Computer Interfaces and Operating Instructions for a Prototype Cartesian Robot

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1.0 Introduction

This manual analyses a prototype Cartesian Robot donated to the Laboratory for Perceptual Robotics (LPR) of the Computer and Information Science Department at the University of Massachusetts at Amherst. The machine was donated to this laboratory by the Flexible Automation Systems Program of the General Electric Company of Schenectady, New York. The manual describes the machine, the alterations made to it by the group, and its operation, and it directs the reader to research projects using this machine. It also refers the reader to related technical reports and to manuals which describe various system components in greater detail. Additional components for the system such as its sensors and the computer system are also discussed. Finally, several controlling routines are described which are written in FORTH.

2.0 General Description

The cartesian-coordinate machine is a robotic manipulator which consists of three sliding (or prismatic) joint axes and a revolute joint axis. These are labeled x, y, z, and θ respectively. Referring to Figure 2.1, the x and y axes are the horizontal axes, the z axis is the vertical axis, and the θ axis is a rotational axis positioned at the lower end of the z axis where the gripper itself is mounted.

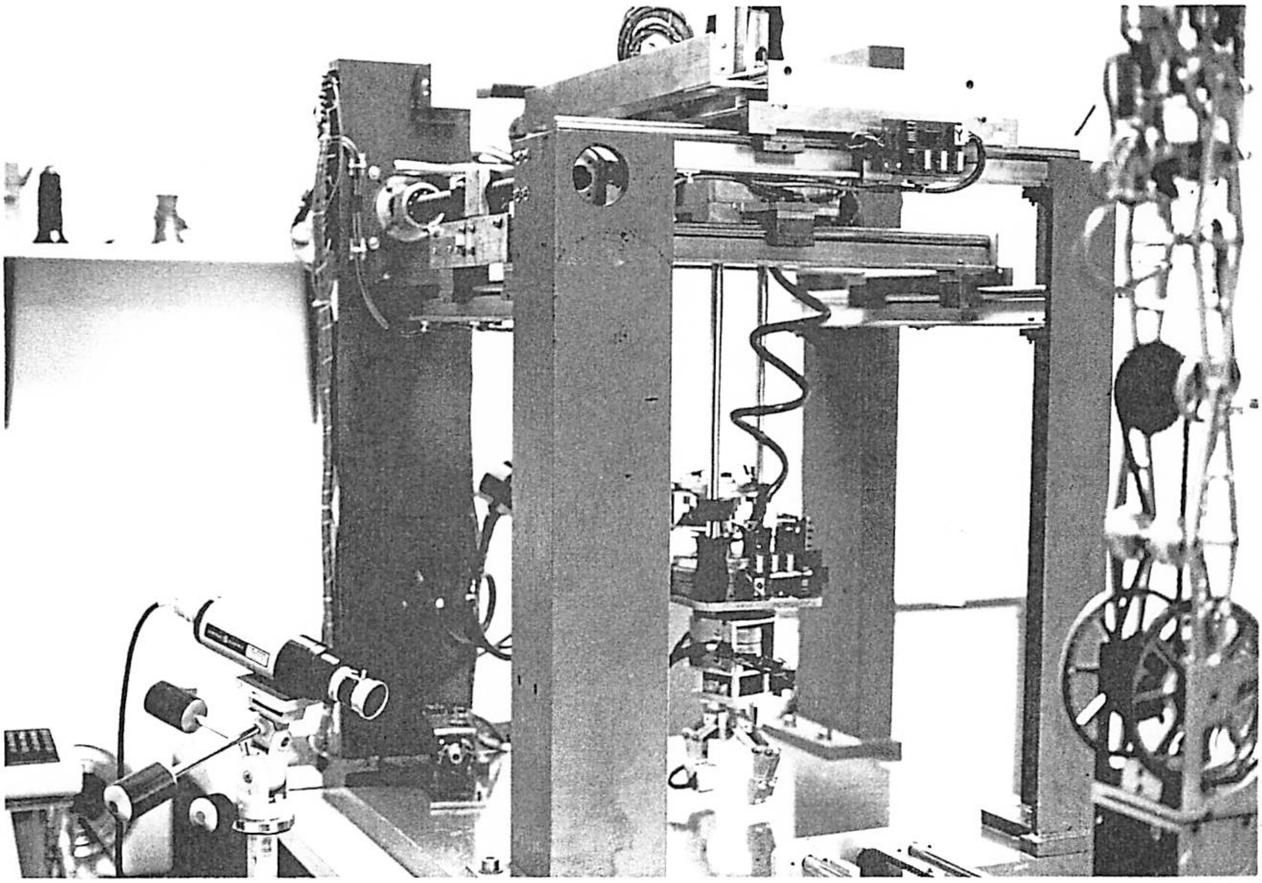

Figure 2.1 The Prototype Cartesian Assembler
At left is the GE CID camera used for visual input. At right is a small revolute joint arm, the Rhino XR-1.

Each axis is driven or actuated by a DC servomotor. The motors for the x and y axes are mounted on the frame of the machine and the motors for the z and θ axes are mounted on the z axis.

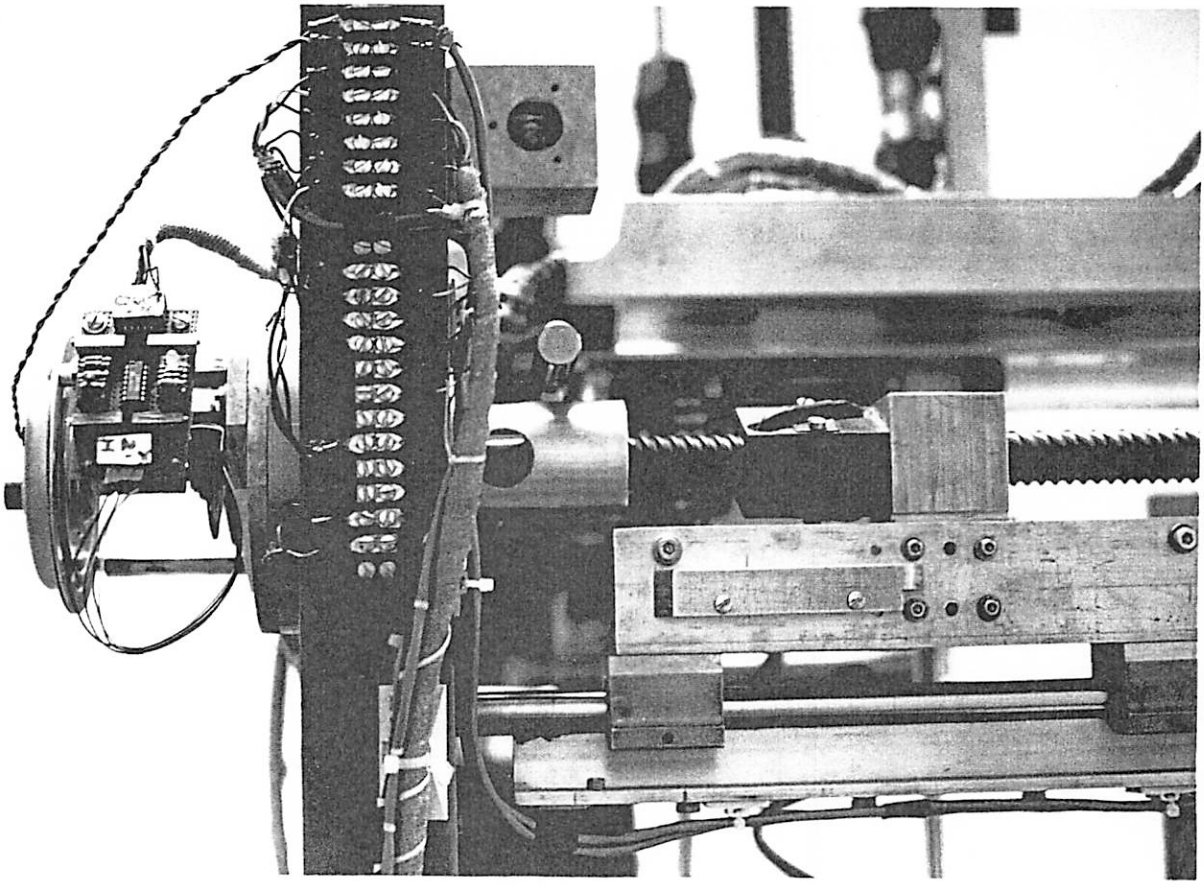

Figure 2.2 Motor and Ball Screw Assembly for x axis.
Also pictured (at left) is the x comparator board mounted at the motor sight (see section 3.A.4) and the barrier strips X1 and X2 (Section 3.A.8).

The motor shaft for each of the linear axes is directly coupled to a threaded shaft or ball screw. (Figure 2.2 depicts this relationship for the x axis). Upon the ball screw lies a large ball nut with threads inside to match those on the screw. Ball bearings are situated between these threads to minimize friction. The ball nut moves (linearly) along the ball screw thus producing the x, y, or z motion (back and forth for x and y and up and down for z). The ball screws for the x and y axes are located on two sides of the frame. The carriage which is the support for the z axis is built upon the ball nuts which move along the x and y axes. The ball screw and (thus the motor) for the z axis is mounted on a fixture which lies at the cross section of the carriages moved by the x and y motors. The motors are described in detail in section 3.A.2.

The z axis is used for vertical motion of the gripper or end effector while the x and y axes produce horizontal end effector movement. The θ axis is rotation about the z axis. Therefore at the end of the z axis the θ axis motor is found. The shaft of this motor allows for 360 degree rotation of a gripper, hand, or mounted tool.

The tachometers and the encoders are mounted on the motors themselves. The tachometer is a generator driven by the rotating motor shaft and produces a voltage proportional to the angular velocity of the motor shaft. This signal is used for velocity feedback. An encoder can be defined as a type of transducer which converts linear or angular position into machine usable data. The encoder signals, used for positional feedback, are described in section 3.A.3.

Figure 2.3, a block diagram of the complete system, should be referred to frequently throughout this manual for a clearer understanding of the relationship between the various components. In addition to the robot itself, another large component is the servoamplifier/power cabinet. The front of the cabinet is shown in Figure 2.4. This cabinet serves two purposes. The first is to house the power transformer and voltage regulators. Voltage sources of 120 volts AC, 208 volts AC, 15 volts DC, and 5 volts DC are needed by various components of the manipulator system. The second half of the cabinet is used for the servoamplifiers (pictured in Figure 2.4). A power amplifier in general provides power to some electrical component. In the case of this system, the amplifiers are servoamplifiers. This means that besides supplying power to the servo motors, they also receive feedback, in this instance velocity feedback. The feedback is used to determine the power that should be delivered to the motors. The servoamplifiers are described in section 3.B. The use of feedback and the description of the servoloops of the system in general are described in section 4.

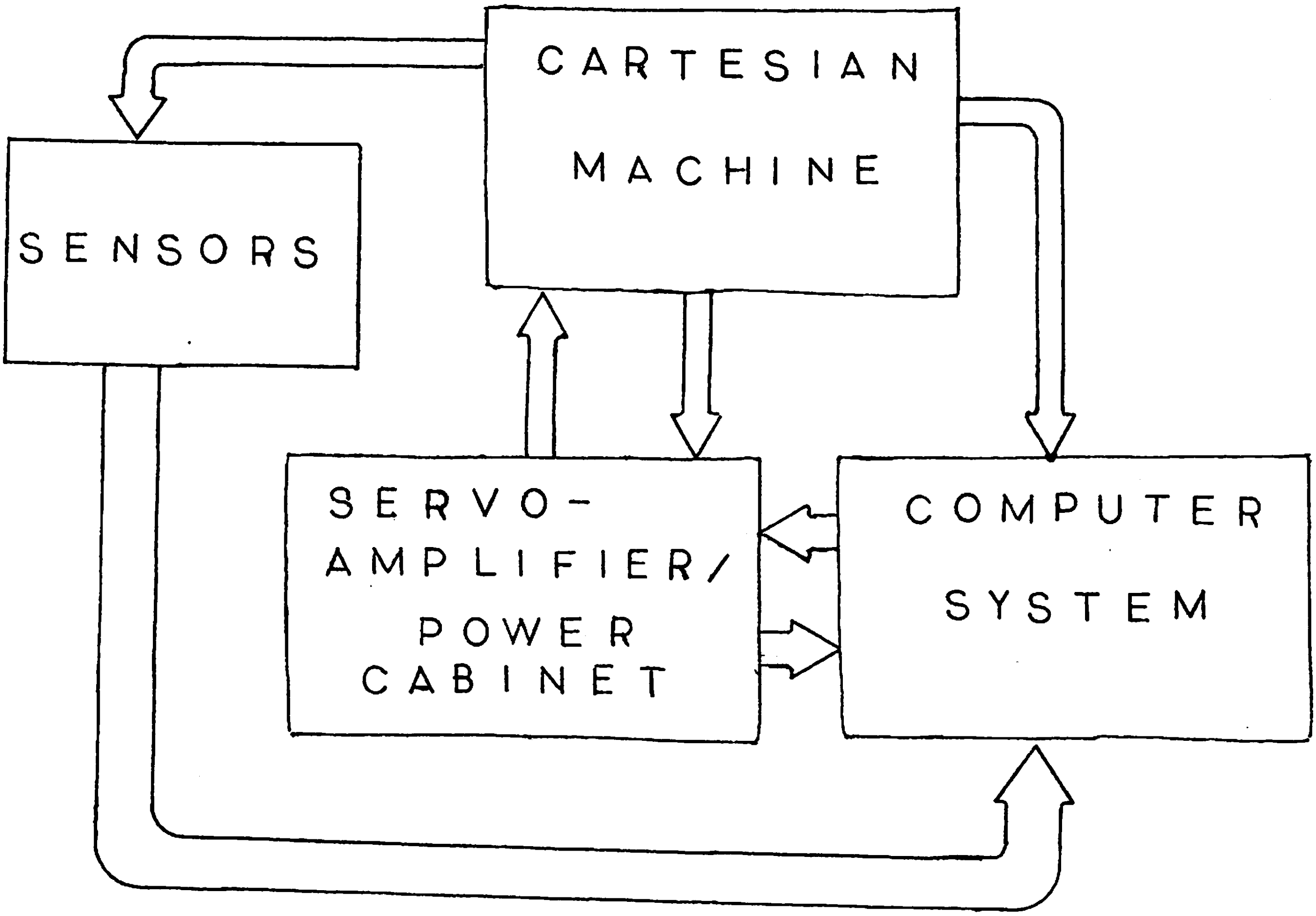

Figure 2.3a The Four Major Cartesian Machine System Components

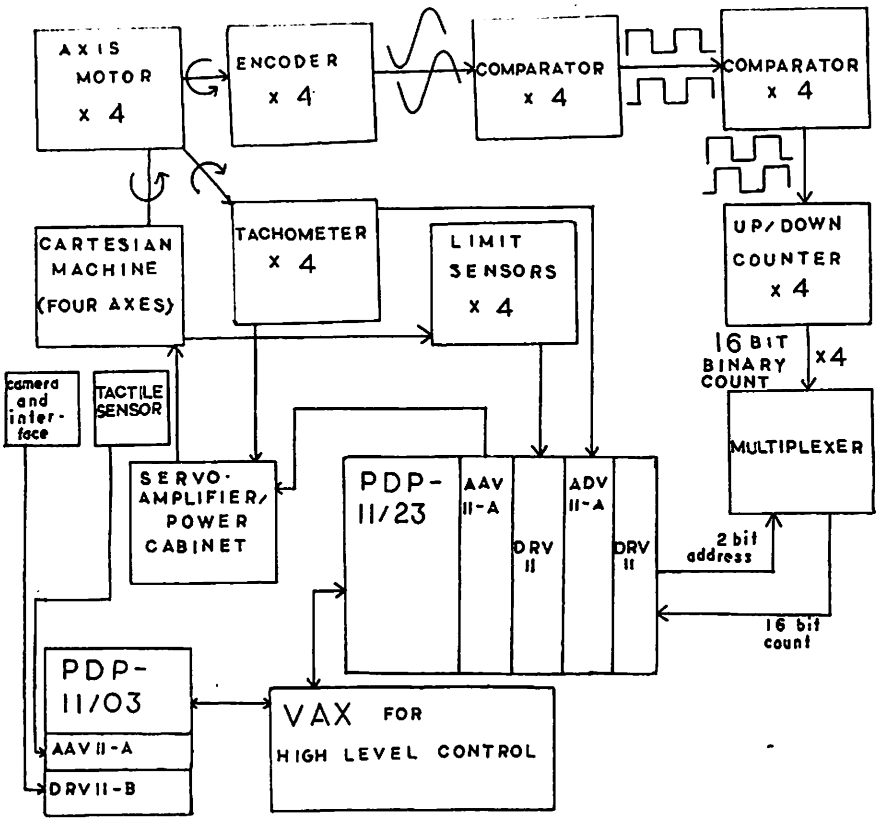

Figure 2.3b Detailed Diagram of Current Cartesian Machine System.
The "CART" has 4 axis motors, 4 encoders, 4 tachometers, etc. Motor rotation is transduced by the encoders which produce waveforms made TTL compatible by voltage comparator circuits. The edges of these waves are counted by the 16-bit counters. The 4 16-bit counts are multiplexed and accessible one at a time via a DRV11 interface by a DEC PDP-11/23 for position feedback. Note that the multiplexer system is soon to be replaced with four single axis controllers which will communicate with the PDP-11/23 and with each other.

Motor angular velocity information is produced by tachometers and used by the PDP-11/23 servoroutines and the servoamplifiers. The servoamplifiers receive desired velocities for the 4 axes from these servoroutines and provide the motor control signals. A GE CID camera and the Overton tactile array sensor provide sensory information to the PDP-11/03.

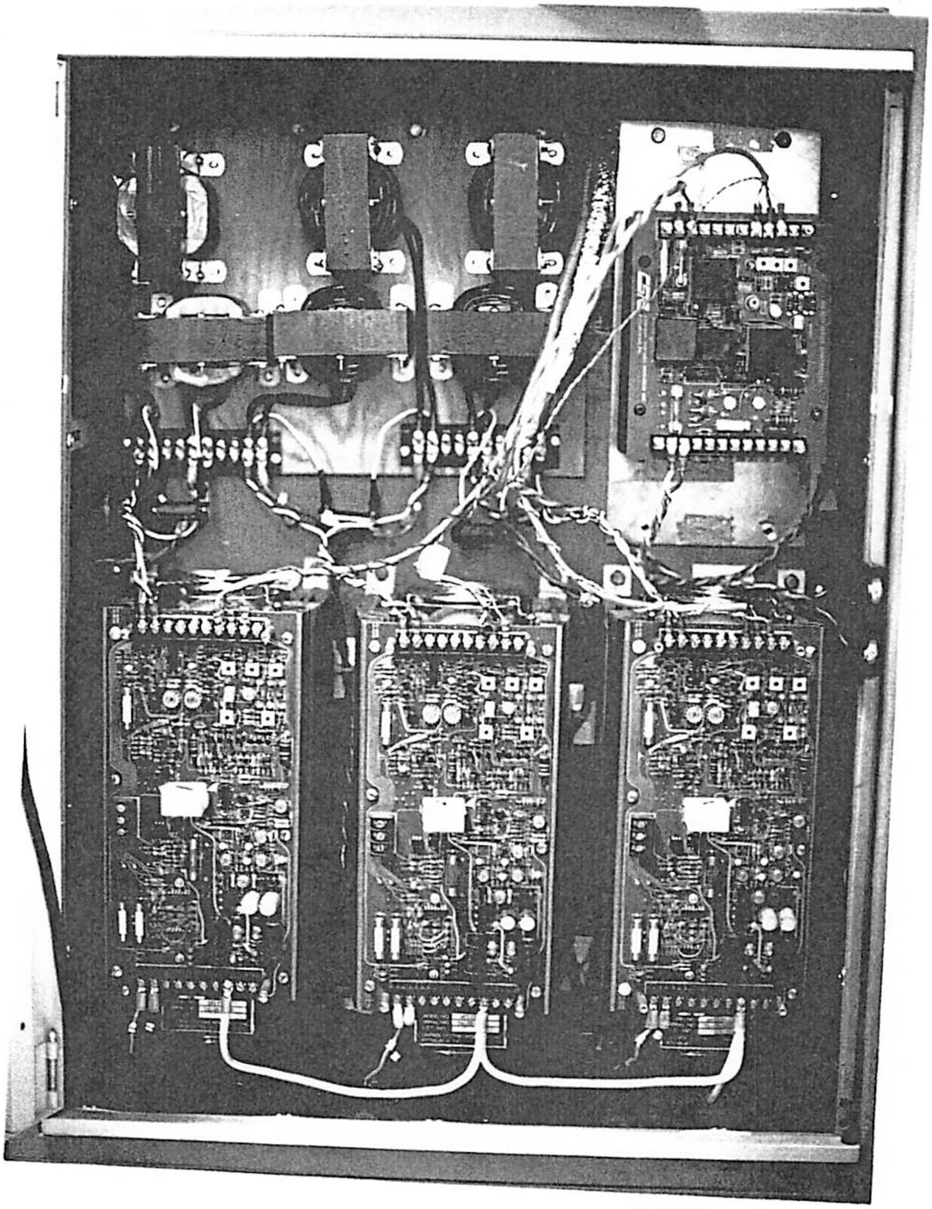

Figure 2.4 Front of the Servoamplifier/Power Cabinet showing the x, y, z, and theta servoamplifiers.

