fifty runs for the position commands which were smaller than 180° and fifty runs for the positions which were greater than 180° were done.

For all the runs, the motor went to the given position and dither signal was found to be $\mp 0.48^\circ$. This was close enough to $\mp 0.36^\circ$ to be satisfactory.

The transient response and frequency response of the system can be found by using the additional system interfacing chips and by writing a new software program. This is recommended for further studies in Chapter Seven.

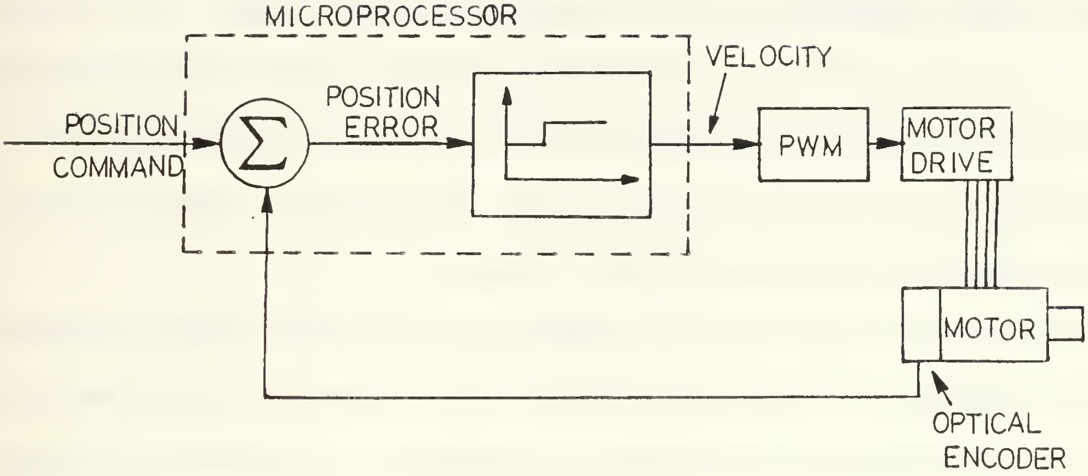


Figure 6.4. Block Diagram of the Position Control System.

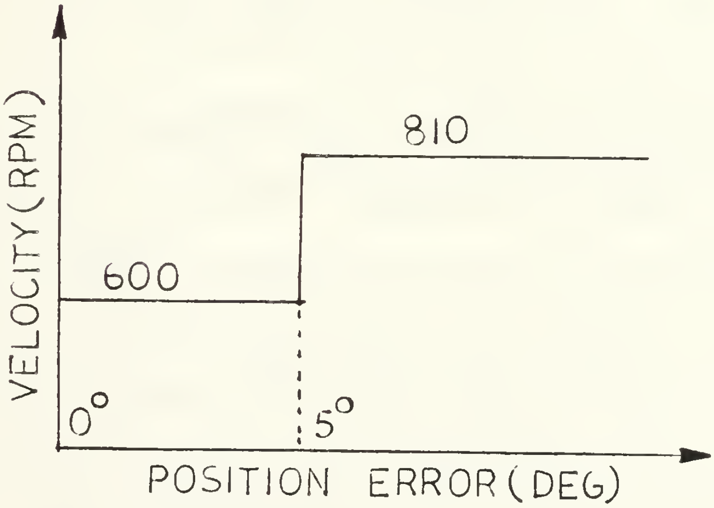


Figure 6.5. Curve Following Block.

VII. SUMMARY AND CONCLUSION

A. REMARKS AND CONCLUSIONS

The brushless DC motor has been shown to have some advantages compare to the conventional DC motor. Brushless DC motors with their disadvantages still are more favorable for use in incremental motion applications. Since commutation is done by switching transistors, pulse width modulation is a desirable option in system design.

The low-cost position sensors such as Hall effect circuits and optical sensing integrated circuits have been found to be highly practical for servo designs. A velocity control system designed by using the Hall effect sensors.

From the analyses, the time constant of the motor as given in the factory specifications was considerably faster than the measured time constant. This was the result of the time delay of the pulse width modulator and the D/A converter.

The transfer function of the system was developed by using an HP spectrum analyzer. The time constant of the system was found by using the transient response data which was measured using a strip chart and storage oscilloscope. The measure of the time constant was found to be identical with the computer simulations of the system transfer function.

The position control of the brushless DC motor was studied by using a Z-80 microprocessor controller. Position feedback was obtained from an incremental optical encoder. The encoder had 1000 resolution per revolution which provided high accuracy for position control. Assembly language was used to write a program for position control. For the Z-80 CPU a 4.915 MHz clock was used. This brought the limitation for maximum speed of the motor to 810 rpm.

The system testing for the position control system was done and was found to be accurate. Since the incremental encoder gives one pulse for 0.36° angular position, the steady state error was programmed to be ∓0.36° to hold the torque on the shaft. The steady state error which was found from the position control system was ∓0.48°.

B. RECOMMENDATIONS FOR FURTHER STUDIES

For the digital tachometer a 16 bit (4 x 4 bit) counter system was used. By using the 24 bit counter system, the performance of the system can be improved.

Eight bit D/A converters were used for both the velocity and position control systems. By using 12 bit D/A converters, the resolution of the system can be increased from 0.2 volts to 0.01 volts.

Instead of the Hall effect sensor, an incremental optical encoder can be used with the velocity estimator to measure the motor speed. The sampling rate will then be faster than the sampling rate using Hall effect sensors.

A 2N 2222 transistor in the motor drive to which the PWM signal is applied will burn out if the transistor transistor logic (TTL) signal is used for the PWM signal. To avoid this, the open collector logic signal with an 820 ohms pull-up resistor should be used for the PWM signal.