3.1 Detailed Description

3.A.1 Motors/Encoders/Tachometers

Figure 3.1 shows the positional relationships between the motors, the encoders, and the tachometers. The encoder is mounted around the base of the motor shaft and appears as a black disk in the figure. The tachometer is mounted at the end of the motor shaft and is supported by the two thin metal cylinders also appearing in the figure, which should be referred to throughout the next three subsections to aid in a visual understanding of these components.

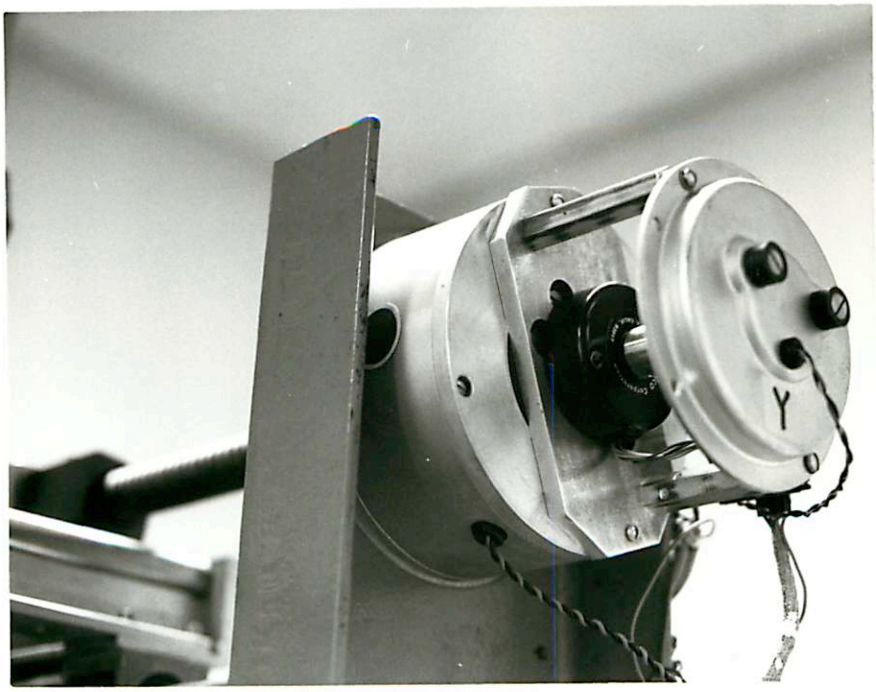

Figure 3.1 A Typical Motor, Encoder, and Tachometer Assembly

Note that the motor is mounted on the frame of the machine and the ball screw (coupled to the motor) can be seen to the left on the other side of the frame.

3.A.2 DC Servo Motors and Tachometers

THE MOTOR

To drive the axes, the machine has four DC servo motors. These motors are made by PMI Motors and are the SERVODISC (TM) MOTORS: U-SERIES (specifically PMI U12M4H). The Motor Specifications are given in Appendix A2.

The direct-current motor consists of a stationary part called the field magnet and a rotating part called the armature. The operation of the DC motor is based on the behavior of a current-carrying wire when subjected to a magnetic field. As explained in [19], pages 535-536, a straight wire experiences a force $F=I*l*B*\text{sine}(\phi)$ where l is the length of the wire, I is the current in the wire, and ϕ is the angle between the wire and the magnetic field B. The direction of the force on an element of a conductor dl is given by the cross product $dF=I*dl \; x \; B$. The vector relationship for a straight current-carrying wire is shown in Figure 3.2.

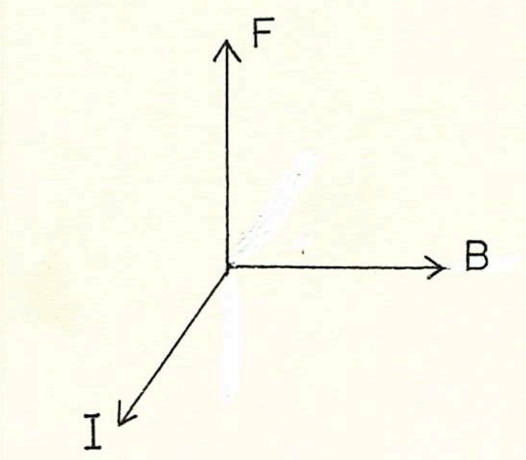

Figure 3.2 Vector Relationship of Force, Current, and Magnetic Field (According to the left hand rule).

The armature of a DC armature motor, the type used in this machine, is a disk with current-carrying windings placed on it in such a way that when subjected to a magnetic field it rotates as a result of the induced force discussed above. This rotation produces rotation of the motor shaft and consequently the desired torque. The output torque of the motor is proportional to the current passed through the windings, the input armature current IA, and the direction of rotation is determined by the polarity of the input armature voltage.

The magnetic field of the motor can be produced via a current-carrying wire which is wound circularly. The current through the wire (called the field current) will induce a magnetic field, and the lines of induction of the field are determined by the shape of the conductor. See [19], chapter 32 for a thorough discussion of this relationship and [4,23] for its application to the magnetic field of a direct-current motor. Field-controlled motors are controlled by varying the magnetic field via the field current. The magnetic field may also be produced by a permanent magnet as it is in the PMI motors and most armature-controlled motors.

A simplified diagram of a DC armature-controlled motor is given in Figure 3.3 and the equivalent circuit in 3.4. Many texts refer to the air gap flux. The magnetic field is often referred to as the flux density and it is the magnetic flux which is used in the calculations below.

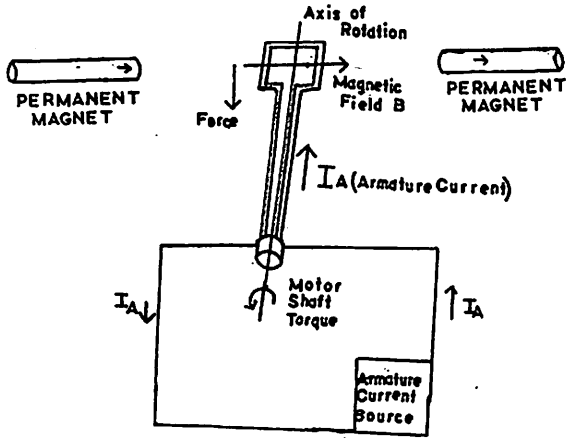

Figure 3.3 Simplified Diagram of DC Armature-Controlled Motor.
As depicted in Zelnes [23]. See this text for a thorough description of DC servomotors.

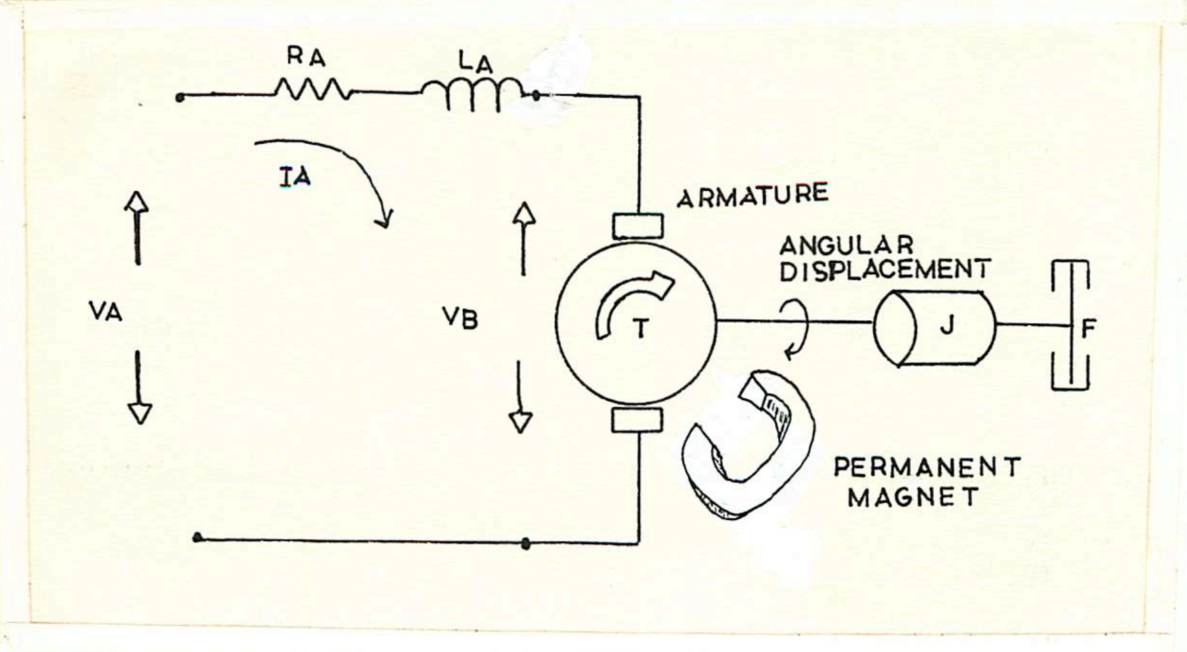

Figure 3.4 Circuit of DC Armature-Controlled Motor.
As depicted in Ogata [13].

The output of the motor is a torque (T) which is directly proportional to the armature current (I_A) so that $T=KT*I_A$ where K_T is the torque-constant of the motor with units lb-ft/amp (or in the case of the PMI motors, oz-in/amp) giving the expected torque units lb-ft. (Note that in the mks system where the unit of force is the newton and the unit of length is the meter, the unit of torque is the newton-meter). The proportionality constant K_T is itself proportional to the (constant) air gap flux. again to Figure 3.3.

The rotating armature induces a voltage (V_B) which is directly proportional to the angular velocity (A_V), in other words the armature speed, and the flux. This voltage is called the electromotive force (emf) and is the work of the magnetic field. Since the flux is constant, the voltage is $V_B=K_E*A_V$ where the constant of proportionality K_E is called the back EMF constant of the motor with units volts/KRPM (KRPM is 1000 rotations per minute). V_B is often called a counter voltage in that it is opposite in polarity to the applied armature voltage. Fortunately this voltage is small enough that a net armature voltage is still produced which is large enough to create a torque.

The applied armature current I_A controls the actual speed of the motor. The current IA is supplied by the servoamplifier which determines the necessary current from the desired velocity of the motor (supplied by the digital-to-analog device located on the AAV11-A interface of the PDP-11/23) and the actual velocity of the motor (received from the tachometer). The servoamplifier is described in section 3.B.

Referring again to Figure 3.4, a differential relationship (due to Kirchoff's Voltage Law) can be derived from the armature circuit:

$$L_A * dI_A/dt + R_A * I_A + V_B = V_A$$

where R_A is the armature resistance and L_A is the armature inductance. This relationship supports the discussion of the electromotive force and its opposition to the armature voltage above. Also, the application of the torque to the inertia and friction results in the differential relationship:

$$J * A_A + F * A_V = T = K_T * I_A$$

where J is the armature inertia, F is its friction and A_A is the angular acceleration of the armature (in other words the first derivative with respect to time of the angular velocity).

THE TACHOMETER

The tachometer (or tachogenerator as it is sometimes called) is a generator which is used as a transducer to convert the motor shaft velocity into a proportional DC voltage. In a similar manner to the DC motor, the DC tachometer employs a permanent magnetic field to induce a voltage which is proportional to the angular velocity of the motor shaft. An armature (within the tachometer housing) is "fitted" about the rotating shaft and is subjected to a fixed magnetic field. Note that this voltage is induced in the same way that the voltage VB was induced in the motor although, since in general the magnetic field or air gap flux will be different, these two voltages are not the same. The tachometer output is approximately 1.03 volts per KRPM (1000 Revolutions per Minute) of the motor shaft and is direction sensitive. Therefore a negative voltage indicates motor shaft rotation in one direction and a positive voltage implies rotation in the other direction.

The output voltage of the tachometer is used for velocity feedback both by the servoamplifier in determining the voltage to apply to the motor armature and by the servoroutines which drive the machine. The tachometers are also made by PMI (and are of type 9FBT).

3.A.3 The Encoder

For position feedback, the system uses optical incremental encoders donated by the Digital Equipment Corporation. An encoder can be defined as a type of transducer which converts linear or angular position into machine usable form. In this case, the encoder converts the angular position of the motor shaft into a square wave with a particular number of cycles per revolution of the shaft depending on the number of slots in the encoder disk described below. The square wave is produced as follows.

The encoder is mounted on the motor shaft as was shown in Figure 3.1 and consists of an encoder block (a phototransistor assembly and a lamp) and the encoder disk. This disk is imprinted with 99 narrow slots which allow light to pass through as the disk rotates with the angular velocity of the shaft. (The number of slots on the disk is somewhat arbitrary and can vary widely from encoder to encoder). The light (produced from the lamp) which passes through each slot is detected by a phototransistor assembly which lies below the rotating disk (whence the term optical encoder). This assembly consists of a pair of phototransistors the output of which is a set of two out of phase square waves. The phase difference is caused by the positioning of the transistors.

The use of a pair of phototransistors allows the derivation of direction information when the appropriate digital circuitry is implemented. A description of the use of this positioning and the digital logic of the circuitry is given in section 3.A.5.

The DEC encoders have four wired connections each. These are +5 volts (red), ground (black), and the two square waves (blue and white).

3.A.4 Voltage Comparator Circuits

The outputs of the encoder must be TTL compatible waves. (The edges of the square waves will be counted in order to assign a numerical value to the linear or angular postion of each axis). A voltage comparator circuit is used to produce this compatibility. Four of the basic components of the circuits, the operational amplifiers, are embodied in National Semiconductor's Voltage Comparator chip, the LM339.

Mounted at each motor location is a comparator board. The x axis board can be seen in Figure 2.2. Through these boards pass the two encoder output waves. To eliminate any noise problems and to ensure a crisp square wave, the two positional output waves of the comparators at the motor location are passed again through another comparator circuit. This second set of circuits is located on the counter board described in section 3.A.5 and are pictured in Figure 3.10.

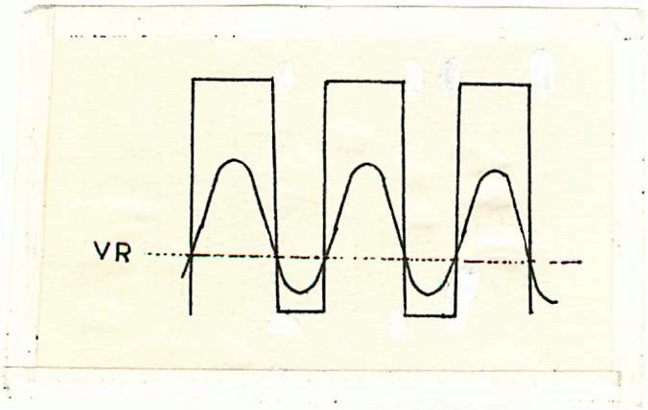

Figure 3.5 Action of Comparator.

The action of the comparator is fairly simple. Referring to Figure 3.5, the comparator outputs a low voltage level until the input voltage (for the first set of comparators the input voltage is the amplitude of the square wave output of the encoder) reaches a preset reference voltage (VR). At this point, when the comparator compares the reference voltage with the input voltage, the comparator output goes high until the input voltage is again lower than the reference voltage. (The comparisons are done by the operational amplifier. Refer to [10] for a description of operational amplifiers and their use in comparator circuits). The output of the comparator is therefore a square wave, adjusted (by use of the potentiometer in the circuit) to have an approximately 50% duty cycle. Appendix 5.A2 gives a detailed description of the derivation of the resistor values and the value of the reference voltage, and the actual layout of the position comparator boards.

3.A.5 Position Counter

Once the two encoder waves have passed through the two comparator circuits, they are sent through a binary up/down counter circuit (there is one counter circuit for each axis). The purpose of this circuit is to obtain a numerical value from the square waves which may be used for positional information by the servoroutines that control the movement of the manipulator. The counter counts each edge of each square wave so that since there are 99 cycles of the square wave for each rotation of the motor shaft, and the two square waves are out of phase, the counter will produce a decimal count of 396 for each rotation of the motor shaft. (Note: the 99 cycles of the square wave correspond to the 99 slots in the encoder disk).

The output of each counter circuit is a sixteen bit binary count. The counter is directional in the sense that the count increases for one direction of travel and decreases for the other. As was mentioned in the last section, the use of two waves (two phototransistors) facilitates this directionality. Consider Figure 3.6 which depicts a cross section of an encoder disk with the black squares representing the sections of the disk between the slots and the white squares representing the slots. Two slots are labelled 1 and 2. An LED (the lamp) is positioned above the disk so that the light passes through the slots where phototransistors A and B, which are positioned underneath it, detect it. Suppose the disk is rotating in direction 1. Then phototransistor A will be the first to detect the coming rising edge (of slot 1) and so the output wave of A will be ahead of phase of the output wave of B. Conversely, if the disk is rotating in direction 2, B will be the first to detect the rising edge (of slot 2) so that the output wave of B will be ahead of phase of the A wave.

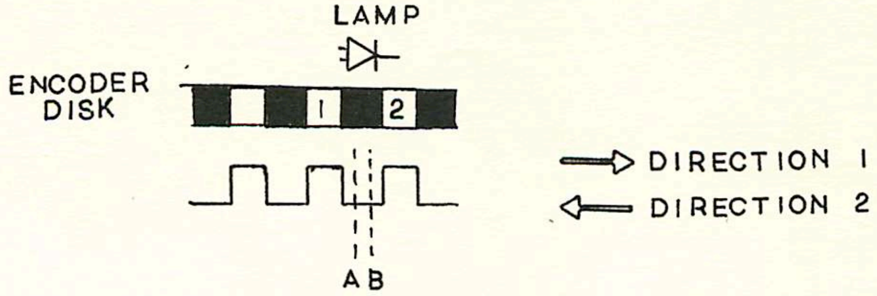

Figure 3.6 Cross Section of Encoder Disk
Phototransistors A and B lie "below" the disk and the lamp (LED) lies above the disk. Detection of slots 1 and 2 is discussed in the text.

The counter then consists of two parts. The first part is the circuit which contains the logic that determines the direction of travel of the encoder disk given the phase difference between the two waves, and the second is the actual counter circuit itself. The direction circuitry is described in Appendix 5.A3 along with the counter circuit. Figure 3.7 is a diagram of the counter circuit board which contains, as may be recalled from the last section, the second set of comparator circuits which prepare the positional waves for counting. A more detailed diagram is given in Appendix A3.

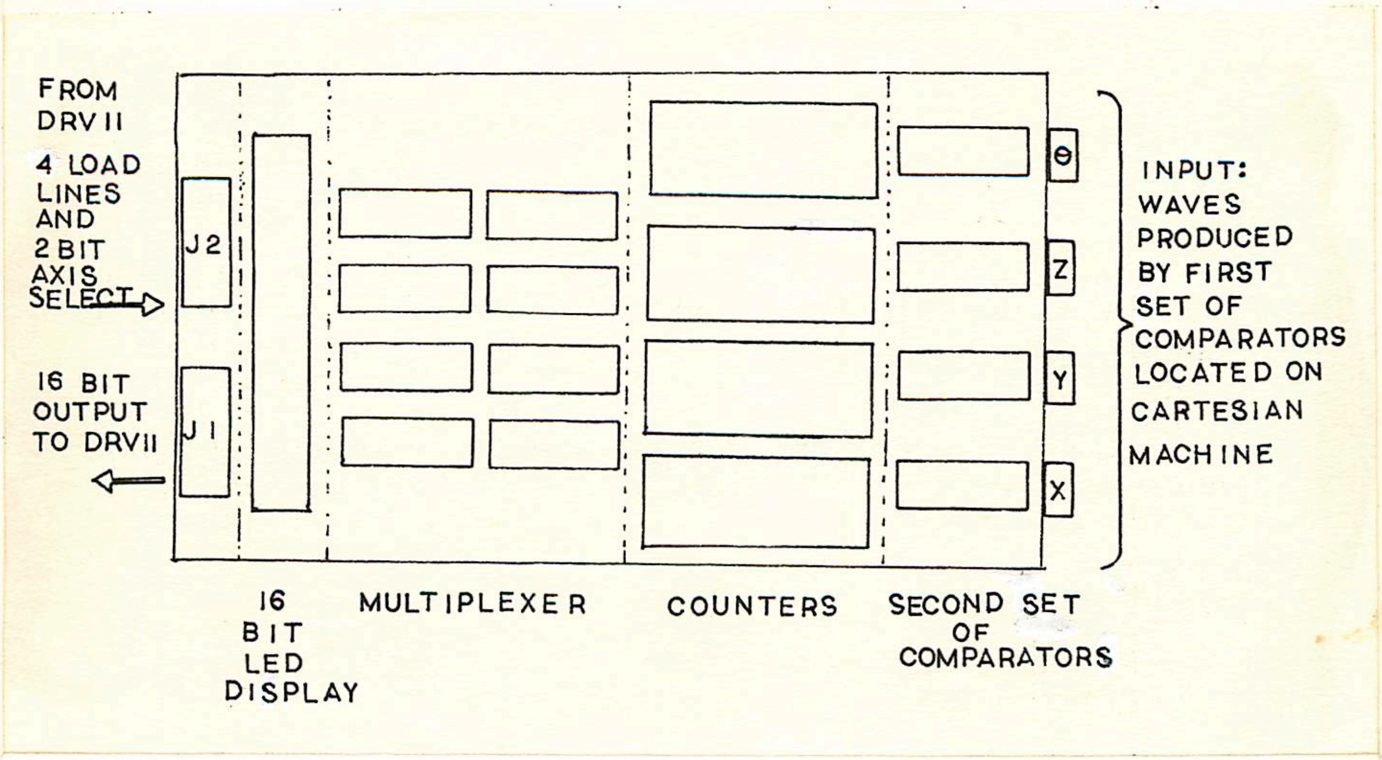

Figure 3.7 Layout of Four Axis Counter Board.

The sixteen bit count from each axis is presently sent to the DRV11 interface of the PDP-11/23 for servo routine processing after it is sent through the multiplexer circuit as described in the next section.

3.A.6 Multiplexer --- Single Axis Controller

A temporary system component is the board of eight dual 4-line-to-1-line multiplexers or data selectors. The IC chip used on this board is the 74LS153. The multiplexer board allows the selection via a two bit binary address of one of the four axis counter outputs to be used as input to the sixteen input lines on the DRV11 designated for this counter input. Without this multiplexer circuit, four sets of sixteen separate lines would be needed to allow access to the four counters by the PDP-11/23. Therefore instead of using sixty-four lines, eighteen are used - sixteen for the actual count from the current axis the machine is controlling, and two for the binary address.

In the servo routines, each axis is assigned a binary number (00,01, 10, and 11 for x,y,z and θ respectively). When position feedback is desired, the routine will output the correct address on the designated output lines on the DRV11 as shown in Figure 3.7. These lines are connected to the address selection pins on the multiplexer chips. Thus the data selection action of the chips will provide the correct corresponding count to the routines. See Appendix A4 for the circuit and LS153 IC descriptions.

The perceptive reader may have wondered if this is the most efficient configuration. Only one processor is devoted to the control of four axes. This may pose a problem when the manipulator axes are moving at high speeds since time sharing limits response time for each axis. It also complicates the design of the routines which would plan the smooth transistion of the manipulator from one point to another. Suppose for example that the manipulator is to move in a diagonal horizontal line. This entails the use of both the x and the y axes. If the machine is to move diagonally rather than first moving as far in, say, the x direction as it must go and then as far in the y direction as it must go, the servo routines become complicated to compensate for the switching back and forth of the processor from one axis to another. It is also desired that the axes arrive at the goal point at the same time. Imagine the problems that arise when the machine is expected to perform an action that involves all four axes! At present these problems must be dealt with in the manner addressed in sections 4.B and 4.C. However in the near future, the single PDP-11/23 processor and the multiplexer circuit will be replaced with single axis controllers. One of these microprocessor controllers will be devoted to each axis, and servo routines will be implemented and tailored for each individual axis. The scenario is that each axis will have a self-contained servo unit composed of the position feedback circuits, the limit sensors (Section 3.A.7), and the processor.

3.A.7 Limit Sensing

This subsystem on the COINS LPR cartesian manipulator provides digital signals indicating the state of each axis. For each axis the information consists of whether or not the axis is within its working range and if not, which extreme has been reached. In the case of the θ axis, the joint is always in range and the information provided concerns the "home" position and the direction from which home was approached.

The output from this system is provided on two connectors: one is wired to accept a 40-conductor ribbon cable attached to a DRV11 input connector while the second is available for other uses. The second connector is intended to provide a current shut-down system with limit information. All outputs are driven by line drivers and thus are capable of driving several loads.

This section documents the hardware comprising this subsystem. The following paragraphs cover the specific definitions of the signals from each axis and the hardware and electronics involved.

Signal Definitions

The x and y axes are identical in regard to the number and definitions of the signals provided by the system. Each axis has three signals derived directly from the Sensing Board and a fourth which is a logical combination of the first and third channels. All signals are TTL level voltages and are capable of driving the normal number of loads, usually about 5. The exclusive-OR combination of signals 1 and 3 indicates whether or not the axis is within its range, the signal high (logic level 1) indicates that the axis is within its range. Signal 2 is used to indicate which end of the travel has been reached. When the axis is viewed from the limit scale side, the right end of the travel is indicated by signal 2 low (logic 0) while the left end is indicated by signal 2 high (1).

The z axis also has four channels with three derived directly from the sensing board. As with the x and y axes, the fourth channel indicates whether or not the axis is within its limits. Since the limit scale for the z axis differs from those for the x and y axes, the derivation of the fourth signal also differs. In this case, the inverse of the channel 2 signal is combined with the channel three signal via an exclusive-OR gate to produce the fourth signal. As before, channel 4 high indicates that the axis is within its range. Channel 1 is used to indicate which end of the travel has been reached. When the z axis is all of the way UP, the channel 1 signal is low (logic level 0).

The θ rotation axis uses only two channels. Its rotational nature theoretically allows infinite movement and therefore limit checking is unnecessary. In practice, the number of rotations made from some starting point must be tracked in order to prevent the cables running to the gripper from wrapping around the wrist and breaking. The limit/home system provides a signal which is to be used as a home indicator and another which indicates the direction from which the home position was approached. Channel 1 indicates that the home marker has been encountered. If channel 2 is high (1), then the wrist was rotating clockwise when viewed from above when the home marker was encountered. Two other signals are brought back from the axis and are always high. These can be used to verify that the electronic systems on the robot are powered.

Table 1 contains the logical values seen on each of the channels at the extremes of the axes. Figure 3.8 contains the designs of the limit scales and the logical values of the channels relative to the scales. This figure should be used to determine the state of any of the channels when they are to be used outside of this system.

Table 1
Logical Values on each of the Channels at Axes Extremes

	Left Extreme (x,y)	Right Extreme (x,y)
Channel 1	1	0
Channel 2	1	0
Channel 3	1	1
Channel 4	0	1

	Top Extreme (z)	Bottom Extreme (z)
Channel 1	0	1
Channel 2	0	1
Channel 3	1	0
Channel 4	0	0

	Rotational Extremes (θ)	
	Clockwise	Counterclockwise
Channel 1	0	1
Channel 2	1	0

System Hardware

This section discusses the hardware making up the limit-sensing system. Figure 3.8 is a block diagram of the components of the system. There are seven discrete components in the system. The first six are duplicated for each axis and consist of the following: limit scale, sensing board, interconnect cable 1, axis comparator board, interconnect cables 2a and 2b, and the master interface board. The following subsections discuss each of these parts in detail.

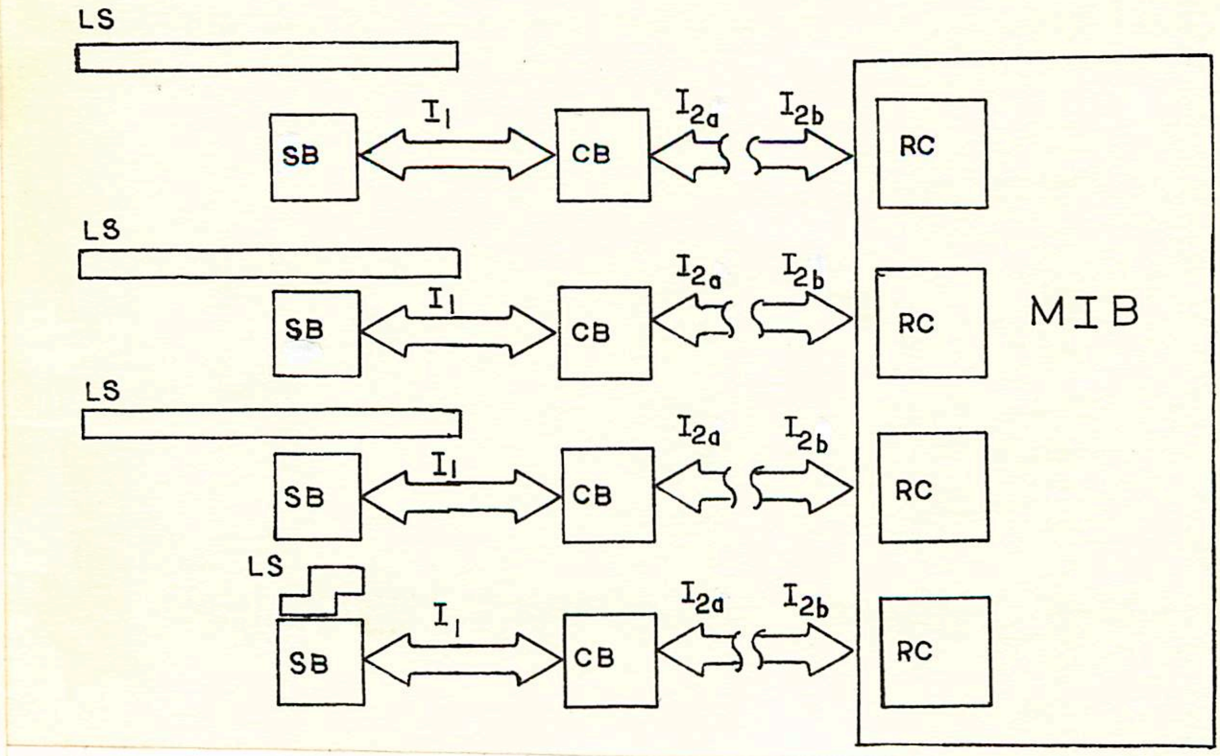

Figure 3.8 Limit Sensing Outline

LS: Limit Scale
SB: Anorad Sensing Board...infrared LED's TIL24
phototransistors TIL604
CB: Comparator Board
MIB: Main Interface Board
I1: Interconnect1.....Connection between SB and CB
I2: Interconnect2..a) Connection between CB and Robot Wiring
b) Connection between Robot Wiring and MIB

Limit Scales

The limit scales are the aluminum vanes which pass through the sensing boards and turn the sensing transistors on and off. The limit scales are always attached to the moving part of the axis which they are tracking. The corresponding sensing board is then attached to the previous axis (the base for the x axis) so that movement of the axis causes relative movement between the scale and sensing board. Each scale has a separate track along which each of the sensing transistors passes. The tracks are cut in such a way as to provide the appropriate turn-on and turn-off points for the sensing transistors. Figure 3.9 illustrates the patterns for the limit scales for the four axes of the cartesian manipulator and the on/off transitions of the associated sensing transistors.

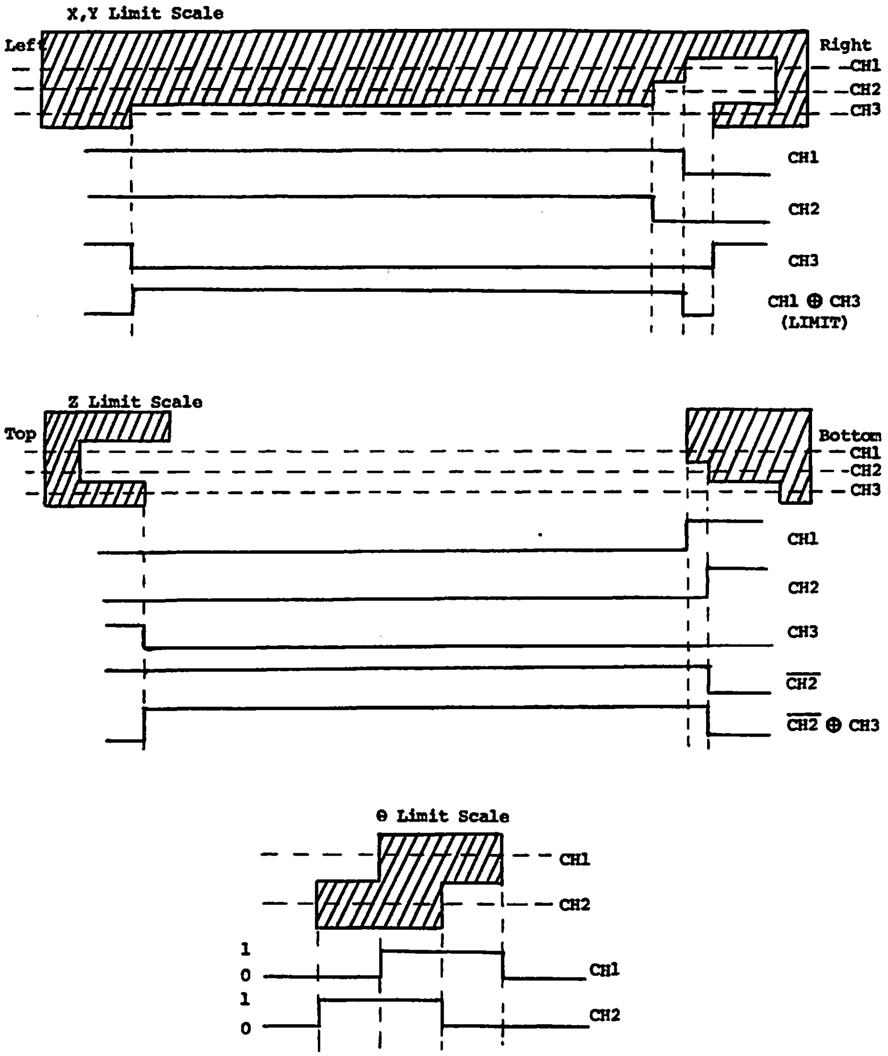

Figure 3.9 Limit/Home Sensing System
Limit Scale and Channel Output Definitions

Sensing Boards

The sensing boards used on the x,y, and z axes were provided on the original machine and were built by Anorad Corporation of Long Island, New York. Each device consists of two small, roughly 1"x1", square printed circuit board held apart by an aluminum spacer. The top board contains three phototransistors and a 10-pin connector. The bottom board contains three infrared light-emitting diodes (LED), one opposing each phototransistor. Figure 3.10 contains the schematic of the sensing boards. The LED's are always powered and, therefore, are producing beams of light which fall on the transistors. When light is falling on a transistor, it is turned on and thus its collector (its output pin) is low. When the beam is interrupted, e.g. by the limit scale, the transistor turns off and its collector floats to the power supply voltage.

The θ axis uses only two channels and requires only two LED/phototransistor pairs.

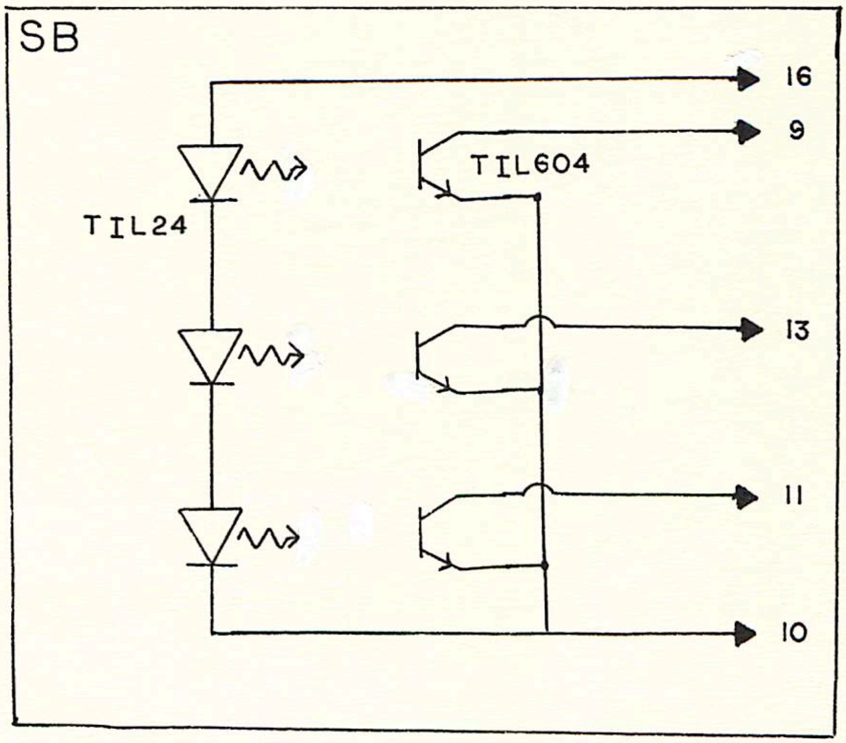

Figure 3.10 Sensing Board Schematic

Interconnect Cable 1

This cable is used to attach a sensing board to an axis comparator board. The cables for the x,y, and z axes are identical and consist of a 8-pin connector on the sensing board end (two rows of 4 pins labelled 9 through 16) and a seven pin connector on the axis comparator end (one row of 7 pins labelled 1 through 7). The connection definitions are provided in Table 2.

Table 2
Connection Definitions for Interconnect Cable 1

I1a (x,y,z-axis)

8 position, 2x4 connector		7 position, 1x7 connector
9....(Channel 1)	-->	4
10....(GND)	-->	1
11....(Channel 3)	-->	6
12 NC		
13....(Channel 2)	-->	5
14 NC		
15 Polarization location		
16....(+15 to LED's)	-->	7
		NC 2
		NC 3

(each numbered from top to bottom with pins pointing left)

Axis Comparator Board

The function of this board is to provide biasing for the phototransistors on the sensing boards, provide current-limited power to the sensing board LED's, and to shape the signals for transmission from the sensing site to the master interface board located off of the robot. This board consists of, essentially, three identical comparator circuits designed around the Motorolla LM339 quad comparator chip. The component layout for each of the boards is provided in Figure 3.11. The schematic for the board is given in Figure 3.12 and the comparator circuit is described in detail in Section 3.A.4 and Appendix 5.A2.

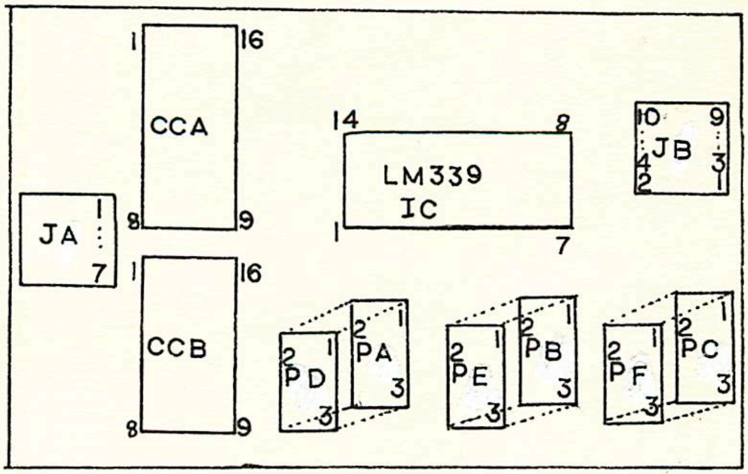

Figure 3.11 Component Layout For The Axis Comparator Board

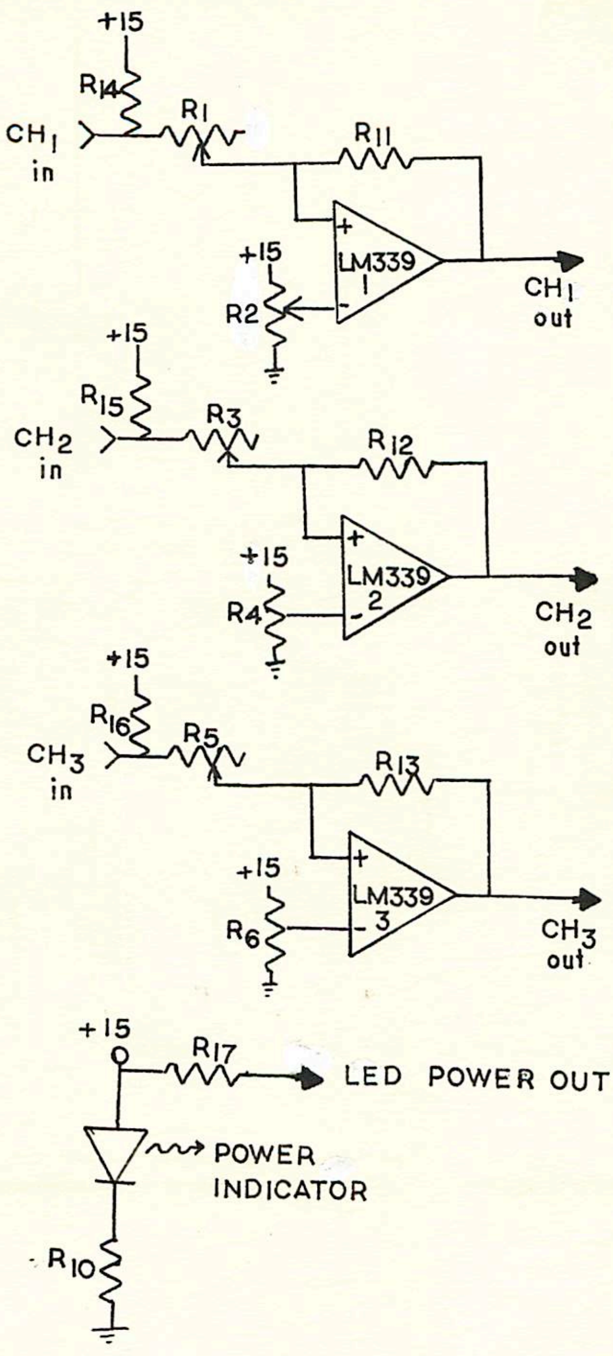

Figure 3.12 Schematic Of Axis Comparator Board

Table 3 contains a list of the parts used in the board, their definitions relative to the function of the circuit, and their board locations. In addition, the definitions of the connector pin-outs are provided. Table 4 contains a complete wire list for the board.