Assembly language was used to program the position control system. There are many high level languages that may be used such as Forth, Basic, Fortran, C, Pascal and Ada. There are many advantages in using a high-level language rather than assembly language because it takes much less time to develop a system. The code is also much more readable and therefore, easier to modify the program with a high-level language.

The transfer function of the system can be found by using a couple more parallel interfacing devices (Intel 8255A) and by modifying the program which was already written.

Since the incremental encoder has two outputs with 90^{o} electrical phase difference, using both outputs instead of one output as a position sensor the steady state error can be programmed to be $\mp 0.18^{o}$. This will require another CPU with a faster clock.

It is recommended that after the circuits are built and it is certain that it is working properly, it would be better to build the circuit using wire-wrap technique to improve the wire layout and also to reduce possible trouble shooting errors.

APPENDIX A

RATING AND SPECIFICATIONS FOR PITTMAN 511 WDG #1 BRUSHLESS DC MOTOR

MOTOR PARAMETER	UNITS	SYMBOL	VALUE
DAMPING CONSTANT $(K_T K_E / R_T)$	N.m/(rad/s)	K_D	1.42×10^{-3}
MOTOR CONSTANT (K_T / R_T)	N.m/ W	K_M	37.7×10^{-3}
MECHANICAL TIME CONST. (J/K_D)	ms	τ_M	14.4
ELECTRICAL TIME CONST. (L/R_T)	ms	τ_E	0.155
MOMENT OF INTERIA	$kg.m^2$	J	20.5×10^{-6}
VISCOUS DAMPING	N.m/(rad/s)	D_F	13×10^{-6}
FRICTION TORQUE	N.m	T_F	3.0×10^{-3}
MOTOR MASS	kg	M	0.60
THERMAL TIME CONSTANT	min	τ_{TH}	15
THERMAL IMPEDENCE(WDG-AMBIENT)	$^0C/W$	R_{TH}	3.2
MAXIMUM WINDING TEMP.	^0C	Θ_{MX}	155

WINDING PARAMETER	UNITS	SYMBOL	VALUE
TORQUE CONSTANT	N.m/A	K_T	29.9×10^{-3}
BECK EMF CONSTANT	V/(rad/s)	K_E	29.9×10^{-3}
STATOR RESISTANCE	ohms	R_T	0.631
STATOR INDUCTANCE	mH	L	0.0975

APPENDIX B

THE DAC CALIBRATION FOR VELOCITY CONTROL SYSTEM

The DAC system was set to 0 to -10 volts output range. If the system range is to be changed an adjustment in the gain offset will be necessary.

To adjust the gain offset of the DAC the following procedure should be applied.

1) Turn off the power of the motor.

2) Turn on the power of the system.

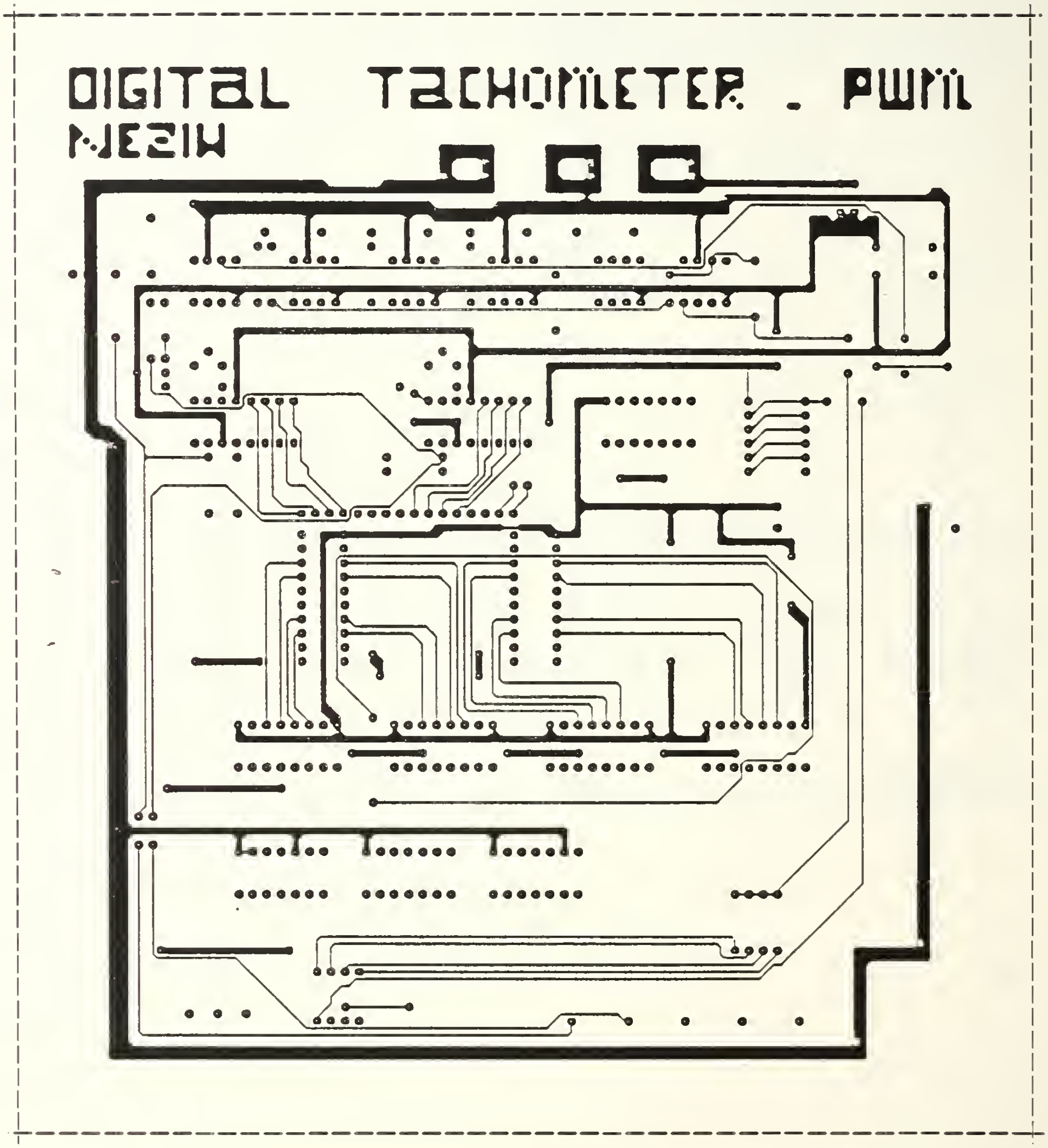
3) Connect the test point '0' to the ground.

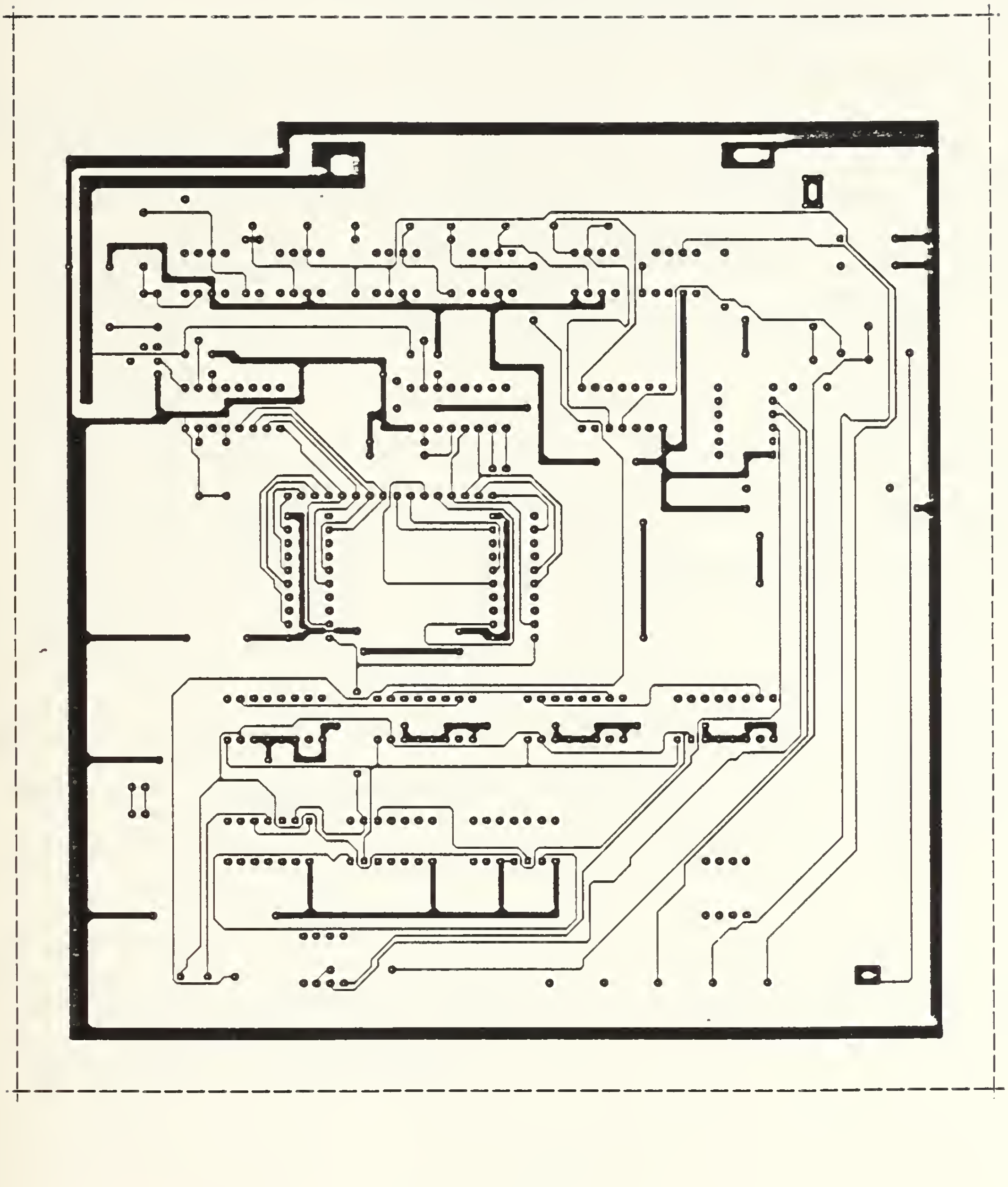
4) Adjust the P1 pot until -5.00 volts is shown.

5) Adjust the P2 pot until -5.00 volts is shown.

APPENDIX C

ARTWORK FOR THE DIGITAL TACHOMETER AND PULSE WIDTH MODULATOR CIRCUIT





APPENDIX D

THE DAC CALIBRATION FOR POSITION CONTROL SYSTEM

The DAC system was set to 0 to -10 volts output range. The gain offset adjustment will be necessary for good system performance.

After pushing the start button, the program will ask to select an option for making calibrations. After selecting the calibration option, the microprocessor sends the signal to the DAC. Minus 4.96 volts should be seen from test point 'C'. If it is not, the P1 pot should be adjusted.