Table 3
Parts used on Axis Comparator Board

COMPONENT	DESCRIPTION	LOCATION (FIG 3.14)
R1	1M-Ohm Potentiometer	PD
R2	1M-Ohm Potentiometer	PA
R3	1M-Ohm Potentiometer	PE
R4	1M-Ohm Potentiometer	PB
R5	1M-Ohm Potentiometer	PF
R6	1K-Ohm Potentiometer	PC
R10	1.5K-Ohm Resistor	CCA3-CCA14
R11	1M-Ohm Resistor	CCA8-CCA9
R12	1M-Ohm Resistor	CCA6-CCA11
R13	1M-Ohm Resistor	CCB2-CCB15
LM339,1	LM339 Comparator Chip	
LM339,2	LM339 Comparator Chip	
LM339,3	LM339 Comparator Chip	
Power Ind.	red LED	CCA2-CCA15
C1(Not Shown)	.01 MicroFarad Cap.	LM339 pin3 - LM339 pin12
R14	1.5K-Ohm Resistor	CCA7-CCA10
R15	1.5K-Ohm Resistor	CCA5-CCA12
R16	1.5K-Ohm Resistor	CCB1-CCB16
R17	1.5K-Ohm Resistor	CCA1-CCA16

Table 4
Wire List for Axis Comparator Board

CONNECTOR	DESCRIPTION
JA1	GND
JA2	NC
JA3	NC
JA4	Channel 1 input
JA5	Channel 2 input
JA6	Channel 3 input
JA7	+V to LED's
JB1	+15 volts in
JB2	GND
JB3	NC
JB4	NC
JB5	Polarization
JB6	Channel 3 output
JB7	NC
JB8	Channel 2 output
JB9	NC
JB10	Channel 1 output

Table 5
Wire List for ACB

LOCATION	DESCRIPTION
JB2-PC3	GND
PC3-PB3	GND
PB3-PA3	GND
PA3-IC12	GND
IC12-CA3	GND
CA3-CB4	GND
CB4-CB6	GND
CB6-CB8	GND
CB4-JA1	GND
JB1-PC1	15 volts
PC1-PB1	15 volts
PB1-PA1	15 volts
PA1-IC3	15 volts
IC3-CA16	15 volts
CA16-CA15	15 volts
CA12-CA10	15 volts
CA10-CB16	15 volts
CB9-CB7	LED-dropping resistor
CB11-CB5	LED-dropping resistor
CB13-CB3	LED-dropping resistor
CA14-CB2	LED-dropping resistor
JA7-CA1	Sensor LED Power
JA4-CA5	Channel 1 input
JA5-CA7	Channel 2 input
JA6-CB1	Channel 3 input
CA5-PD2	Connection
CA7-PE2	Connection
CB1-PF2	Connection
PA2-IC4	Channel 1 reference voltage
PB2-IC6	Channel 2 reference voltage
PC2-IC8	Channel 3 reference voltage

Table 5 continued

LOCATION	DESCRIPTION
PD1-CA6	Connection
PE1-CA8	Connection
PF1-CB2	Connection
CA6-IC5	Connection
CA8-IC7	Connection
CB2-IC9	Connection
CA11-IC2	Feedback Channel 1
CA9-IC1	Feedback Channel 2
CB15-IC14	Feedback Channel 3
IC2-JB6	Channel 1 output
IC2-CB14	Channel 1 output LED
IC1-JB8	Channel 2 output
IC1-CB12	Channel 2 output LED
IC14-JB10	Channel 3 output
IC14-CB10	Channel 3 output LED

No Connection Points: PD3,PE3,PF3,JA3,JB3,JB4,JB5,JB7,JB9,
IC10,IC11,IC13,CA4,CA13

3.A.8 Barrier Strips/Wiring

The wiring on the cartesian machine is described in this section. There are a large number of different leads with signals running to and from the machine. The organization of these leads is based on a series of barrier strips mounted on various parts of the machine. Crimped wires run from the machine components such as the motor, etc. to these barrier strips. The x and y axes have 2 barrier strips each, mounted on the frame beside the motor. These are labelled x1,x2 and y1, y2 respectively. x1 and y1 have 8 connections and x2 and y2 have 10 connections. The connections for these two sets are shown in Figure 3.13. Note that the number of connections on each strip reflects only the available strips at the time of the actual machine wiring and has no special significance.

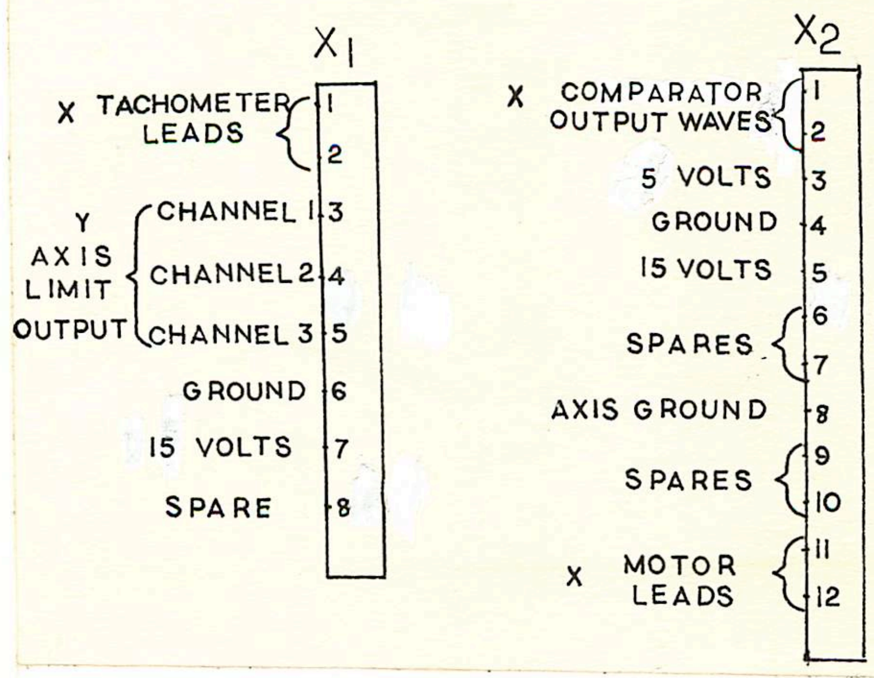

Figure 3.13 Connections for Barrier Strips X1 and X2.
The configuration is the same for Y1 and Y2. Note that the y, axis Limit Output (Channels 1,2, and 3) is on the x barrier strips. Similarly, the x Limit Output is on the y barrier strips.

The θ axis has a set of 2 barrier strips mounted on a vertical plate just beside the θ axis motor and a third strip on a vertical plate above the motor. These are labelled t1(8 connections), t2(6), and t3(4). The limit sensing connections for the θ axis are on t1 and the θ encoder/comparator information is on t2. The θ motor and tach leads are found on t3. (The connections for this set are shown in Figure 3.14). These three strips are connected via a helical multi-conductor cable to a set of four barrier strips v1(10), v2(7), v3(16) and v4(7) mounted on the carrier frame below the z axis motor. These are used to connect the leads coming from t1, t2 and t3 and from the z-axis motor, tachometer, encoder, and limit sensing connections. See Figure 3.15 for this configuration.

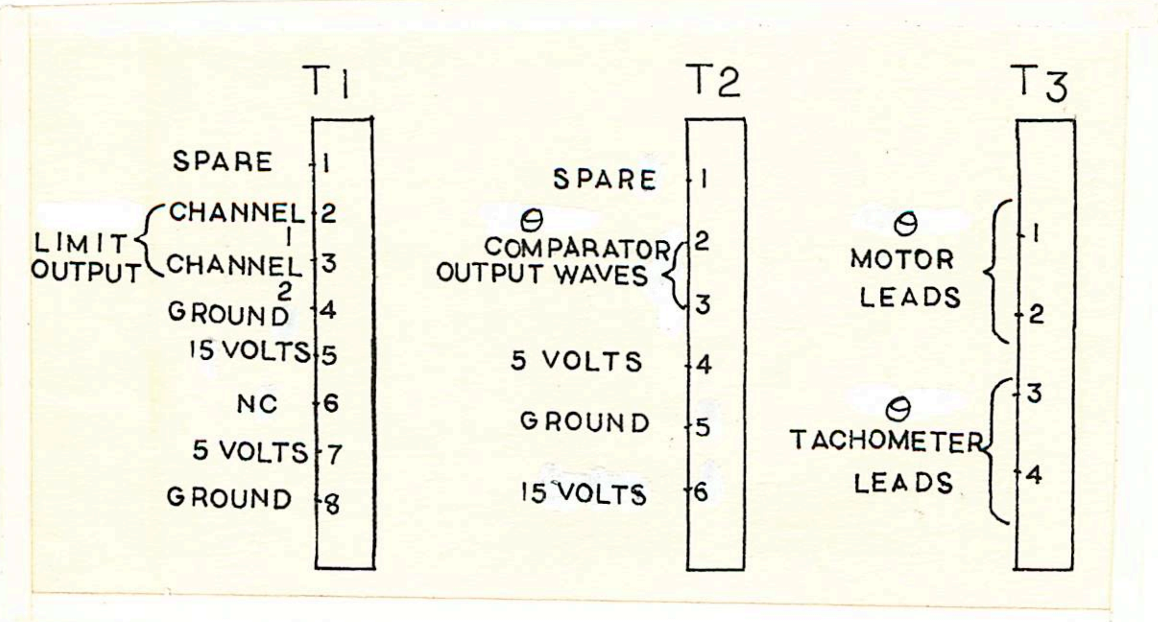

Figure 3.14 Connections on Barrier Strips T1 through T3.

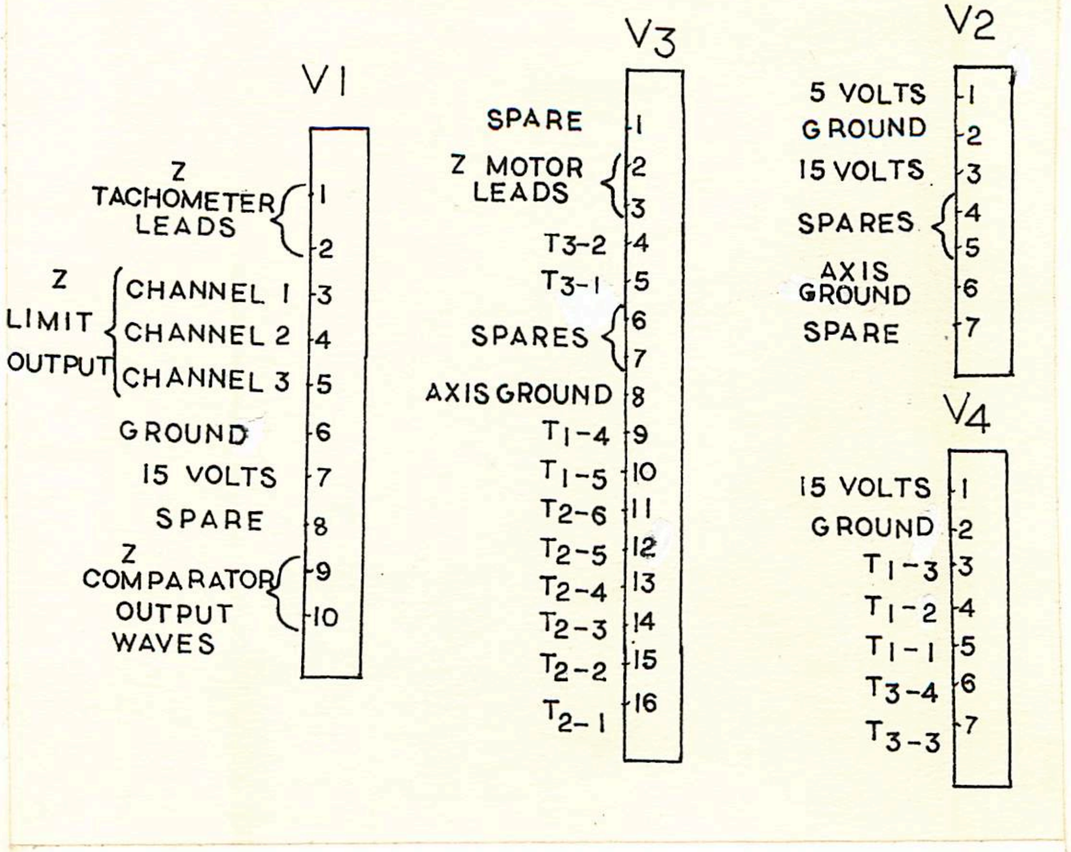

Figure 3.15 Connections on Barrier Strips V1 through V4.

Finally, the signals from the z and θ axes (i.e. from v1 through v4) are run through shielded wire to a set of four horizontal barrier strips mounted on the top of the front of the machine labelled u1,u2,u3, and u4. These strips have 4, 20, 13, and 4 connections respectively. Figure 3.16 shows the connections of v1 through v4 to u1 through u4.

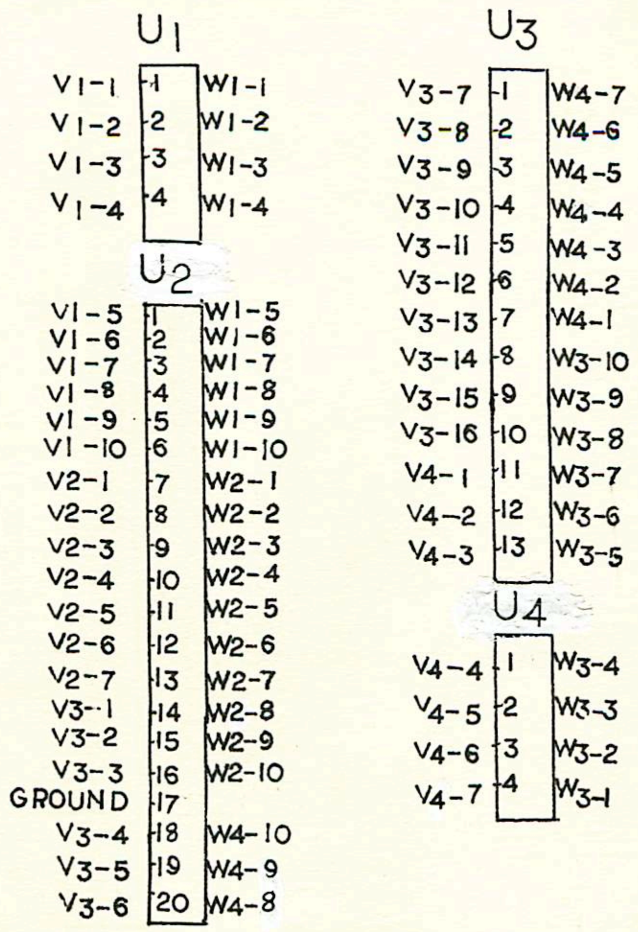

Figure 3.16 Connections on Barrier Strips U1 through U4.

All of the signal lines of the four axes are connected now from u1,u2,u3,u4,x1,x2,y1, and y2 to a set of 4 columns of vertical barrier strips mounted on a white board on the front of the machine table. This final set of strips is labelled w1,w2,w3,w4,w5,w6,w7,w8, and w9. w1 through w7 have 10 connections and w8 and w9 each have 6. Most of the signals running to these strips are also carried in shielded wire to prevent noise problems. Figure 3.17 shows the configuration of the w1 through w9 barrier strips on the front of the machine table while Figure 3.18 shows what component signal each connection in these four columns carries.

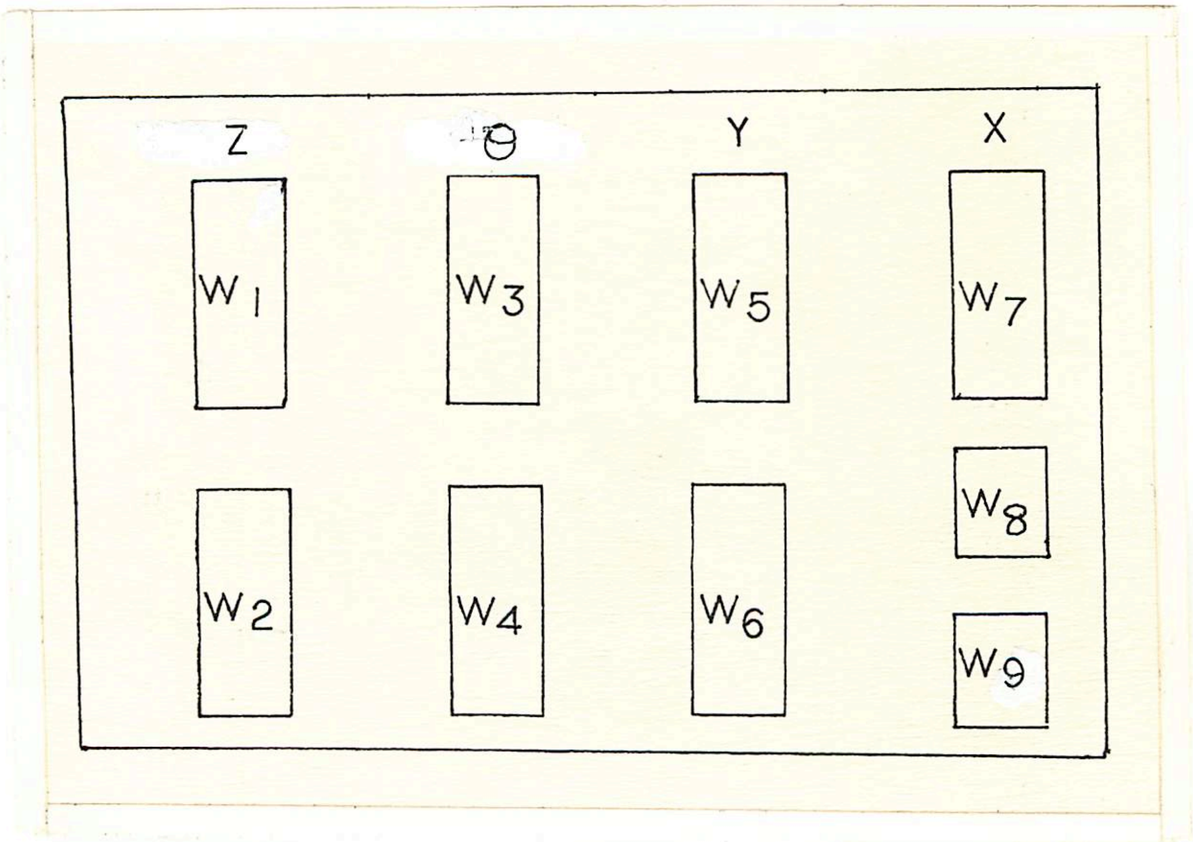

Figure 3.17 The Four Columns of Barrier Strips (W1 through W9) mounted on a white board on the front of the machine table.

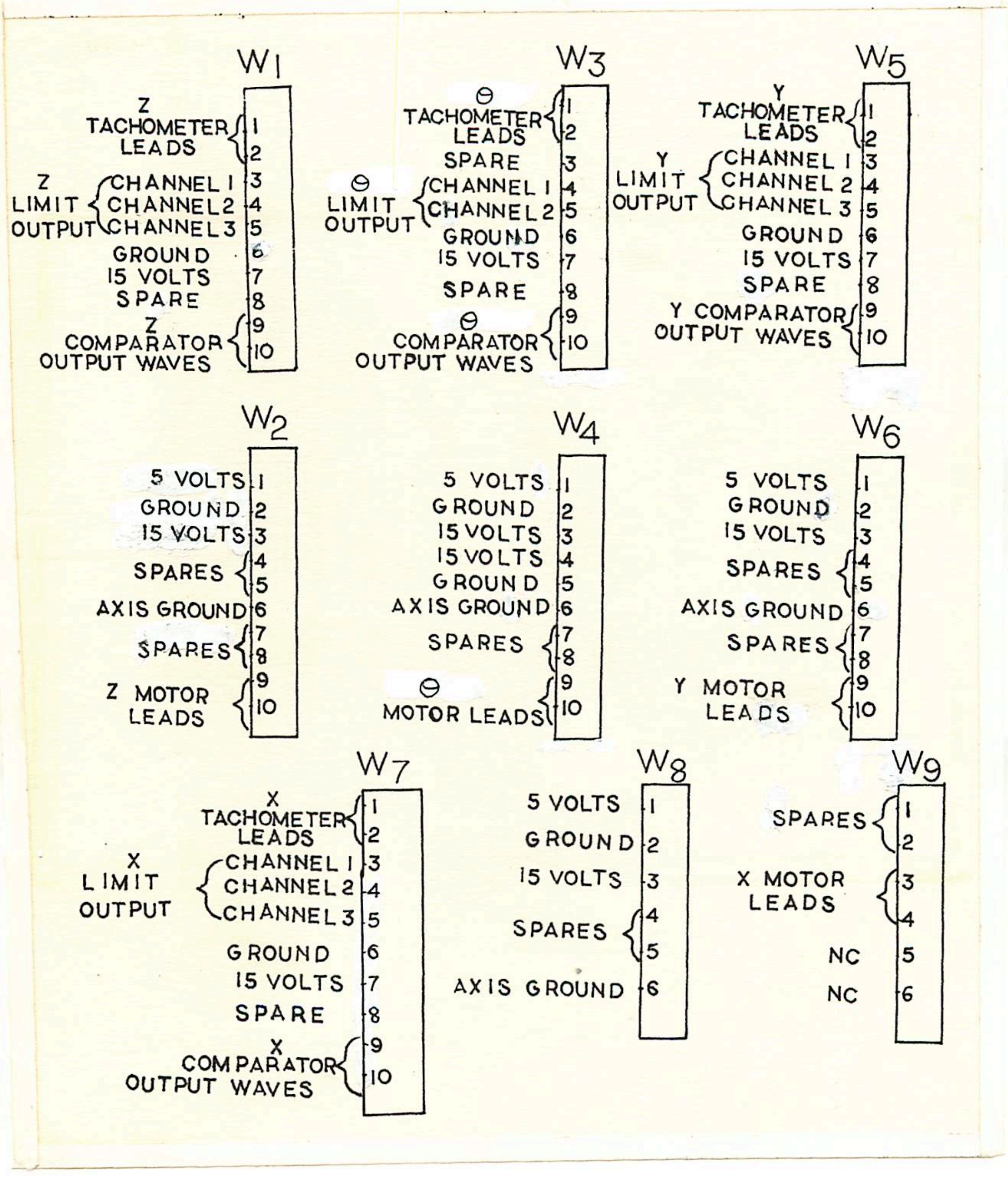

Figure 3.18 Connections on Barrier Strips W1 through W9.

The strips w1 through w9 are the final set of strips on the machine itself. Leads from them go directly to the servoamplifier cabinet and the computer interface board. This is a large board mounted on the wall in the computer room. The counter board, the limit sensing board, and the camera interface are located here. Cables are run to this board for connections between the machine (via barrier strips w1 through w9) and these interface boards.

3.B Servoamp/Power Cabinet

3.B.1 Servoamplifiers NC122F and NC101F

The servoamplifiers used are three Control Systems Research, Incorporated (Pittsburgh, Pa.) Model NC122F DC servo controllers for the x,y, and z axes and a Model NC101F for the θ axis. (The differences between the two models are not significant for this discussion and can be found in the manuals). All of these servoamplifiers are housed in the front of the servoamplifier/power cabinet as depicted in Figure 2.4. The Operating and Service Manual [5] available in the laboratory describes the servoamplifiers in detail, the theory of their operation, and maintenance and the initial set-up procedure.

Each servoamplifier or controller is part of a closed loop velocity servo system. The output of the controller is the armature current to be applied to the motor it is controlling and the output of the closed loop system is the actual angular velocity of the motor. Figure 3.19 is a diagram of this feedback system. (The term closed loop refers to the fact that the present output (the velocity) is used to determine the future output of the system).

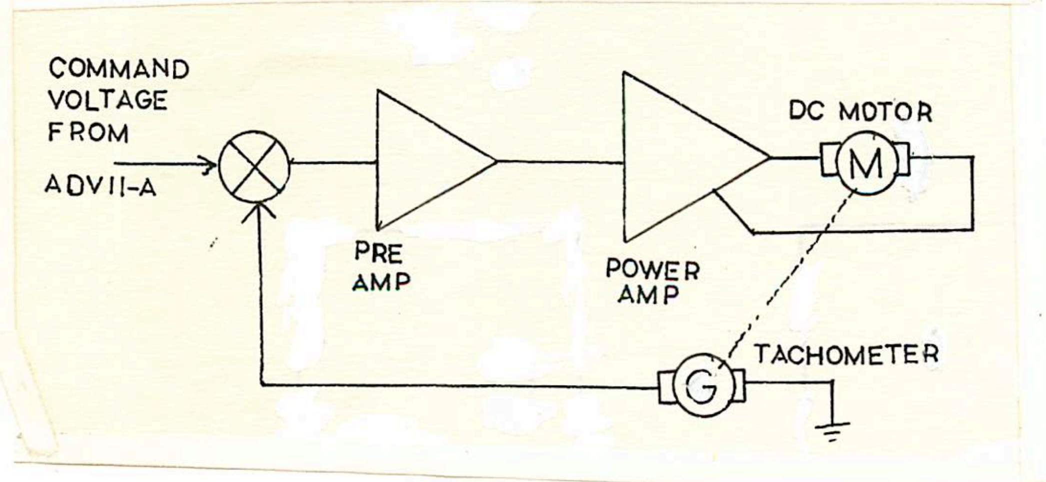

Figure 3.19 Closed Loop Velocity Servo System.

The Control Systems Research servoamplifier is composed of two parts, the preamplifier section and the power amplifier section. In the preamplifier section, the amplifier takes the difference between the actual angular velocity of the motor (on terminal 3) measured by the tachometer and the desired velocity (on terminal 2) from the AAV11-A D/A converter and amplifies the resulting voltage difference. The power amplifier section uses this voltage signal and a feedback (voltage) signal which represents the motor load current to determine what the applied armature current to the motor should be. The difference between these two signals is passed to a hysteretic switch (with a constant threshold) which outputs a square wave to the power semiconductor section and from there to the motor.

The output of each servoamplifier (terminals 9 and 10) is the actual armature current to be supplied to the corresponding motor to achieve the desired torque on that motor. The polarity of the signals on these terminals determines the direction of rotation of the motor shaft.

CRS controllers are switching-mode controllers which employ Two-State Modulation, a concept patented by Control Systems Research, Inc. The two switching techniques used in Two-State Modulation are pulse-width modulation (PWM) and frequency modulation. The output signal to the motor is actually a square wave of fixed amplitude (thus of fixed voltage). This wave can be modulated (via modulating the hysteretic switch of the power amplifier section) in two ways - either by modulating the duty cycle or pulse width (PWM) or by modulating the frequency (frequency modulation). Consider the wave form of Figure 3.20. This wave is pulse-width modulated only since the frequency remains fixed.

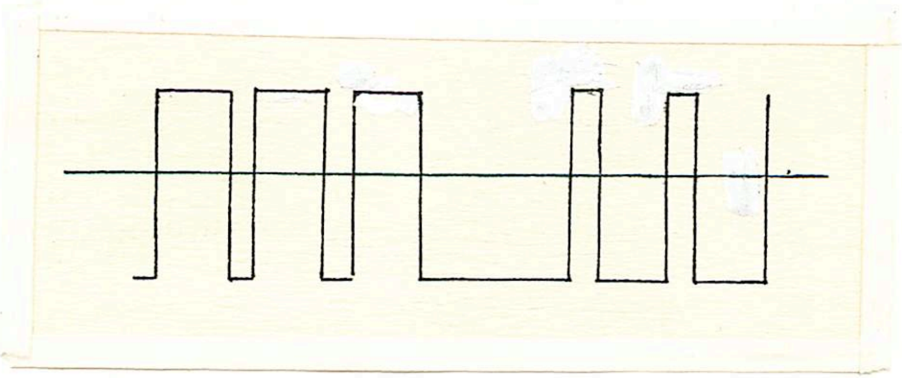

Figure 3.20 Pulse Width Modulated Wave

The current delivered to the load (the motor), while a pulse of a given polarity is applied to the load, increases exponentially with the amount of time the pulse is applied. This is a result of the load inductance. The longer the pulse, the larger the (armature) current will become, and the faster the motor will turn in that direction. When the next pulse is applied (in the opposite polarity), the current will increase exponentially in the opposite direction. Thus to produce a net motor movement in one direction, the pulses for that direction must be maintained longer than the pulses in the other direction. The larger the desired motor speed, the longer the pulses of the correct polarity are maintained. In Two-State Modulation, the switching transistors may even cease to switch and deliver one long pulse (in one direction) whence the frequency modulation of the controlled signal. With the Two-State concept, a larger full speed is available than with PWM since strictly PWM controllers must switch at a fixed rate whereas the Two-State controller can handle changing load and command signal conditions more efficiently by ceasing to switch (the reader is referred to the manual [5] for the more on the Two-State theory).

The output of terminal 8, the current monitor output, is proportional to the actual load current (.25 volts/ampere of the load current) and can be used as a type of force feedback since it is an indication of the motor torque (recall from section 3.A.2 that $T=K_T*I_A$ where K_T is the torque-constant of the motor, I_A is the armature current and T is the motor torque).

3.B.2 Power

In Figure 3.21, the power transformer and the relay and switching circuit are configured. (To gain an understanding of transformers, see [19], chapter 36). The cartesian machine power cabinet originally had switches located on the front to turn power on and off. The original switches on the cabinet were replaced with larger, safer switches. The green "on" switch, which is normally open, is enclosed in a cylindrical hub which prevents accidental pushing. The red "off" switch (normally closed) is a large mushroom switch which is easily pushed. Note that these are momentary switches. For example the "on" switch is normally open. When it is pressed it is closed, but when the pressure is removed, it returns to its normal (open) state.

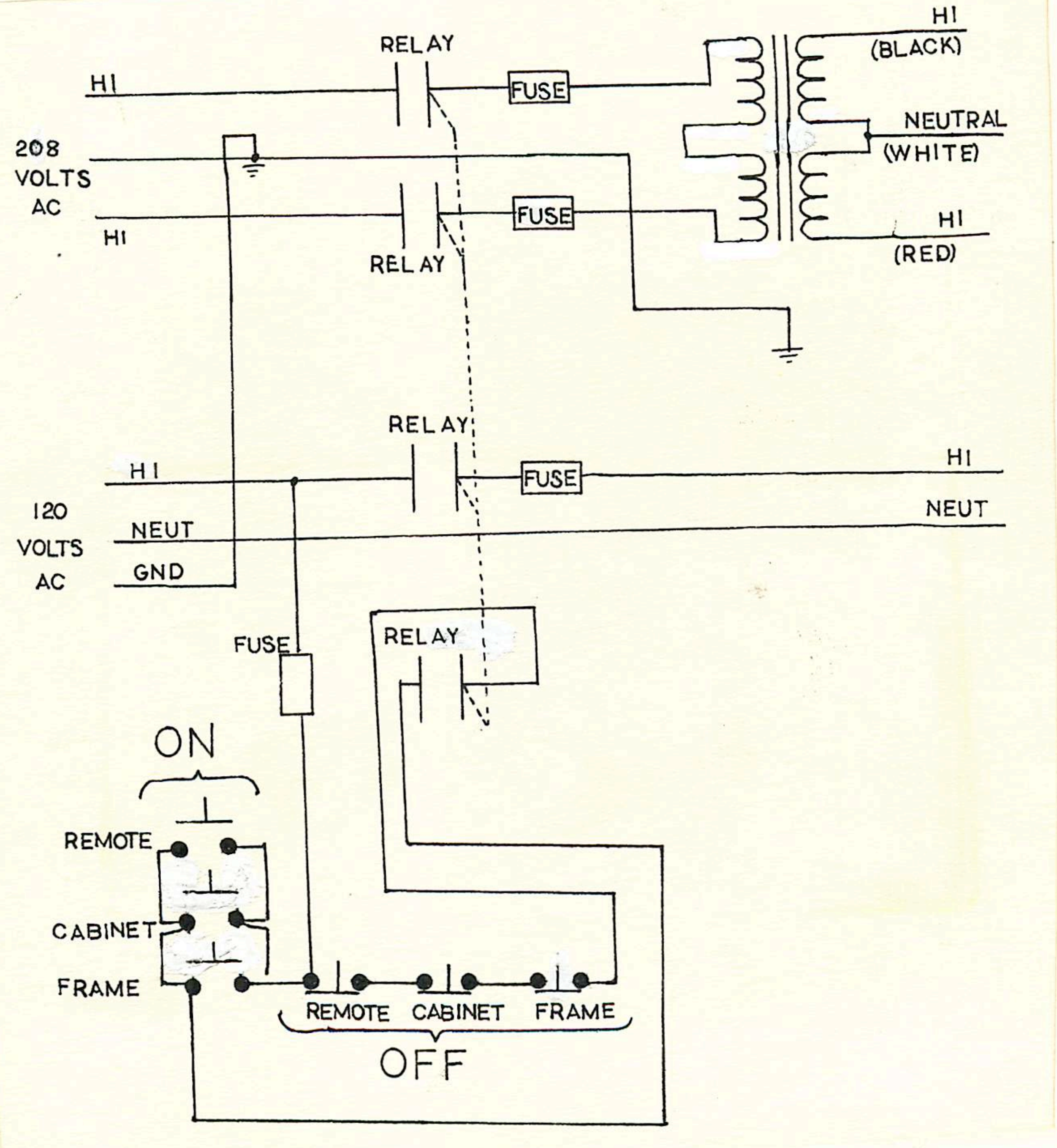

Figure 3.21 Power Transformer and Switch Configuration

In the course of machine testing, it was found that a remote-switch box was needed so that the machine could be turned on and off at the terminal location. Two smaller switches were built into a metal box with a long cable running between it and the power cabinet. This is the remote switching unit. The black on switch is also enclosed in a cylindrical hub and is normally open. The red off switch is normally closed. Another set of green and red switches will also be placed directly on the frame of the machine.

The purpose of the switches is to activate or deactivate the relays of the circuit. A relay can be thought of as a switching device which controls a larger power. The relays in this circuit are normally open so that only when one of the "ON" switches is pressed does the relay close. Consider Figure 3.22. When a current is switched on (via one of the three "on" switches) in the wire coiled about the magnet, a force is exerted on the armature of the relay (this phenomenon is discussed in Section 3.A.2). The armature is attracted via this force to the magnetic core and the contact (on the left in Figure 3.22) is closed. When the current to the coil about the magnet is turned off (via one of the three "off" switches) there is no longer a force attracting the armature and the spring action causes the relay contact to open. (See [7]).

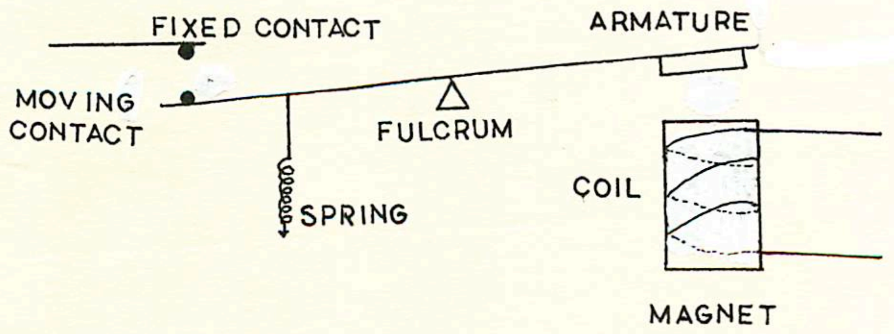

Figure 3.22 Simplified Diagram of Electromagnetic Relay. See [3].

The amplifiers use 208 volts AC and 120 volts AC. A 120 volt line is also connected to the power supply box. This power is used by voltage regulators in the cabinet to generate a 15 volt and a 5 volt DC supply. It is these supplies which are used for power to the comparator, counter, multiplexer, and limit sensing circuits. A twisted-triple cable of three colors, white for +15 v, red for +5 v, and green for ground, is run between these voltage regulators in the power cabinet to the large computer interface board (mounted on the wall in the computer room as mentioned in section 3.A.8) to supply power to these interface boards.

3.C Additional Components

Besides the components described above which act as an interface between the cartesian machine and the computer, there is the computer itself. At present, the computer used to run the servo routines is a DEC PDP-11/23 with two DRV11 bus interfaces, an ADV11-A analog-to-digital converter module, and a AAV11-A digital-to-analog converter module. The DRV11 consists of 16 input lines (used for the 16-bit count from the multiplexer board), and 16 output lines (four of these are used to clear the counters as will be described in Appendix A3) for data handling. The 2-bit address used to select the axis count for the currently controlled axis is placed by 11/23 (FORTH) software in the two control/status registers (CSR0 and CSR1) of the DVR11.

The ADV11-A is a 12-bit successive approximation analog-to-digital converter (See [11] for a treatment of this type of A/D device). It includes a multiplexer section to allow up to 16 inputs. Four of these inputs are used for the four tachometer signals, and four for the output of terminal 8 of the servoamplifiers which carry the actual motor load currents as described in section 3.B.1. The remaining 8 will be used for the interfacing of the Overton tactile sensor [14] mentioned below. The 11/23 software must perform the A/D multiplexer channel selection through the use of 4 bits (8-11) of the control/status register (CSR) located on the ADV11-A module.

The AAV11-A is a 4-channel, digital-to-analog converter module. These four channels are used to send a desired velocity to each of the four servoamplifiers which control the axes. Software routines on the 11/23 place a 12-bit (digital) number in a holding register for each channel and it is this binary number which is converted to analog form by the module. See [6] for a thorough description of these three interface modules.

Other important components are the sensors and their interfaces. A General Electric TN2201 Solid State Automation Camera is the visual sensor. It is supported by a PN2210A Automation Interface also manufactured by GE and a Poynting Products, Inc. Model 108 Digital Video Memory. Documentation on these products is available from the manufacturers and the accompanying manuals are also available in the LPR. The images from the camera will first be processed in a DEC PDP-11/03 using a DRV11-B DMA interface. Information on this device is also available in [6]. The computer system configuration and its future development will be the subject of a COINS technical report (to appear) written by a member of the LPR.

Other sensors include an 8x16 analog tactile array sensor developed by Overton [14]. Sonar is also under discussion as a possible usable sense. Many sensory devices will be developed in the course of the research work on this machine as the higher-level control routines become more and more capable of using environmental information.

At the end of the z axis lies a gripper or mounted tool. At present a two-fingered gripper shown in Figure 3.23 and built and donated by Digital Equipment Corporation is installed on the manipulator. The gripper motor (a stepper motor) is interfaced with the same encoder/comparator/counter configuration as the axis motors. However, instead of using a servoamplifier for velocity servoing, all such servoing (including position servoing), must be done with software. Documentation for this gripper has been written as a LPR Memo [9]. The laboratory is now installing a nine degree of freedom Salisbury hand. This dextrous unit is composed of three fingers with three joints each (whence the nine dofs).

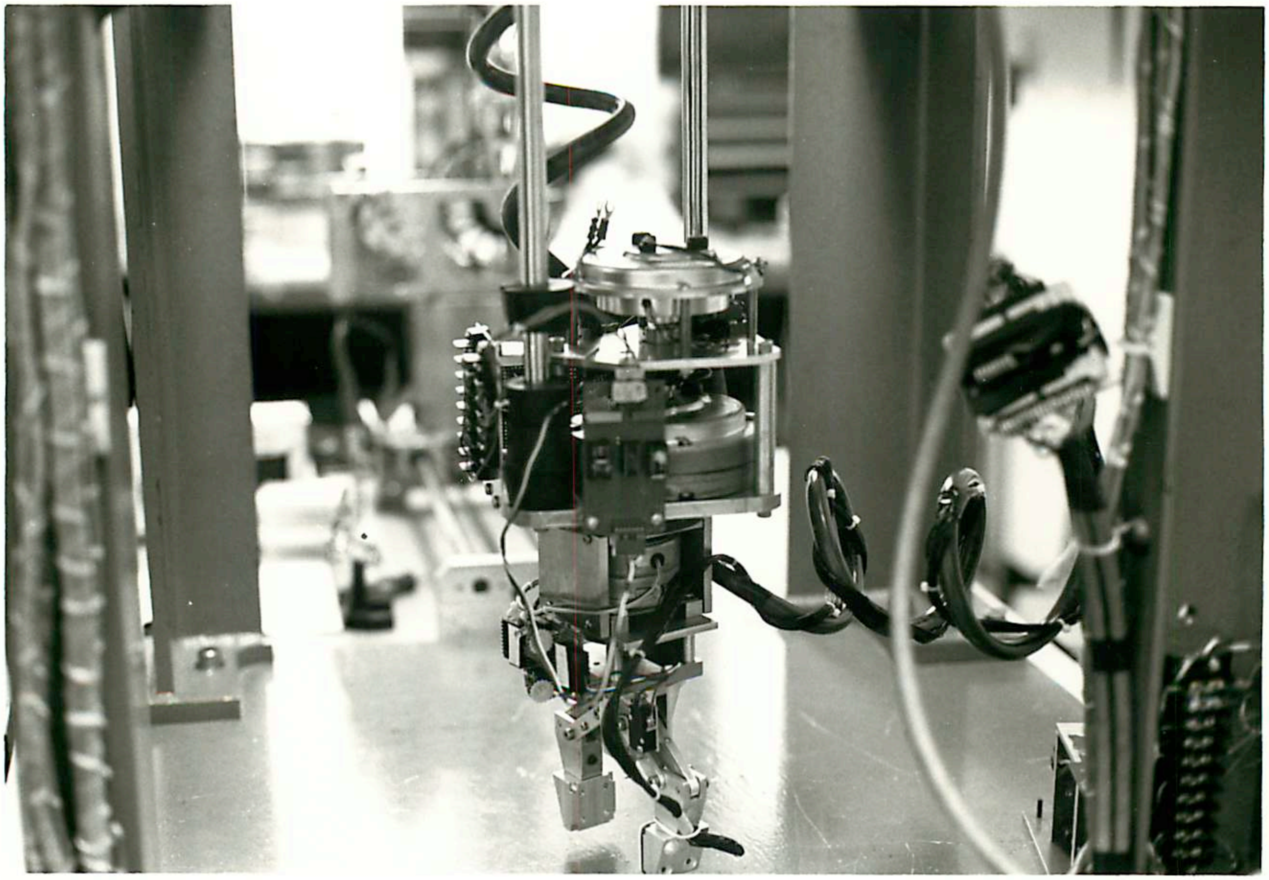

Figure 3.23 Two-Fingered Gripper Mounted on z axis. See [9].

For a more detailed description of the status of the laboratory, the reader is directed to [16].

4.0 Description of Operation

4.A Operation Instructions

BRINGING THE SYSTEM UP

1) First the power must be turned on in the laboratory.
The switches can be found in a large "breaker" box inside the lab.

☞ 1a) The main switch must be turned on first (this is not numbered, but lies at the top of all the switches in the box and is labelled "main").

☞ 1b) Number 12 which is the 208 volt power supply and number 13 which is the 120 volt supply are switched on next. Note in fact that number 12 supplies the power to the servoamplifiers and number 13 supplies power to the voltage regulators that produce the 15 and 5 volt DC power used on the interfacing boards.

2) Before the cartesian machine is actually turned on, the PDP-11/23 FORTH system must be "brought up."

☞ 2a) Place the disk in the RL02 drive (or the floppy disk in the RX02) and flip up the "ON" and "HALT" switches located on the front of the processor panel.

☞ 2b) When using the RL02 drive, wait for the yellow "LOAD" light (located on the front of the drive) to light then press it.

☞ 2c) When the white "READY" light turns on, the disk is loaded and the "RESET" switch located beside the "ON" and "HALT" switches on the processor panel may be flipped up.