APPENDIX E

CHARACTERISTIC OF THE OPTICAL ENCODER

Definitions

Electrical Degrees:

1 shaft rotation = 360 mechanical degrees
= N electrical cycles
1 cycle = 360^o electrical degrees.

Position Error:

The angular difference between the actual shaft position and its position as calculated by counting the encoder's cycles.

Cycle Error:

An indication of cycle uniformity. The difference between an observed shaft angle which gives rise to one electrical cycle, and the nominal angular increment of 1/N of a revolution.

Phase:

The angle between the center of pulse A and the center of pulse B.

Index Phase:

For counter-clockwise rotation is illustrated above, the index phase is defined as

$$\Phi_I = \frac{\Phi_1 - \Phi_2}{2}$$

Φ_1 is the angle, in electrical degrees, between the falling edge of I and falling edge of B. Φ_2 is the angle, in electrical degrees, between the rising edge of A and the rising edge of I.

Index Phase Error:

The Index Phase Error ($\Delta\Phi_2$) describes the change in the Index Pulse position after assembly with respect to the A and B channels over the recommended operating conditions.

APPENDIX F

MC 68661B OPERATION AND PROGRAMMING

Prior to initiating data communications, the MC 68661B operational mode must be programmed by performing write operations to the mode and command registers. The EPCI can be reconfigured at any time during the execution of the program.

The MC 68661B register formats are summarized as follows:

MODE REGISTER 1 (MR 1)

MR17	MR16	MR15	MR14	MR13 MR12	MR11 MR10
Sync Async		Parity Type	Parity Control	Character Length	Mode and Baud Rate Factor
Async: Stop Bit Length 00 = Invalid 01 = 1 stop bit 10 = 1½ stop bits 11 = 2 stop bits		0 = Odd 1 = Even	0 = Disabled 1 = Enabled	00 = 5 bits 01 = 6 bits 10 = 7 bits 11 = 8 bits	00 = Synchronous 1X rate 01 = Asynchronous 1X rate 10 = Asynchronous 16X rate 11 = Asynchronous 64X rate
Sync: Number of SYN char 0 = Double SYN 1 = Single SYN	Sync: Transparency Control 0 = Normal 1 = Transparent				

MODE REGISTER 2 (MR2)

MR27-MR24											MR23-MR20
	TxC	RxC	Pin 9	Pin 25		TxC	RxC	Pin 9	Pin 25	Mode	Baud Rate Selection
0000	E	E	TxC	RxC	1000	E	E	XSYNC	RxC TxC	sync	See baud rates in table 1
0001	E	I	TxC	1X	1001	E	I	TxC	BKDET	async	
0010	I	E	1X	RxC	1010	I	E	XSYNC'	RxC	sync	
0011	I	I	1X	1X	1011	I	I	1X	BKDET	async	
0100	E	E	TxC	RxC	1100	E	E	XSYNC	RxC TxC	sync	
0101	E	I	TxC	16X	1101	E	I	TxC	BKDET	async	
0110	I	E	16X	RxC	1110	I	E	XSYNC'	RxC	sync	
0111	I	I	16X	16X	1111	I	I	16X	BKDET	async	

COMMAND REGISTER (CR)

CR7 CR6	CR5	CR4	CR3	CR2	CR1	CR0
Operating Mode	Request To Send	Reset Error	Sync Async	Receive Control (RxEN)	Data Terminal Ready	Transmit Control (TxEN)
00 = Normal operation 01 = Async Automatic echo mode Sync SYN and or DLE stripping mode 10 = Local loop back 11 = Remote loop back	0 = Force RTS output high one clock time after TxSR serialization 1 = Force RTS output low	0 = Normal 1 = Reset error flags in status register (FE OE PE DLE detect)	Async Force break 0 = Normal 1 = Force break	0 = Disable 1 = Enable	0 = Force $\overline{DTR}$ output high 1 = Force $\overline{DTR}$ output low	0 = Disable 1 = Enable
			Sync: Send DLE 0 = Normal 1 = Send DLE			

There is one MC 68661B device in the system. Mode register 1 address is CE Hex, mode register 2 address is 7D Hex and command register address is 5 Hex.

APPENDIX G

INTEL 8255A OPERATION AND PROGRAMMING

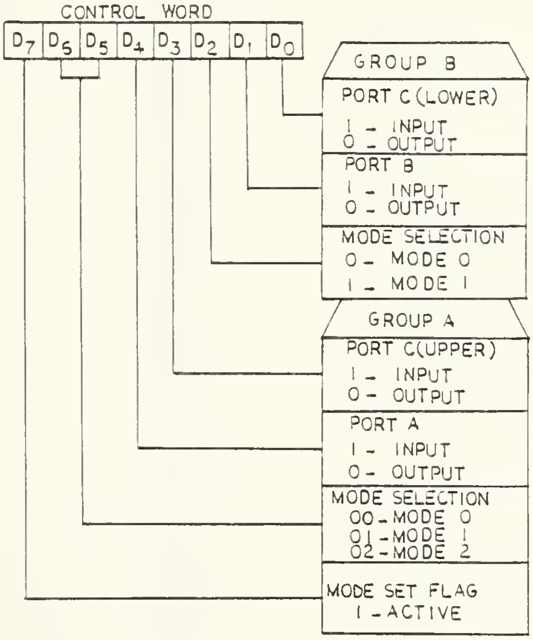
The Intel 8255A contains three 8-bit ports (A, B, and C). All can be configured in a wide variety of functional characteristics by the system software. There are three basic modes of operation that can be selected:

Mode 0 - Basic Input/Output

Mode 1 - Strobed Input/Output

Mode 2 - Bi-directional Bus

Mode definition control word format is as follows:



There is one 82557A device in the system. Port address is 89 Hex. This means port A and port B are at output; port C is at input mode.