☞ 2d) When using a floppy disk in the RX02, the "RESET" switch may be flipped right after the "HALT."

3) After flipping the "RESET" switch, the terminal message will be "Start?" Type in "DL" if using the RL02 and "DY0" if using the RX02 drive. A short message should follow ended with the FORTH prompt "OK." At this point the core of the FORTH system is loaded (presently this is done with the command "200 LOAD"; in the near future the core will be automatically loaded) and other blocks containing "routines" or FORTH "words" for the cart machine should be loaded. For a more thorough explanation of this procedure, see [16].

4) One of the blocks containing the cart machine FORTH words must contain a word which will send zero velocity to the servoamplifiers. In other words, the digital to analog converters of the AAV11-A interface module (described in section 3.C) corresponding to velocity must be sent the equivalent of a zero voltage so that the servoamplifier for each axis "sees" a desired velocity of zero for its corresponding

axis.

☞ *THIS MUST BE DONE BEFORE THE CART MACHINE IS TURNED ON!* ☜

If this is not done, there is an arbitrary desired velocity on the D/A converter for each axis and this velocity may be very large. If this is the case, when the machine is turned on, it will exhibit "run away" behavior and may damage objects in the work space or even damage itself. Again, send a zero desired velocity to each axis BEFORE turning the machine on.

5) To actually turn the machine on, one of the switches described in section 3.B.2 (either on the power cabinet, the cart machine itself, or on the remote switch unit) needs to be pressed. Recall that the "on" switches are encased in a cylindrical hub to prevent accidental switching. The user should be ready to press one on the "stop" switches at this time in case erratic behavior occurs. If all goes right, the machine is ready for movement via FORTH routines (see sections 4.B and 4.C). If all does not go right, either the above procedure has not been followed correctly or there is a problem in the system. See the Trouble Shooting section (Appendix A5) in this case.

BRINGING THE SYSTEM DOWN

1) When the user is done with the system and it is ready to be turned off, the cart machine itself is turned off first. This is done simply by pressing one of the "off" switches. As a word of caution, if the z axis does not have a brake (as is the case at present), either it must be positioned before turn off to its lowest point (closest to the table top of the work space), or it must be held when the off is pressed so that it does not fall.

2) When turning off the PDP-11, first press the yellow "LOAD" switch on the drive if using the RL02 and when it lights, flip down the "HALT" and "ON/OFF" switch (on the front of the processor panel). If using the RX02 (and therefore a floppy disk), **REMOVE THE DISK** before turning the machine off. Failure to do this could ruin the disk. Note that once again for the RX02, the "LOAD" light may be ignored and once the floppy is removed, the machine may be immediately turned off (via flipping down of the "ON/OFF" switch).

- **NOTE**

The PDP-11 should ALWAYS be turned off when not in use. The reasons for this are the heat build-up inherent in the machine and the possibility of accidental power-downs and power-ups which could "crash" and ruin the disks.

3) Finally, the power switches in the "breaker" box ("main", 12, and 13) should be switched off upon leaving the lab.

4.B FORTH

The version of FORTH used for low-level control of the GE Cartesian Machine is the UMASS/LLE FORTH-79 Revision 3.1. This language was chosen for its versatility as a high-level language and as an assembly language. The ease of interaction with the computer interfaces and I/O devices made FORTH attractive for use in robot control.

The FORTH system is composed of a set of standard commands or definitions called words. The user uses these definitions to build words to implement the desired application. Words may also be defined directly in assembler code using FORTH Assembler.

FORTH is also an operating system which performs the usual functions (text editing, compilation, assembling, interpretation, I/O, etc) An excellent reference for those wishing a light introduction to FORTH is [3]. Documentation on the UMASS/LLE FORTH version is forthcoming [17].

FORTH routines used in this configuration are described algorithmically in the next section. The actual code for moving the machine axes to desired points uses interrupt processing so that one processor can control all four axes and the gripper. This of course is a temporary scenario used until the single axis controllers are implemented. The code uses FORTH Assembler, is described in the following section (4.C) and is listed in Appendix A6.

Note that while the 11/23 system is programmed in FORTH, the VAX system will most likely be programmed in LISP for high-level control.

4.C Servomechanism Description/Control

The cartesian machine is driven via a set of servoamplifiers (3.B.1) (one for each axis motor). These amplifiers provide the signals (to the motors) depending on the desired velocity of the motor shaft (supplied by the computer system which controls that particular axis), and the actual velocity provided by the tachometer. In other words the motor-tachometer-amplifier system is a self-contained velocity servoloop. Using this velocity servoloop as a base, servoroutines have been written (in FORTH) to control the movement of the machine.

It is the encoder which provides positional feedback for the position control loop. The controlling signal for each axis is a velocity signal which is sent to the AAV11-A interface and delivered to the servoamplifiers. The inputs to the position servo are the desired position, the actual position (in terms of encoder counts), and a maximum velocity allowable for each axis. Since the same controlling routine is used for all four axes, arrays indexed by register R0 of the PDP-11 were constructed for the desired position, the maximum velocity, and the current velocity being sent to the amplifiers. A state table is also used to record whether each axis has ceased to move (i.e_. is within a user-chosen range of the desired position). This information is used to determine whether to position-servo each axis. The code for these routines is included in Appendix A6 and is discussed below.

A standard speed trajectory control scheme is used with an acceleration period, a constant speed period (at the maximum velocity), and a deceleration period. The period changes do not depend on time, but on the absolute value of the difference between the desired and the actual distance. Figure 4.1 depicts this trajectory and also shows the trajectory which results if the distance to be travelled is relatively small.

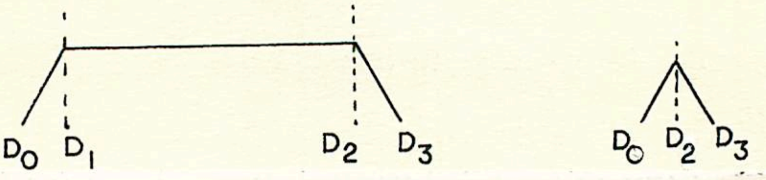

Figure 4.1 The velocity trajectory of the point-to-point position servo. D_0 = Initial Position; D_1 = Point where Vel = Maxvel; D_2 = Point where Vel > (D_3-D_2); D_3 = Desired Position. At left is the normal trajectory. At right is the case where the distance to be travelled is so short that the maximum velocity is never reached.

The velocity during the acceleration phase is actually a step function with a user-chosen increment (also stored in a four-element array). The control velocity is incremented at each sampling until it reaches the maximum velocity or (for a short distance) until the distance to be travelled is less than the output velocity signal. When the velocity/position relationship reaches this point (D_2 in Figure 4.1), the velocity signal becomes proportional to the distance left to travel. In actuality, this deceleration phase velocity is also a step function since the velocity signal is reset at discrete instances. An overall configuration of the position control servo system is given in Figure 4.2.

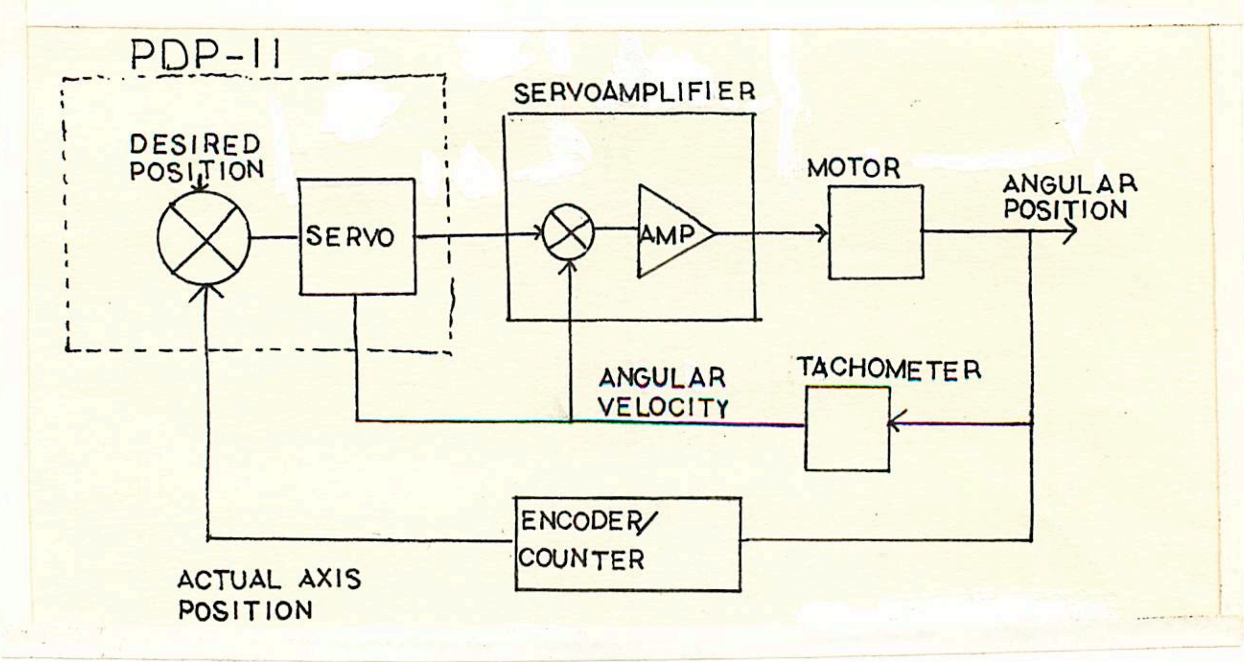

Figure 4.2 Axis Position Servo System.

The first step in adaptive control has been taken in the form of a routine which corrects the drift inherent in the servoamplifiers when a zero velocity is requested. If a zero is sent via the AAV11-A to the amplifier, a strictly zero velocity is not always the result, even when the amplifiers are balanced beforehand. Thus a drifting of the axis results. Part of the Change.Speed macro of blocks 1004-1007 checks for such a drift using another state table called Command.Status. If it is determined via use of this table that an axis is no longer being position-servoed, the routine checks to see if the axis position is still within the desired range. If not, the value which (currently) represents a zero velocity is appropriately incremented or decremented by one. The same algorithm compensates for loading effects.

Control schemes for each axis will be implemented on PDP-11 systems. These single axis controllers will eliminate the need for the interrupt driver currently in use to emulate them. The code for this interrupt driver may also be found in Appendix A6.

The use of these interrupt routines allows the position-servoing to take place while other routines are concurrently run on the FORTH level. This is necessary at this time since both high level routines for axis movement and the low level position servo routines are being run on the same processor. The result is that the high level routines are run normally, but are interrupted every 1/60th of a second (the system clock runs at 60 Hertz). The interrupt routine is the position servo routines which updates the output velocities for each of the four axes.

Routines to control the currently used two-fingered gripper which is actuated by a stepper motor have been run synchronously with the above routines. Some of these routines are described in [9].

The control algorithm given above allows only point to point movement of the machine. In other words, one point at a time is specified, the machine axes move to that point and stop, then the next point is specified. In a complex task, the robot will need to move continuously through various points in the workspace. Continuous path motion algorithms using spline interpolation of desired trajectory segments are now being developed and are based on works such as Paul [15]. Note that such routines must anticipate and allow for changes in trajectory plans.

The use of tactile and visual information will be integrated with the trajectory generation routines for decision-based planning and machine movement. A new robotic language, the Perceptual Robotics Language, is developing and encompasses these sensory-motor routines within a schema-based configuration. [12] gives a description of the new language and other existing robotic languages. [14] is the basis for the implementation of schemas in the evolving language of the LPR.

Higher level adaptive-learning control routines will also be implemented on the cartesian machine. Such routines are based upon an Associative Search Network (ASN) designed by the Adaptive Networks Group of the COINS Department of the University of Massachusetts. The idea is to search for the correct manipulator control actions and to learn from the experience. The effect of the control signals is to move the joint variables by certain fixed amounts. The ASN receives a reinforcement which is used to determine the effects (good or bad) of its previous action(s) to accomplish learning. See [1].

5.0 Appendices

Appendix A1. Motor Specifications

The following are the motor specifications for the PMI U12M4H Servodisc (TM) Motor as given by the manufacturer:

	SYMBOL	UNITS	U12M4HA VALUE
MOTOR PERFORMANCE: INCREMENTAL MOTION CONTROL			
Peak Torque	TP	OZ IN	1625.7
Continuous Stall Torque	TS	OZ IN	11511.8.8
Peak Current	IP	AMPS	65.2
Continuous Stall Current	IS	AMPS	6.32
Peak Acceleration, No Load	AP	KRAD/SEC/SEC	162.6
Cogging Torque	TC	OZ IN	0
MOTOR PERFORMANCE: RATED			
Torque	T	OZ IN	151.4
Speed	N	RPM	3000.0
Power Output	P	WATTS	335.6
Terminal Voltage	E	VOLTS	66.2
Current	I	AMPS	6.55
No Load Speed at Rated Voltage	NM	RPM	3494.9
Max Permissible Dissipation at Rated Speed	PL	WATTS	98.4
MOTOR CONSTANTS: INTRINSIC (AT 25 DEG C)			
Torque Constant	KT	OZ IN/AMP	25.03
Back EMF Constant	KE	VOLTS/KRPM	18.50
Terminal Resistance(at 4 amps)	RT	OHMS	1.170
Armature Resistance	RA	OHMS	1.030
Average Friction Torque	TF	OZ IN	6.5
Viscous Damping Constant	KD	OZ IN/KRPM	2.69
Moment of Inertia	JM	OZ IN SEC-SEC	.01000
Armature Inductance	L	MICRO HENRY	<100.0
Temperature Coeff of KE	C	%/DEG C RISE	-.02
Number of Commutator Bars	Z		141
Number of Poles of Magnetic Field	PF		8

	SYMBOL	UNITS	U12M4HA VALUE
MOTOR CONSTANTS: DERIVED (AT 25 DEG C)			
Mechanical Time Constant Without Load	TM	MILLISEC	2.31
Electrical Time Constant	TE	MILLISEC	<.10
Speed Regulation Constant Term Voltage	RM	RPM/OZ IN	2.21
THERMAL RESISTANCE (Mounted on Aluminum Heat Sink 8x16x3/8 inch)			
Armature to Ambient at Stall	RAA	DEG C/WATT	1.90
Armature to Ambient at 3000 RPM	RAA	DEG C/WATT	1.27
Forced Through-Air Cooled:			
Arm to Amb With Air Flow of .4 LBS/MIN	RAA	DEG C/WATT	.80
Arm to Amb With Air Flow of .8 LBS/MIN	RAA	DEG C/WATT	.51
Arm to Amb With Air Flow of 2.0 LBS/MIN	RAA	DEG C/WATT	.26
PHYSICAL CHARACTERISTICS			
Motor Diameter	D	IN	5.5
Motor Length	LG	IN	2.78
Motor Weight	W	LBS	11.0

Address of PMI:

PMI Motors
Division of Kollmorgen Corporation
5 Aerial Way, Syosset, New York 11791
(516) 938-8000 ; TWX 510-221-1875

Appendix A2. Comparator Theory

This appendix is a derivation, from specifications of the desired behavior, of the comparator circuit shown in Figure 5.2. The first specification is that the circuit have a high input impedance. Roughly, this means that the input resistance is ideally infinite (in practice of course it is very large, but finite), and therefore the circuit will draw no current and hence not affect the input (e.g. the output of the encoder). The impedance relationship is $V=Z*I$ where V is the voltage, I is the current, and Z is the input impedance. (See Bobrow, [2]). The current is $I=V/Z$ so that as Z becomes very large, the current I approaches zero.

The second specification is that the circuit exhibits as large a hysteresis as possible within the limits prescribed by the input signal. For example, suppose the input is a wave with voltage ranging from 0 volts to 5 volts The desired behavior of the comparator circuit is that it outputs a high voltage when the input is at 5 volts and a low (zero) voltage when the input is at 0 volts. The question is when exactly should the switching occur? Consider the switch from low to high. If it is designed to occur at the first deviation from zero, faulty switching may result due to noise on the input signal line. Switching must occur only when the input signal is actually changing from low to high or high to low. To assure this, the comparator switches to high when the deviation from zero reaches a certain voltage H_{LV} (Low Hysteresis Voltage Level) and switches to low when the deviation from, for example 5V, reaches another voltage H_{HV} (High Hysteresis Voltage Level). This causes the output square wave to be slightly behind (in phase relationship) the input wave. Such behavior is called hysteresis as mentioned above. See Figure 3.5 for clarification.

The following derivation may be used for either the first set of comparators (mounted on the motors) or the second (found on the counter board). The derivation is in symbolic form and actual values are discussed later. The operational amplifier (op amp), which has the desired high input impedance, is the basis for the comparator circuit. For a discussion of operational amplifiers and their characteristics, see [2,10,11]. See also [11] for a thorough treatment of comparators. The op amps incorporated in the LM339 have been designed specifically by National Semiconductor for use as comparators.

In Figure 5.1a, the symbol for an op amp is shown with two input voltages (inverting and noninverting) V_s and V_r and an output voltage V_o. The output voltage V_o is grounded if $V_s<V_r$ and floats at an arbitrary voltage or "don't care" state if $V_s \geq V_r$. To force the output high when V_s is greater than or equal to V_r, the output is "tied to" +V, the supply voltage for the circuit to be determined later, via a small resistor R_o (see Figure 5.1b). This resistor is sometimes called a "pull-up" resistor.

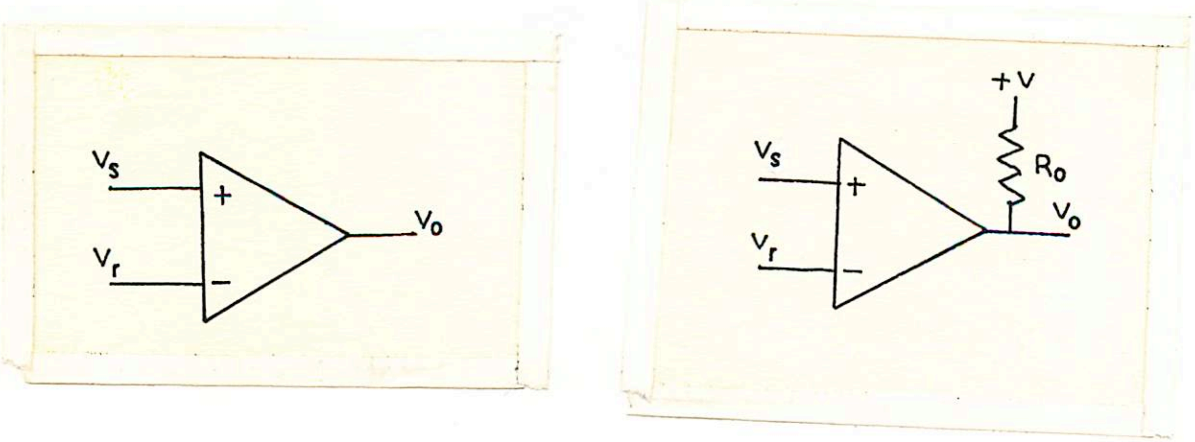

Figure 5.1
a) Simple Comparator
b) Comparator with Output tied high.

Now the hysteresis behavior must be built into the circuit. The two hysteresis values H_{LV} and H_{HV} are first chosen. If the input voltage range is rather wide, H_{HV} can be set to V_{in}(max)-1 and H_{LV} to V_{in}(min)+1 where V_{in} is the input signal voltage.

There are two cases for the behavior of the final circuit which follow from the discussion above:

Case1: If $(V_o = 0)$ and $(V_{in} > H_{HV})$

then switch to $V_o = +V$ (high)

Case2: If $(V_o = +V)$ and $(V_{in} < H_{LV})$

then switch to $V_o = 0$ (low)

These cases must correspond to switching conditions for the comparator itself. In other words $(V_o = 0)$ and $(V_{in} \geq H_{HV})$ must imply that V_s is greater than or equal to V_r. $(V_o = +V)$ and $(V_o \leq +V)$ must imply that V_s is less than V_r. Since the conditions in both cases include a condition on the output, feedback from output to input is introduced via a resistor R_f into the circuit as in Figure 5.2.

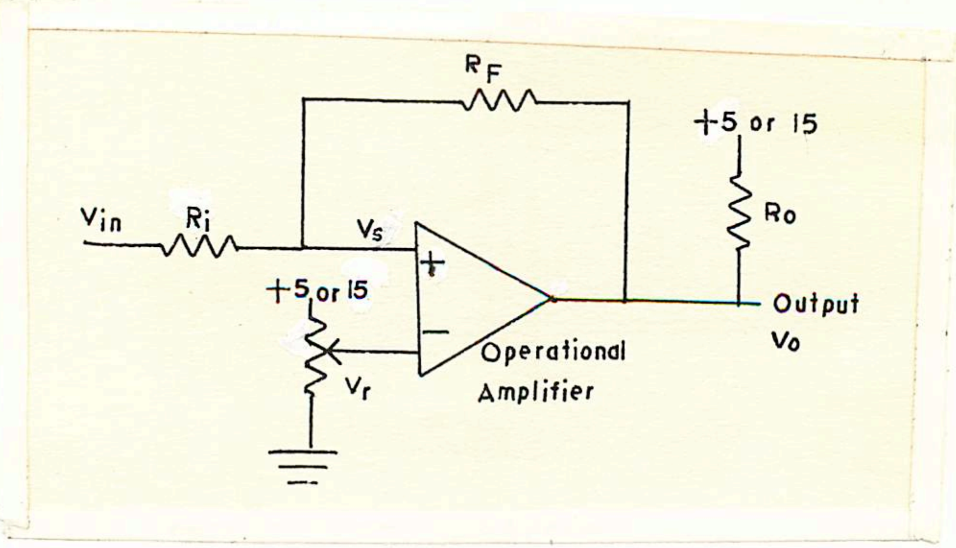

Figure 5.2 Complete Comparator Circuit

V_{in} is an input to the circuit via resistor R_i. Note that changes in R_i will affect the value of V_s as will R_f so that the correct choices for these two resistors will assure proper switching behavior. The two cases are reconfigured as follows:

Case1: Switching from Low to High

Hypothesis: $V_{in} = H_{HV}$ and V_o = Ground (low)

Discussion:

Because of the "infinite" impedance of the op amp, there is no current through it (see discussion above and Bobrow [2]). The equivalent circuit is shown in Figure 5.3. Note that the "pull-up" resistor R_o is negigible (since $(R_i+R_f)>>R_o$) and is therefore ignored.

Figure 5.3 Equivalent Circuit for Comparator in Case 1.

By Ohm's Law, $V=I*R$.

Also $I = \frac{H_{HV}}{R_i+R_f}$ where I is the circuit current.

Since the switch to high is caused by the relation $V_s>V_r$

and $V_s = I*R_f$ implies that

$$V_s = H_{HV} * \frac{R_f}{R_i+R_f}$$

then $\frac{H_{HV} * R_f}{R_i+R_f} > V_r$ causes low to high switching behavior

Case2: Switching from High to Low

Hypothesis: $V_{in} = H_{LV}$ and $V_o = +V$ (high)

Discussion:

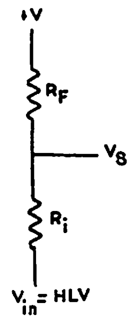

Figure 5.4 Equivalent Circuit for Comparator in Case 2.

The equivalent circuit in this case is shown in Figure 5.4. The current through the circuit is equal to the voltage drop over the resistance. Therefore:

$$I = \frac{V-H_{LV}}{R_i+R_f}$$

Since the switch from high to low is caused by the relation $V_s<V_r$, and

$$V_s = H_{LV} + I*R_i \quad \text{implies}$$

$$V_s = H_{LV} + (V-H_{LV}) * \frac{R_i}{(R_i+R_f)} \quad ,$$

then when

$$H_{LV} + (V-H_{LV}) * \frac{R_i}{(R_i+R_f)} < V_r,$$

a switch from high to low occurs.
Reference [2] includes a good treatment on the derivation of such voltages.

The circuit variables are:

H_{LV}
The choice of these hysteresis values depends on the input signal
H_{HV}

R_i chosen based on the relations derived above

R_f based on the input impedance desired. Since a high input impedance is desired, R_f is assigned a large value...typically 1 MegaOhm (1000K Ohm)

V_r chosen based on the relations derived above and is set with the input potentiometer as shown in Figure 5.2

Consider the equality of the voltages V_s and V_r. Then the relations above may be equated, giving

$$\frac{H_{HV} * R_f}{(R_i+R_f)} = H_{LV} + \frac{(V-H_{LV}) * R_i}{(R_i+R_f)}$$

Solving for R_i,

$R_i = R_f*(H_{HV} - H_{LV})/V$ where R_f = 1M Ohm.

Now V_r may be solved by substitution of R_i.

The values for R_i and V_r obtained above may be used only if the assumption holds that none of the voltage or resistive values change by any amount. This is a faulty assumption in any practical circuit analysis. Consider now Figure 5.5. This is an abstract graph of the two relations derived in the two switching cases. The shaded areas delineate the allowable values for R_i and V_r for each relation as shown in the Figure key. The point of intersection shown has the values for R_i and V_r derived above by equating the relations. The intersection of the shaded areas shows the range of values for R_i and V_r which will force the proper switching behavior. Values for these two variables should be chosen in this area and then SUBSTITUTED BACK into the orignal relations to make sure that the values for H_{HV} and H_{LV} have not significantly changed. If this is the case, new values must be chosen within the shaded intersection and the process repeated.

Comparator Circuit Variables in Use:

For the first set of (position) comparators:
H_{HV} = 4 Volts
H_{LV} = 1 Volts
R_i = 220K Ohms
V_r = 3.3 Volts

For the second set of (position) comparators:

H_{HV} = 13.7 Volts
H_{LV} = 1.4 Volts
R_i = 820K Ohms
V_r = 7.5 Volts

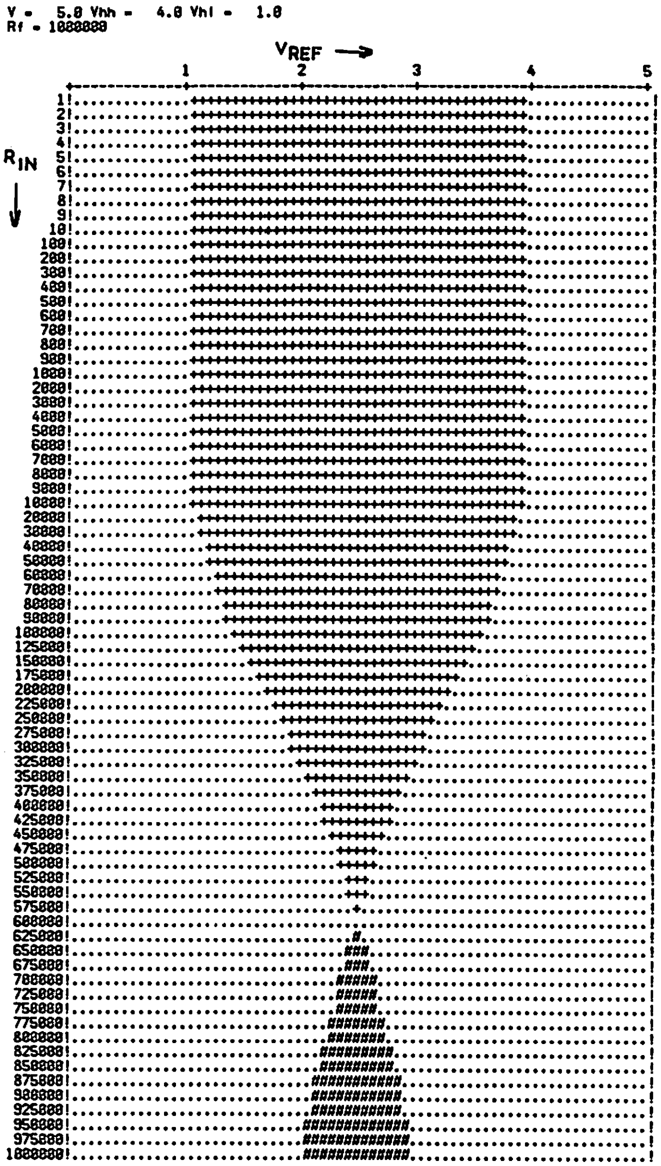

Figure 5.5 Abstract Graph of V_r versus R_i in Comparator Circuit.

Figure 5.6 is the pin configuration of the LM339 Voltage Comparator Chip. Figure 5.7 shows the actual PC board diagram of the position comparator. Note that the pull-up resistors for the first set of comparator boards (mounted on the motors) are actually found on the second set of boards. This configuration was chosen with noise prevention in mind. These figures will be beneficial if any trouble shooting is necessary as will be discussed in Appendix A5. Table 1 is a Wire list of the first set of comparator boards.

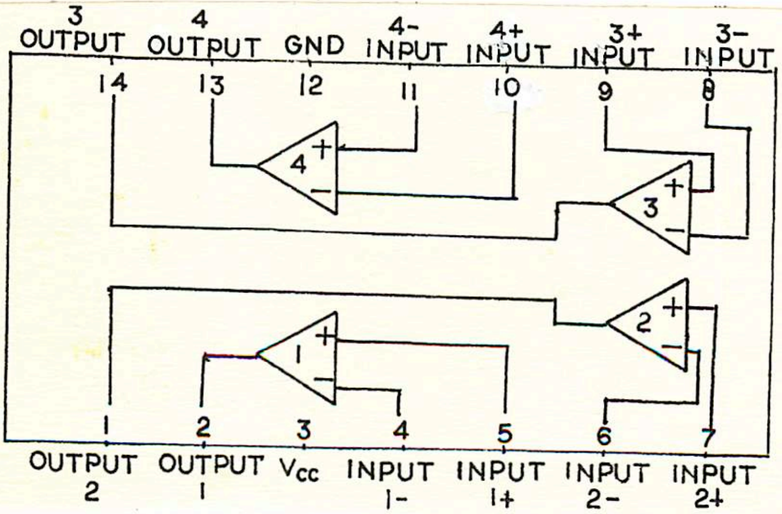

Figure 5.6 Pin Configuration for LM339 Voltage Comparator Chip.

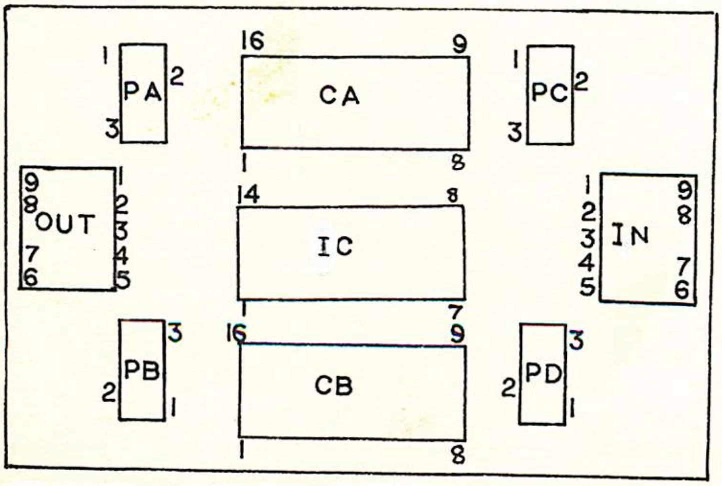

Figure 5.7 Layout of Position Comparator Board. Note that PC, PD, and OUT are found only on the first set of comparator boards.

Table 1

Location	Description
IN5-CB8	GND
CB7-CB8	GND
CB7-CB10	GND
CB10-CB9	GND
CB9-CB8	GND
OUT5-CB	GND
CA3-IC12	GND
IC12-CB10	GND
PA3-CA13	GND
PB3-IC10	GND
PC3-CB9	GND
PD3-CB9	GND
CB11-CB7	GND
IN4-CA2	5 VOLTS
CA2-CA1	5 VOLTS
CA1-CA16	5 VOLTS
CA16-CA15	5 VOLTS
CA15-CA14	5 VOLTS
OUT4-CA2	5 VOLTS
PA1-CA1	5 VOLTS
PB1-CA14	5 VOLTS
PC1-CA15	5 VOLTS
PD1-CA15	5 VOLTS
OUT1-IC3	15 VOLTS
IC3-CB12	15 VOLTS
CA14-CA3	Yellow LED: +5 Power Indicator
CA3-CA4	Connection
CA4-CA13	470 Ohm LED dropping resistor
CB12-CB5	Red LED: +15 Power Indicator
CB5-CB6	Connection
CB6-CB11	470 Ohm LED dropping resistor

(Table 1 continued)

Location	Description
IN1-CA9	Channel 3 input: from encoder
CA9-CA8	Channel 3 input resistor
CA8-IC9	Channel 3 input connection
IN2-CB4	Channel 2 input: from encoder
CB4-CB13	Channel 2 input resistor
CB13-IC7	Channel 2 input connection
IN6-CB3	Channel 4 input
CB3-CB14	Channel 4 input resistor
IN7-CA10	Channel 1 input
CA10-CA7	Channel 1 input resistor
CA12-CA8	Channel 3 feedback connection
CA5-CA12	Channel 3 feedback resistor
CA5-IC14	Channel 3 feedback connection
IC14-OUT2	Channel 3 output
CB1-IC7	Channel 2 feedback connection
CB16-CB1	Channel 2 feedback resistor
IC1-CB16	Channel 2 feedback connection
IC1-OUT3	Channel 2 output
CB2-CB15	Channel 4 feedback resistor
CA11-CA6	Channel 1 feedback resistor
IC13-OUT7	Channel 4 output
IC2-OUT6	Channel 1 output
PA2-IC8	Channel 3 reference voltage
PB2-IC6	Channel 2 reference voltage
PC2-IC11	Channel 4 reference voltage
PD2-IC4	Channel 1 reference voltage

Table 2 is the wire list for the second set of comparator boards. (refer also to Figure 5.7).

Table 2

Location	Description
CA16-CA15	GND
CA16-CA1	GND
CA1-CA2	GND
CA1-IC12	GND,IC Ground
CA15-GND line	GND
CA16-PA3	GND
CA16-PB3	GND
CB7-CB8	15 Volts
CB7-CB9	15 Volts
CB9-CB10	15 Volts
IC3-CB8	15 Volts,IC Power
CA4-CB12	15 Volts
CA4-PA1	15 Volts
CB7-PB1	15 Volts
CA14-CA3	1K-Ohm Pullup Resistor (to 5 Volts) for Channel 3 Output (ENC A)
CB11-CB6	1K-Ohm Pullup Resistor (to 5 Volts) for Channel 2 Output (ENC B)
CA13-CA4	1K-Ohm Pullup Resistor (to 15 Volts) for input A (output of first comparator)
CB12-CB5	1K-Ohm Pullup Resistor (to 15 Volts) for input B (output of first comparator)
CA9-IN9	Channel 3 input (from first comparator)
CA9-CA8	Channel 3 input resistor
CA8-IC9	Channel 3 input connection

(Table 2 continued)

Location	Description
IN2-CB4	Channel 2 input (from first comparator)
CB4-CB13	Channel 2 input resistor
CB13-IC7	Channel 2 input connection
IN6-CB3	Channel 4 input connection
CA12-CA8	Channel 3 feedback connection
CA5-CA12	Channel 3 feedback resistor
CA5-IC14	Channel 3 feedback connection
CB1-IC7	Channel 2 feedback connection
CB16-CB1	Channel 2 feedback resistor
IC1-CB16	Channel 2 feedback connection
PA2-IC8	Channel 3 reference voltage
PB2-IC6	Channel 2 reference voltage

Inter-comparator Connections (refer also to Figure 5.8)

Location	Description
CB,θ19 - 15 Volt Supply Line	15 Volts
CB,Z10 - CB,θ8	15 Volts
IC,Y3 - CB,Z8	15 Volts
IC,X3 - CB,Y9	15 Volts
EX,X5 - CA,T3	5 Volts
EX,X4 - CB,T11	5 Volts
EX,X3 - CA,Z3	5 Volts
EX,X12 - CB,Z11	5 Volts
EX,X11 - CA,Y3	5 Volts
EX,X10 - CB,Y11	5 Volts
EX,X9 - CA,X3	5 Volts
EX,X8 - CB,X11	5 Volts
IC14 - D3	ENC A (for all 4 axes)
CB6 - D4	ENC B (for all 4 axes)

Appendix A3. Counter Theory and Logic

As was described in Section 3.A.5, the counter circuit for each axis consists of two parts. These are the actual binary up/down counters, and the direction determination circuit. Figure 5.8 is a block layout of the counter circuit as it appears on the board. (Recall that there are four such circuits on the currently used four-axis board as indicated in Figure 3.7).

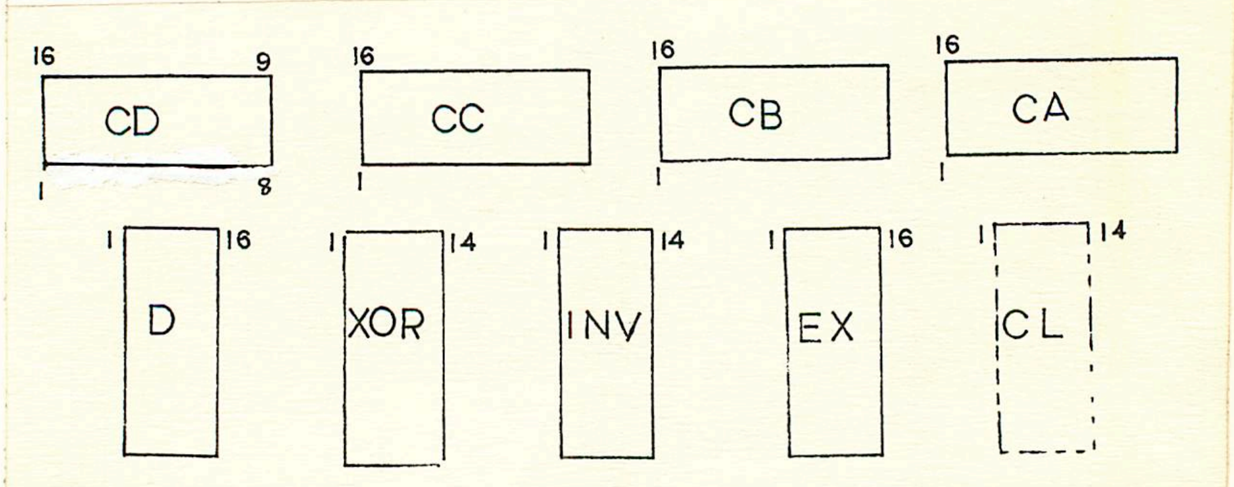

Figure 5.8 Layout of General Counter Circuit
CL is found only on the z axis counter.

Counting Logic

The counter circuit described in Section 3.A.5 is a 16-bit synchronous up/down counter which uses four 74LS191 4-bit binary up/down counters. The pin configuration for the 191 is given in Figure 5.9, and the counter circuit is given in Figure 5.10. The main components of the 191 are the four master-slave flip-flops (see [22]). The outputs, pins 3,2,6, and 7, of these flip-flops (which compose the count) are triggered on a low-to-high transisition of the clock input square wave on pin 14. This clock is also a part of the board and is described later in this appendix. The clock frequency is approximately .08 M Hertz which is sufficiently fast to trigger all change of states of the 191's and the 174's in the other part of the circuit which also use the clock input.

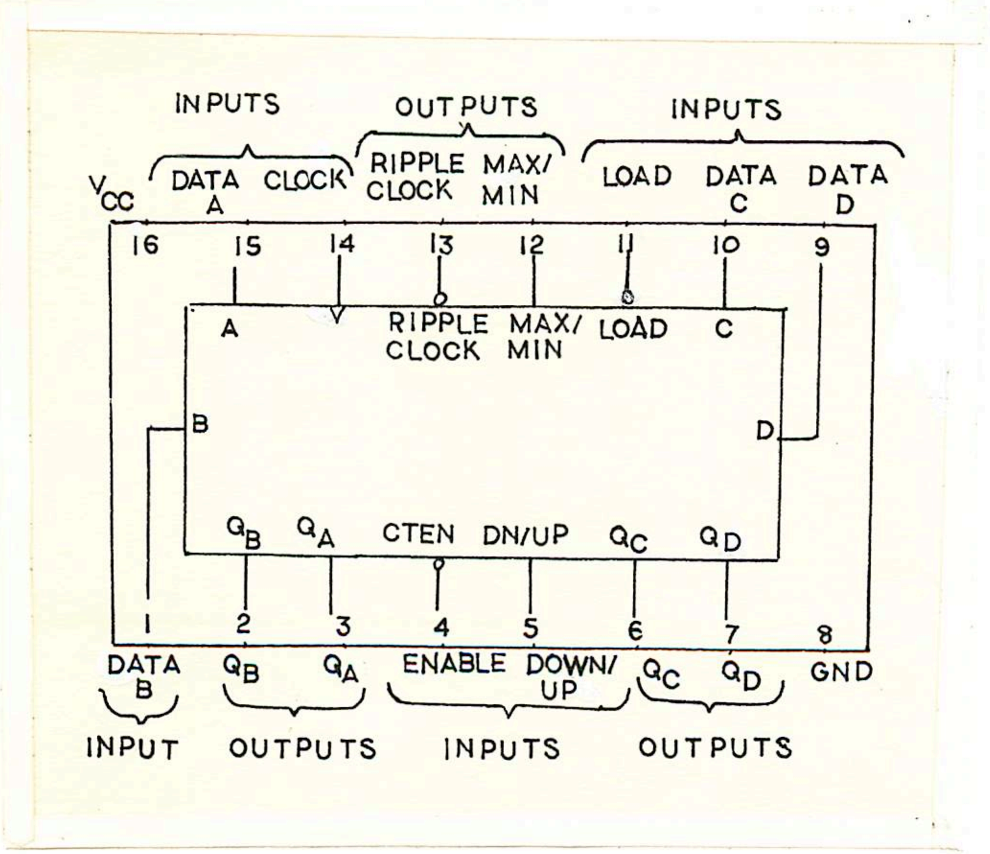

Figure 5.9 Pin Configuration of 74LS191 4-bit Binary Counter Chip.