APPENDIX H

MAIN PROGRAM

```
;
;
;
;
;        POSITION CONTROL & CALIBRATION PROGRAM
;
;
;
PPIA            EQU     1800H
PPIB            EQU     1801H
PPIC            EQU     1802H
PPICONT         EQU     1803H
EDATA           EQU     1000H
ESTAT           EQU     1001H
EMODE           EQU     1002H
ECOMD           EQU     1003H
RAMBASE         EQU     800H
POS             EQU     801H
DIR             EQU     803H
DIRD            EQU     804H
CHAR            EQU     805H
COUNT           EQU     806H
MPDAD           EQU     807H
MPRAD           EQU     809H
RESAD           EQU     80BH
SUM1            EQU     810H
SUM2            EQU     812H
SUM3            EQU     814H
ML1             EQU     816H
ML2             EQU     817H
ML3             EQU     818H
VEL             EQU     819H
CR              EQU     0DH
LF              EQU     0AH
                ORG     2000
                LD      SP,0BFFH          ; SET STACK POINTER
                LD      A,0CEH
                LD      (EMODE),A         ; SET MODE1 REGISTER FOR EPCI
                LD      A,7DH
                LD      (EMODE),A         ; SET MODE2 REGISTER FOR EPCI
                LD      A,5
                LD      (ECOMD),A         ; SET COMMAND REGISTER FOR EPCI
                LD      A,89H
                LD      (PPICONT ,A       ; SET MODE REGISTER FOR PPI
LOO1:           LD      A,0
                LD      (PPIA),A
                LD      IX,HEAD1
                CALL    ECHO
                LD      IX,SPACE
                CALL    ECHO
                LD      IX,HEAD2
                CALL    ECHO
                LD      IX,HEAD3
                CALL    ECHO
LOO11:          CALL    GETCHAR           ; GET CHARACTER FROM CRT
```

```
                LD      IX.CHAR
                CALL    RECALL
                LD      A,(CHAR)
                SBC     A.30H
                CP      1
                JP      Z,L002          ; CALIBRATION PROGRAM
                LD      A,(CHAR)
                SBC     A,30H
                CP      2
                JP      Z,START1        ; POSITION CONTROL PROGRAM
                CALL    ERROR
                JP      L0011
L002:           LD      IX,HEAD5        ; CALIBRATION PROGRAM
                CALL    ECHO
                LD      IX,SPACE
                CALL    ECHO
                LD      IX,HEAD6
                CALL    ECHO
                LD      IX,HEAD7
                CALL    ECHO
                LD      IX,HEAD8
                CALL    ECHO
                LD      IX,HEAD9
                CALL    ECHO
                LD      A,7FH           ; SEND CALIBRATION SIGNAL
                LD      (PPIA),A        ; SEND TO THE PORT
                CALL    GETCHAR
                CP      CR              ; IS IT CARRIAGE ?
                JP      Z,L001
                LD      IX,ERROR
                CALL    ECHO
                JP      L002
START1:         LD      IX,HEAD10
                CALL    ECHO            ;PRINT HEADER
                LD      IX,HEAD11
                CALL    ECHO
                LD      IX.HEAD12
                CALL    ECHO
                LD      IX,HEAD13
                CALL    ECHO
                LD      IX.HEAD14
                CALL    ECHO
                CALL    GETCHAR         ;GET POSITION FROM CRT
                LD      A.(CHAR)        ; POSITION(ASCII) ---> A
                LD      IX,CHAR
                CALL    RECALL
                SBC     A,30H           ; STRIP ASCII
                LD      (ML1).A         ; FIRST DIGIT
                CALL    GETCHAR         ; GET POSITION FROM CRT
                LD      A,(CHAR)        ; POSITION(ASCII) ---> A
                LD      IX.CHAR
                CALL    RECALL
                SBC     A.30H           ; STRIP ASCII
                LD      (ML2),A         ; SECOND DIGIT
                CALL    GETCHAR         ; GET POSITION FROM CRT
```

```
                LD      A,(CHAR)        ; POSITION(ASCII) ---> A
                LD      IX,CHAR
                CALL    RECALL
                SBC     A,30H           ; STRIP ASCII
                LD      (ML3),A         ; THIRD DIGIT
                CALL    GETCHAR
                CP      CR              ; IS IT CARRIAGE RETURN ?
                JP      Z,GO            ; YES, CONTINUE
                LD      IX,ERROR
                CALL    ECHO            ; ERROR ENTER AGAIN
                JP      START1
GO:             LD      H,0
                LD      L,64H
                LD      (MPDAD),HL
                LD      H,0
                LD      A,(ML1)
                LD      L,A
                LD      (MPRAD),HL
                CALL    CPY88           ; MULTIPLEXTION
                LD      IX,(RESAD)
                LD      (SUM1),IX       ; FIRST BINARY
                LD      H,0
                LD      L,0AH
                LD      (MPDAD),HL
                LD      H,0
                LD      A,(ML2)
                LD      L,A
                LD      (MPRAD),HL
                CALL    CPY88           ; MULTIPLEXTION
                LD      IX,(RESAD)
                LD      (SUM2),IX       ; SECOND BINARY
                LD      H,0
                LD      A,(ML3)
                LD      L,A
                LD      (SUM3),HL       ; THIRD BINARY
                LD      IX,(SUM1)
                LD      DE,(SUM2)
                ADD     IX,DE
                LD      DE,(SUM3)
                ADD     IX,DE
                LD      (POS),IX        ; POSITION IN BINARY
                LD      B,0
                LD      C,0
                LD      DE,(POS)        ; LOAD POSITION ---> DE
                LD      HL,01F4H        ; 180 DEGREES (500 COUNT) LIMIT
                AND     A
                SBC     HL,DE           ; IS IT GREATER THEN 180 DEG. ?
                JP      Z,CWD
                JP      P,CWD
                JP      M,CCWD
CWD:            LD      A,0             ; CW=0
                LD      (DIR),A
                JP      ANSC
CCWD:           LD      A,1             ; CCW=1
                LD      (DIR),A
```

```
ANSC:         LD      A,(DIR)
              LD      (PPIB),A
              LD      A,80H
              LD      (PPIA),A
              LD      A,(DIR)
              AND     01H             ; CW=0  CCW=1
              JP      Z,START2        ; DIRECTION ----> CW
              JP      STRT3A          ; DIRECTION ----> CCW
START2:       LD      A,(PPIC)        ; CHECK THE ENCODER
              LD      H,A             ; A ---> H
              AND     01H
              JR      Z,START2        ; NO PULSE CHECK AGAIN
              LD      A,H             ; PHASE B ---> A
              AND     02H             ; CW=0 CCW=1
              JP      Z,CW2           ;
CCW2:         LD      A,1
              LD      (DIRD),A
              JP      CONT2A
CW2:          LD      A,0
              LD      (DIRD),A
CONT2A:       LD      HL,(POS)        ; GET POSITION
              AND     A
              SBC     HL,BC           ; COMPARE THE POSITION
              JP      Z,NEGAT2        ; AT THE POINT
              JP      M,NEGAT2        ; BEYOND THE POINT
              JP      P,POSIT2        ; NOT AT THE POINT
POSIT2:       LD      A,(DIRD)        ; DIRECTION OF THE MOTOR
              AND     01H
              JP      NZ,CCW2A        ; CCW=1 CW=0
CW2A:         INC     BC              ; CLOCK WISE ROTATION
              LD      HL,(POS)        ; LOAD POSITION
              AND     A               ; CLEAR FLAGS
              SBC     HL,BC           ; COMPARE THE POSITIN
              JP      P,POS1A
              LD      A,H
              CPL                     ; COMPLEMENT
              LD      H,A
              LD      A,L
              CPL                     ; COMPLEMENT
              ADD     A,1
              LD      L,A
POS1A:        LD      D,H
              LD      E,L
              LD      L,12H           ; 5.76 DEG. POSITION LIMIT
              LD      H,0             ;
              SBC     HL,DE
              JP      M,SEP1          ; SPEED COMMAND
              LD      A,0D8H
              JR      CONT1
SEP1:         LD      A,0E8H
CONT1:        LD      H,0             ; CW=0
              LD      (PPIA),A        ; SEND SPEED COMMAND
              LD      A,H
              LD      (PPIB),A        ; SEND DIRECTION
WAIT1:        LD      A,(PPIC)        ; CHECK THE ENCODER
```

```
            AND     01H
            JP      NZ,WAIT1
            JP      START2
CCW2A:      DEC     BC              ; COUNTERCLOCK WISE ROTATION
            LD      HL,(POS)        ; LOAD POSITION
            AND     A               ; CLEAR FLAGS
            SBC     HL,BC           ; COMPARE THE POSITIN
            JP      P,POS2A
            LD      A,H
            CPL                     ; COMPLEMENT
            LD      H,A
            LD      A,L
            CPL                     ; COMPLEMENT
            ADD     A,1
            LD      L,A
POS2A:      LD      D,H
            LD      E,L
            LD      L,10H           ; 5.76 DEG. POSITION LIMIT
            LD      H,0             ;
            SBC     HL,DE
            JP      M,SEP2          ; SPEED COMMAND
            LD      A,0D8H
            JR      CONT2
SEP2:       LD      A,0E8H
CONT2:      LD      H,0             ; CW=0
            LD      (PPIA),A        ; SEND SPEED COMMAND
            LD      A.H
            LD      (PPIB),A        ; SEND DIRECTION
WAIT2:      LD      A,(PPIC)        ; CHECK THE ENCODER
            AND     01H
            JP      NZ,WAIT2
            JP      START2
NEGAT2:     LD      A,(DIRD)
            AND     01H
            JP      NZ,CCW2B        ; CCW=1 CW=0
CW2B:       INC     BC              ; CLOCK WISE ROTATION
            LD      HL,(POS)        ; LOAD POSITION
            AND     A               ; CLEAR FLAGS
            SBC     HL,BC           ; COMPARE THE POSITIN
            JP      P,POS3A
            LD      A,H
            CPL                     ; COMPLEMENT
            LD      H,A
            LD      A,L
            CPL                     ; COMPLEMENT
            ADD     A,1
            LD      L,A
POS3A:      LD      D,H
            LD      E,L
            LD      L,10H           ; 5.76 DEG. POSITION LIMIT
            LD      H,0             ;
            SBC     HL,DE
            JP      M,SEP3          ; SPEED COMMAND
            LD      A,0D8H
            JR      CONT3
```

```
SEP3:       LD      A,0E8H
CONT3:      LD      B,1             ; CCW=1
            LD      (PPIA),A        ; SEND SPEED COMMAND
            LD      A,B
            LD      (PPIB),A        ; SEND DIRECTION
WAIT3:      LD      A,(PPIC)        ; CHECK THE ENCODER
            AND     01H
            JP      NZ,WAIT3
            JP      START2
CCW2B:      DEC     BC              ; COUNTERCLOCK WISE ROTATION
            LD      HL,(POS)        ; LOAD POSITION
            AND     A               ; CLEAR FLAGS
            SBC     HL,BC           ; COMPARE THE POSITIN
            JP      P,POS4A
            LD      A,H
            CPL                     ; COMPLEMENT
            LD      H,A
            LD      A,L
            CPL                     ; COMPLEMENT
            ADD     A,1
            LD      L,A
POS4A:      LD      D,H
            LD      E,L
            LD      L,10H           ; 5.76 DEG. POSITION LIMIT
            LD      H,0             ;
            SBC     HL,DE
            JP      M,SEP4          ; SPEED COMMAND
            LD      A,0D8H
            JR      CONT4
SEP4:       LD      A,0E8H
CONT4:      LD      B,1             ; CCW=1
            LD      (PPIA),A        ; SEND SPEED COMMAND
            LD      A,B
            LD      (PPIB),A        ; SEND DIRECTION
WAIT4:      LD      A,(PPIC)        ; CHECK THE ENCODER
            AND     01H
            JP      NZ,WAIT4
            JP      START2
STRT3A:     LD      DE,(POS)
            LD      HL,03E7H        ; 180 DEG. LIMIT
            AND     A
            SBC     HL,DE
            LD      (POS),HL        ; SHORTEST PATH
START3:     LD      A,(PPIC)        ; CHECK THE ENCODER
            LD      H,A
            AND     01H             ; NO PULSE CHECK AGAIN
            JR      Z,START3
            LD      A,H
            AND     02H             ; CW=0 CCW=1
            JP      Z,CW3
CCW3:       LD      A,1
            LD      (DIRD),A
            JP      CONT3A
CW3:        LD      A,0
            LD      (DIRD),A
```

```
CONT3A:         LD      HL,(POS)        ; GET POSITION
                AND     A
                SBC     HL,BC
                JP      Z,NEGAT3
                JP      P,POSIT3
                JP      M,NEGAT3
POSIT3:         LD      A,(DIR3)
                AND     01H
                JP      NZ,CCW3A        ; CCW=1 CW=0
CW3A:           DEC     BC              ; CLOCK WISE ROTATION
                LD      HL,(POS)        ; LOAD POSITION
                AND     A               ; CLEAR FLAGS
                SBC     HL,BC           ; COMPARE THE POSITIN
                JP      P,POS5A
                LD      A,H
                CPL                     ; COMPLEMENT
                LD      H,A
                LD      A,L
                CPL                     ; COMPLEMENT
                ADD     A,1
                LD      L,A
POS5A:          LD      D,H
                LD      E,L
                LD      L,10H           ; 5.76 DEG. POSITION LIMIT
                LD      H,0             ;
                SBC     HL,DE
                JP      M,SEP5          ; SPEED COMMAND
                LD      A,0D8H
                JR      CONT5
SEP5:           LD      A,0E8H
CONT5:          LD      H,1             ; CCW=1
                LD      (PPIA),A        ; SEND SPEED COMMAND
                LD      A,H
                LD      (PPIB),A        ; SEND DIRECTION
WAIT5:          LD      A,(PPIC)        ; CHECK THE ENCODER
                AND     01H
                JP      NZ,WAIT5
                JP      START3
CCW3A:          INC     BC              ;COUNTERCLOCK WISE ROTATION
                LD      HL,(POS)        ; LOAD POSITION
                AND     A               ; CLEAR FLAGS
                SBC     HL,BC           ; COMPARE THE POSITIN
                JP      P,POS6A
                LD      A,H
                CPL                     ; COMPLEMENT
                LD      H,A
                LD      A,L
                CPL                     ; COMPLEMENT
                ADD     A,1
                LD      L,A
POS6A:          LD      D,H
                LD      E.L
                LD      L,10H           ; 5.76 DEG. POSITION LIMIT
                LD      H,0             ;
                SBC     HL,DE
```

```
         JP     M,SEP6          ; SPEED COMMAND
         LD     A,0D8H
         JR     CONT6
SEP6:    LD     A,0E8H
CONT6:   LD     H,1             ; CCW=1
         LD     (PPIA),A        ; SEND SPEED COMMAND
         LD     A,H
         LD     (PPIB),A        ; SEND DIRECTION
WAIT6:   LD     A,(PPIC)        ; CHECK THE ENCODER
         AND    01H
         JP     NZ,WAIT6
         JP     START3          ; GO CHECK FOR ENCODER
NEGAT3:  LD     A,(DIRD)
         AND    01H
         JP     NZ,CCW3B        ; CCW=1 CW=0
CW3B:    DEC    BC              ; CLOCK WISE ROTATION
         LD     HL,(POS)        ; LOAD POSITION
         AND    A               ; CLEAR FLAGS
         SBC    HL,BC           ; COMPARE THE POSITIN
         JP     P,POS7A
         LD     A,H
         CPL                    ; COMPLEMENT
         LD     H,A
         LD     A,L
         CPL                    ; COMPLEMENT
         ADD    A,1
         LD     L,A
POS7A:   LD     D,H
         LD     E,L
         LD     L,12H           ; 5.76 DEG. POSITION LIMIT
         LD     H,0             ;
         SBC    HL,DE
         JP     M,SEP7          ; SPEED COMMAND
         LD     A,0D8H
         JR     CONT7
SEP7:    LD     A,0E8H
CONT7:   LD     H,0             ; CW=0
         LD     (PPIA),A        ; SEND SPEED COMMAND
         LD     A,H
         LD     (PPIB),A        ; SEND DIRECTION
WAIT7:   LD     A,(PPIC)        ; CHECK THE ENCODER
         AND    01H
         JP     NZ,WAIT7
         JP     START3
CCW3B:   INC    BC              ; COUNTERCLOCK WISE ROTATION
         LD     HL,(POS)        ; LOAD POSITION
         AND    A               ; CLEAR FLAGS
         SBC    HL,BC           ; COMPARE THE POSITIN
         JP     P,POS8A
         LD     A,H
         CPL                    ; COMPLEMENT
         LD     H,A
         LD     A,L
         CPL                    ; COMPLEMENT
         ADD    A,1
```

```
                LD      L,A
POS8A:          LD      D,H
                LD      E,L
                LD      L,120H          ; 5.76 DEG. POSITION LIMIT
                LD      H,0             ;
                SBC     HL,DE
                JP      M,SEP8          ; SPEED COMMAND
                LD      A,0D8H
                JR      CONT8
SEP8:           LD      A,0E8H
CONT8:          LD      H,0             ; CW=0
                LD      (PPIA),A        ; SEND SPEED COMMAND
                LD      A,H
                LD      (PPIB),A        ; SEND DIRECTION
WAIT8:          LD      A,(PPIC)        ; CHECK THE ENCODER
                AND     01H
                JP      NZ,WAIT8
                JP      START3
;
;
;
;
HEAD1:          DB      CR,LF,'* WHICH PROGRAM WOULD YOU LIKE TO USE ?',CR,LF,'$
HEAD2:          DB      CR,LF,'     1- SYSTEM CALIBRATION ',CR,LF,'$'
HEAD3:          DB      CR,LF,'     2- POSITION CONTROL ',CR,LF,'$'
HEAD4:          DB      CR,LF,'  ENTER THE NUMBER AND HIT THE RETURN ',CR,LF,'$'
HEAD5:          DB      CR,LF,'* SYSTEM CALIBRATION PROGRAM *',CR,LF,'$'
HEAD6:          DB      CR,LF,'  - CHECK THE CHECK POINT C ',CR,LF,'$'
HEAD7:          DB      CR,LF,'  - YOU SHOULD SEE -4.96 VOLTS ',CR,LF,'$'
HEAD8:          DB      CR,LF,'  - IF YOU DO NOT, ADJUST WITH 50 K POT ',CR,LF,'
HEAD9:          DB      CR,LF,'  - IF YOU ARE DONE HIT THE RETURN ',CR,LF,'$'
HEAD10:         DB      CR,LF,'* POSITION CONTROL PROGRAM *',CR,LF,'$'
HEAD11:         DB      CR,LF,'  - ENTER THE POSITION IN COUNTS ',CR,LF,'$'
HEAD12:         DB      CR,LF,'  - MAXIMUM 999 COUNTS ( 359.4 DEGREES)',CR,LF,'$
HEAD13:         DB      CR,LF,'  - ENTER IN THREE DIGITS (012) ',CR,LF,'$'
HEAD14:         DB      CR,LF,'  - HIT THE RETURN ',CR,LF,'$'
SPACE:          DB      CR,LF,'.',CR,LF,'$'
QUE1:           DB      CR,LF,'ENTER THE POSITION IN COUNTS(292)',CR,LF,'$'
QUE2A:          DB      CR,LF,'ENTER THE DIRECTION',CR,LF,'$'
QUE2B:          DB      CR,LF,'CW = 0  CCW = 1 ',CR,LF,'$'
SONM:           DB      CR,LF,'MOTOR AT THE GIVEN POSITION',CR,LF,'$'
ERROR:          DB      CR,LF,'ERROR !!! TRY AGAIN',CR,LF,'$'
COUN:           DB      CR,LF,'+++ POSITION +++',CR,LF,'$'
R1:             DB      CR,LF,'READY TO SEND COUNT',CR,LF,'$'
R2:             DB      CR,LF,'COUNT HAS SENT',CR,LF,'$'
;
;
;
;
;
;
;
;
;
```

```
;
;       S U B R O U T I N E S
;
;
;
GETCHAR:        LD      A,(ESTAT)       ;GET EPCI STATUS
                AND     2               ;IS A CHARACTER ENTERED ?
                JR      Z,GETCHAR       ;NO, CHECK AGAIN
                LD      A,(EDATA)       ;YES, GET CHARACTER
                LD      (CHAR),A        ;STORE IN A
                RET
;
;
;
;
ECHO:           LD      A,(ESTAT)       ;GET EPCI STATUS
                AND     1               ;IS EPCI READY ?
                JR      Z,ECHO          ;NO, CHECK AGAIN
                LD      A,(IX)          ;LOAD MESSAGE
                CP      '$'             ;CHECK THE LAST CHARACTER
                JR      Z,FIN           ;LAST CHARACTER
                LD      (EDATA),A       ;SEND CHARACTER
                INC     IX              ;NEXT CHARACTER
                JR      ECHO            ;XMIT NEXT CHARACTER
FIN:            RET
;
;
;
;
RECALL:         LD      A,(ESTAT)       ;GET EPCI STATUS
                AND     1               ;IS EPCI READY ?
                JR      Z,RECALL        ;NO, CHECK AGAIN
                LD      A,(IX)          ;LOAD CHARACTER
                LD      (EDATA),A       ;SEND CHARACTER
                RET
;
;
;
;
CPY88:          LD      BC,(MPRAD)
                LD      B,8
                LD      DE,(MPDAD)
                LD      D,0
                LD      HL,0
MULT:           SRL     C
                JR      NC,NOADD
                ADD     HL,DE
NOADD:          SLA     E
                RL      D
                DEC     B
                JP      NZ,MULT
                LD      (RESAD),HL
                RET
                DS      22
                END
```

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