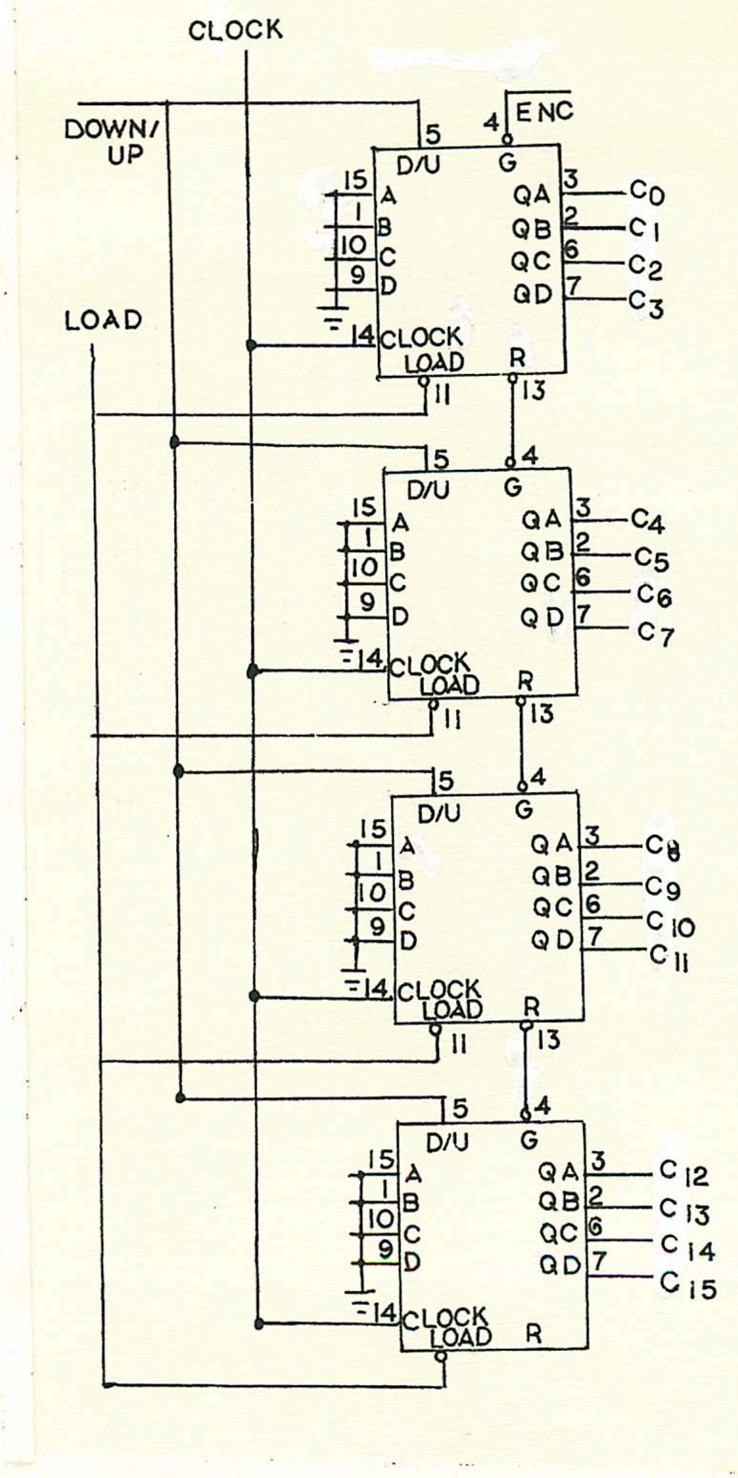

Figure 5.10 16-Bit Binary Up/Down Counter Circuit.

The counters have a load feature which is used in this application as a clearing function. When pin 11, the load pin, is held high, the output is the current count. When the load pin is held low, the values on the input pins, pins 15, 1, 10, and 9, are sent to the outputs. Thus all inputs have been grounded so that when the load line is sent a low value from the DRV11, the counter is cleared. In other words, all outputs drop to low. This is a useful feature in a "home-finding" routine implemented on the manipulator: the axis is slowly moved to one end of its range (the "home" end). When the end is reached (this is determined by the limit sensors of Section 3.A.7 or is detected by sampling the count of the particular axis until it does not change for a certain amount of time), a low value is sent out to pin 11 via the DRV11 and the count is cleared, thus creating a "fresh-start" situation on the counter at the home location of the axis.

Note that all clock inputs are tied together. For this reason, the counter is a synchronous one which implies that all changes of state occur simultaneously rather than in a rippling manner. (Ripple or asynchronous counters can be built where the output of one flip-flop is the clock input of the next, but because of this property the speed of these counters is too limited for a high-speed mechanism such as this manipulator. See [10,22] for a thorough explanation of these characteristics).

The direction of the count is determined by pin 5 of the 191, the Down/Up pin. When this pin is low, the counter counts up. When it is high, the counter counts down. The value given to these pins (the fifth pins on the four 191's are all tied together) is a result of the three chips used in the direction determination part of the circuit described below.

Another input of the 191 is the enable pin (pin 4). When this pin is low, the counter counts as described. A high value on this pin inhibits all counting. The enable input of the first 191 is an output of the other circuitry to be described in the following paragraphs and is basically held low when either of the encoder waves changes state. (This should make sense since it is the edges of these waves that are being counted). The input to this pin is marked ENC in Figure 5.10. The enable pins on the remaining three 191's (which produce the higher order bits of the count) are connected to pin 13 of the preceding 191. This pin is called the ripple/clock of the chip. It can be thought of as the "carry bit" of the counter and is held low (thus enabling a count on the otherwise inhibited succeeding counter) when either an overflow (which occurs when the counter is counting up) or an underflow (during a "count down") condition exists.

Direction Logic

A 74LS174 (a Hex D-type flip-flop), a 74LS86 (a quadruple 2-input exclusive or), and a 74LS04 (a hex 2-input inverter) make up the circuitry of the logic which precedes the counter and provides the ENC signal mentioned above and the Down/Up signal also described which determines the direction of the count. Figure 5.11 shows the pin configurations of these three IC chips. The inputs to this part of the circuitry are the two square waves which are the outputs of the second set of comparators and are symbolized as ENC A and ENC B in Figure 5.12 which shows the interconnections of the circuit. The two outputs are marked DOWN/UP (which goes to the down/up pin described above) and ENC (which goes to the enable described above).

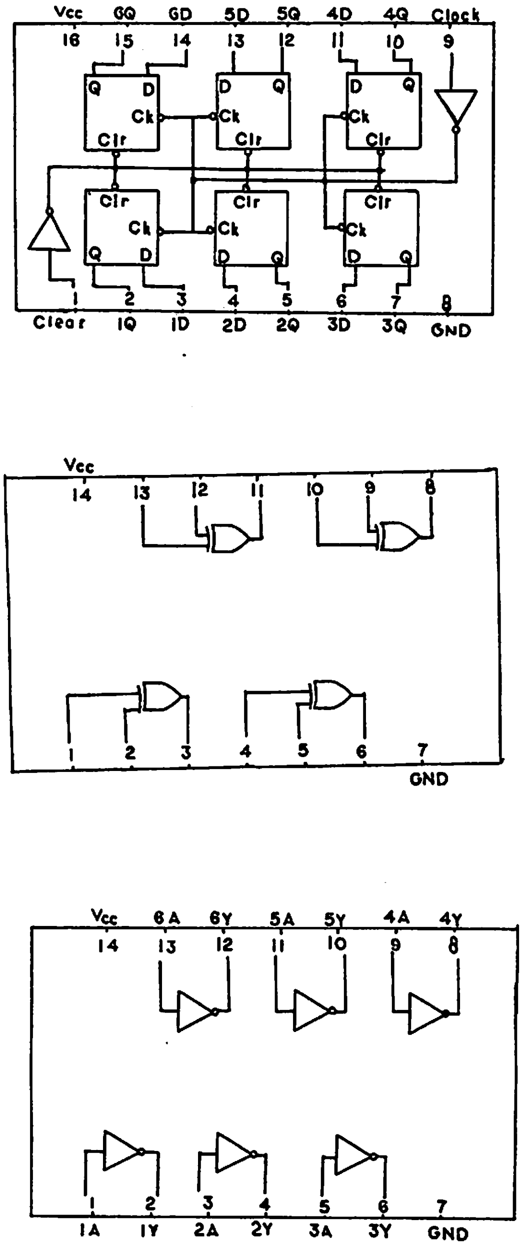

Figure 5.11 Pin Configurations of LS174, LS86 and LS04 IC chips.

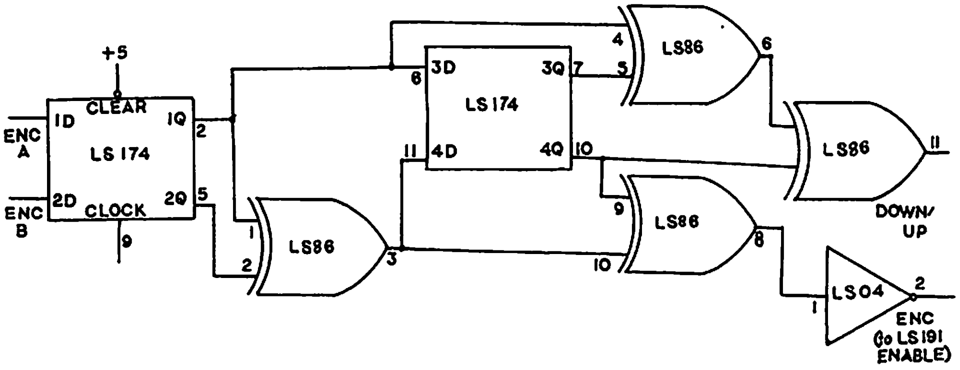

Figure 5.12 Direction Logic Circuit Preceding Counter Circuit.

The D-type flip-flop records the state of its input on a low-to-high transistion of the clock. Because of the logic configuration of these flip-flops and the exclusive-OR's (86's), the ENC output line goes low for just one clock pulse only when a new change of state of the input occurs. Since this line (ENC) is attached to the enable pin of the first of the counter chips (191's) this is the desired behavior. When either of the two inputs (Enc A or Enc B) changes state (goes low or goes high), the counter must record this action and so must be enabled. However, if it is enabled for more than one clock pulse, it will register more than one count thus creating a false count.

The circuitry also outputs the Down/Up signal for the counters. The single count enabled for the "one clock pulse wide" ENC signal is added to the current count if the down/up pin is low (i.e. the counter is counting up) and is subtracted from the current count if the DOWN/UP output to the down/up pin is high (i.e. the counter is counting down). Figure 5.13 is a truth table, over time, of the signals at each of the various connections of this part of the circuit. The signal points are labelled in Figure 5.12. The input waves used in constructing the truth table are also shown in Figure 5.13 and an example change of direction is incorporated in them. Note that the DOWN/UP output oscillates and might seem to indicate a corresponding oscillating count. However, recall that this signal is useless unless the counter is enabled by the ENC signal and at the times when this signal is low, the DOWN/UP output is indeed at the right logic level depending on the phase difference of the two waves as was discussed in section 3.A.5.

enc A (1D)	enc B (2D)	1Q (3D)	2Q 86-2	86-3 (4D)	3Q 86-5	4Q 86-10	86-6 86-12	enc 86-8	Down/Up 86-11	Clock
0	0	0	0	0	0	0	0	0	0	^
0	0	0	0	0	0	0	0	0	0	H
1	0	0	0	0	0	0	0	0	0	L
1	0	1	0	0	0	0	0	0	0	^
1	0	1	0	1	0	0	1	1	1	H
1	0	1	0	1	0	0	1	1	1	L
1	0	1	0	1	1	1	1	1	1	^
1	0	1	0	1	1	1	0	0	1	H
1	0	1	0	1	1	1	0	0	1	L
1	1	1	0	1	1	1	0	0	1	L
1	1	1	1	1	1	1	0	0	1	^
1	1	1	1	0	1	1	0	0	1	H
1	1	1	1	0	1	1	0	1	1	L
1	1	1	1	0	1	0	0	1	1	^
1	1	1	1	0	1	0	0	1	1	H
1	1	1	1	0	1	0	0	0	0	L
0	1	1	1	0	1	0	0	0	0	L
0	1	0	1	0	1	0	0	0	0	^
0	1	0	1	1	1	0	0	0	0	H
0	1	0	1	1	1	0	1	1	1	L
0	1	0	1	1	0	1	1	1	1	^
0	1	0	1	1	0	1	0	1	1	H
0	1	0	1	1	0	1	0	0	1	L
0	0	0	1	1	0	1	0	0	1	L
0	0	0	0	1	0	1	0	0	1	^
0	0	0	0	0	0	1	0	1	1	H
0	0	0	0	0	0	1	0	1	1	L
0	0	0	0	0	0	0	0	1	1	^
0	0	0	0	0	0	0	0	0	1	H
0	0	0	0	0	0	0	0	0	0	L
1	0	0	0	0	0	0	0	0	0	L
1	0	1	0	0	0	0	0	0	0	^
1	0	1	0	1	0	0	0	0	0	H
1	0	1	0	1	0	0	1	1	1	L
1	0	1	0	1	1	1	1	1	1	^
1	0	1	0	1	1	1	0	0	1	H
1	0	1	0	1	1	1	0	0	1	L
1	1	1	0	1	1	1	0	0	1	L
1	1	1	1	1	1	1	0	0	1	^
1	1	1	1	0	1	1	0	0	1	H
1	1	1	1	0	1	1	0	1	1	L
1	1	1	1	0	1	0	0	1	1	^
1	1	1	1	0	1	0	0	0	1	H
1	1	1	1	0	1	0	0	0	0	L
0	1	1	1	0	1	0	0	0	0	L
0	1	0	1	0	1	0	0	0	0	^
0	1	0	1	1	1	0	0	0	0	H
0	1	0	1	1	1	0	1	1	1	L
0	1	0	1	1	0	1	1	1	1	^
0	1	0	1	1	0	1	1	1	1	H
0	1	0	1	1	0	1	0	0	1	L

Figure 5.13 Signal Values Over Time of Counter Direction/Enable Circuit. Note that " ^ " in the "Clock" column signifies a rising edge.

enc A (1D)	enc B (2D)	1Q (3D)	2Q 86-2	86-3 (4D)	3Q 86-5	4Q 86-10	86-6 86-12	enc 86-8	Down/Up 86-11	Clock
0	0	0	1	1	0	1	0	0	1	L
0	0	0	0	1	0	1	0	0	1	^
0	0	0	0	0	0	1	0	0	1	H
0	0	0	0	0	0	1	0	1	1	L
0	0	0	0	0	0	0	0	1	1	^
0	0	0	0	0	0	0	0	0	1	H
0	0	0	0	0	0	0	0	0	0	L
0	1	0	0	0	0	0	0	0	0	L
0	1	0	1	0	0	0	0	0	0	^
0	1	0	1	1	0	0	0	0	0	H
0	1	0	1	1	0	0	0	1	0	L
0	1	0	1	1	0	1	0	1	0	^
0	1	0	1	1	0	1	0	0	0	H
0	1	0	1	1	0	1	0	0	1	L
1	1	0	1	1	0	1	0	0	1	L
1	1	1	1	1	0	1	0	0	1	^
1	1	1	1	0	0	1	1	0	1	H
1	1	1	1	0	0	1	1	1	0	L
1	1	1	1	0	1	0	1	1	0	^
1	1	1	1	0	1	0	1	0	1	H
1	1	1	1	0	1	0	1	0	1	L
1	0	1	1	0	1	0	1	0	1	L
1	0	1	0	0	1	0	1	0	1	^
1	0	1	0	1	1	0	1	0	1	H
1	0	1	0	1	1	0	0	1	0	L
1	0	1	0	1	1	1	0	1	0	^
1	0	1	0	1	1	1	0	0	0	H
1	0	1	0	1	1	1	0	0	1	L
0	0	1	0	1	1	1	0	0	1	L
0	0	0	0	1	1	1	0	0	1	^
0	0	0	0	0	1	1	0	0	1	H
0	0	0	0	0	1	1	1	1	0	L
0	0	0	0	0	0	0	1	1	0	^
0	0	0	0	0	0	0	0	0	0	H
0	0	0	0	0	0	0	0	0	0	L
0	1	0	0	0	0	0	0	0	0	L
0	1	0	1	0	0	0	0	0	0	^
0	1	0	1	1	0	0	0	0	0	H
0	1	0	1	1	0	0	0	1	0	L
0	1	0	1	1	0	1	0	1	0	^
0	1	0	1	1	0	1	0	1	0	H
0	1	0	1	1	0	1	0	0	1	L
1	1	0	1	1	0	1	0	0	1	L
1	1	1	1	1	0	1	0	0	1	^
1	1	1	1	0	0	1	1	0	1	H
1	1	1	1	0	0	1	1	1	0	L
1	1	1	1	0	1	0	1	1	0	^

(Figure 5.13 continued)

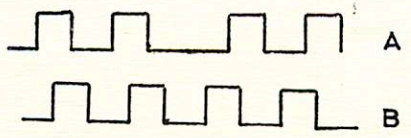

Table 1 gives the wire connections of the general counter (for each axis) and the extra components (including the clock described below) found at each counter location on the board. Refer to Figure 5.8 which shows the labelled sockets and chips for this table.

Table 1

General Counter

Location	Description
CA16-CB16	5 Volts
CB16-CC16	5 Volts
CC16-CD16	5 Volts
CD16-D16	5 Volts
D16-XOR14	5 Volts
XOR14-INV14	5 Volts
INV14-EX14	5 Volts
CA8-CB8	GND
CB8-CC8	GND
CC8-CD8	GND
EX7-INV7	GND
INV7-XOR7	GND
XOR7-D8	GND
CC8-GND LINE	GND
INV7-GND LINE	GND
XOR7-GND LINE	GND

For CA,CB,CC, & CD:

Location	Description
C8-C9	Input tied to ground
C9-C10	Input tied to ground
C10-C15	Input tied to ground
C15-C1	Input tied to ground
CA13-CB4	Connection
CB13-CC4	Connection
CC13-CD4	Connection
CA14-CB14	Connection
CB14-CC14	Connection
CC14-CD14	Connection
CD14-D9	Connection
CA11-CB11	Connection
CB11-CC11	Connection
CC11-CD11	Connection

(Table 1 Continued)

D1-D16	Clear (held high)
D2-D6	Connection
D6-XOR1	Connection
XOR1-XOR4	Connection
D5-XOR2	Connection
D11-XOR3	Connection
XOR3-XOR10	Connection
D7-XOR5	Connection
D10-XOR9	Connection
XOR9-XOR13	Connection
XOR6-XOR12	Connection
XOR8-INV1	Connection
INV2-CA4	Connection

EX (Extra Component Socket) Connections

EX,X (Power (5 V) Distributor)

EX1...6, 8...12	All connected: +5 power pins
EX14	NC
INV7-EX7	GND Connection
INV14-EX1	Power (+5) Connection
EX,X11-EX,Y9	Power (+5) Connection

EX,Y (Ground Distributor)

EX8...EX14	All connected: Ground
INV14-EX14	Power (+5) Connection
INV7-EX7	Ground Connection
EX,Y9-EX,X11	Power (+5) Connection
EX7-CA,X8	Ground Connection for CA,X8
EX7-EX6	Extra Ground Connection
EX6-EX5	Extra Ground Connection
EX5-EX4	Extra Ground Connection
EX4-EX3	Extra Ground Connection
EX8	red wire of twisted pair for external power source (+5 volts)

(Table 1 Continued)

EX,Z and CL (Clock Circuit)
(note EX,Z is 7706 clock chip carrier)

Location	Description
INV,Y14-EX14	Power Connection (+5)
EX,Z14-EX,Y13	Power Connection (+5)
D,Z8-EX7	Ground Connection
INV14-EX7	Ground Connection
INV,Z3-EX10	Clock Signal Inversion Input
INV,Z4-EX,013	Clock Signal Inversion Output
EX4-EX8	Connection
EX8-EX9	Connection
EX8-CL6	Connection
CL6-CL11	100 pFarad Capacitor
CL11-CL12	Connection
CL12-CL5	100 pFarad Capacitor
CL5-EX1	Connection
EX1-EX2	Connection
EX3-EX6	Connection
EX5-EX6	Connection
EX6-CL1	Connection
CL2-CL15	1.5K Resistor
CL15-CL16	Connection
CL16-CL1	1K Resistor
CL2-EX2	Connection

EX,0 (Clock Signal Distribution)

EX13-INV,Z4	Clock Signal Inversion Connection
EX7-INV,07	Connection
EX14-INV,014	Connection
EX,014-EX,Y13	Connection
EX8-D,X8	Clock Signal Connection
EX9-D,Y8	Clock Signal Connection
EX10-D,Z8	Clock Signal Connection
EX11-D,08	Clock Signal Connection

The Clock

The clock input to the circuits mentioned above is produced by an oscillator circuit using an MC14011 7706 quad NAND chip. The pin configuration of the chip is shown in Figure 5.14. The actual clock circuit with the component values appears in Figure 5.15. In the previous table (Table 1) the layout of the clock circuit (as it appears on the counter board) is detailed and is found on components EX,Z and CL. The frequency of the clock is .08MHZ.

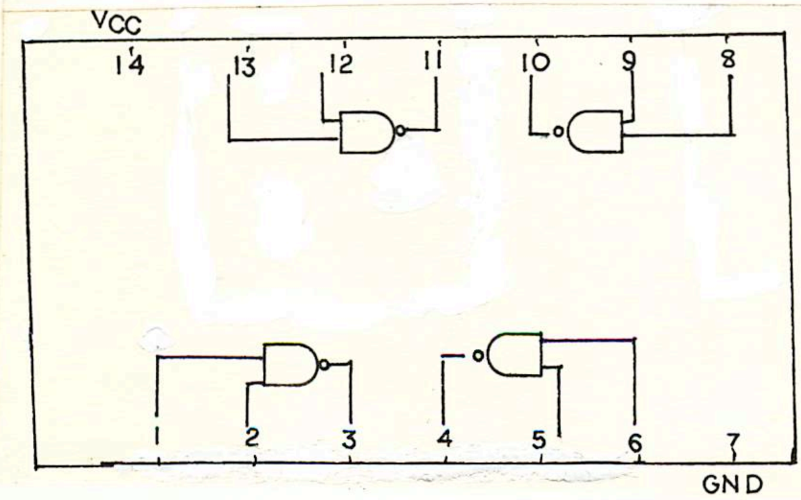

Figure 5.14 Pin Configuration of MC14011 Quad NAND Chip.

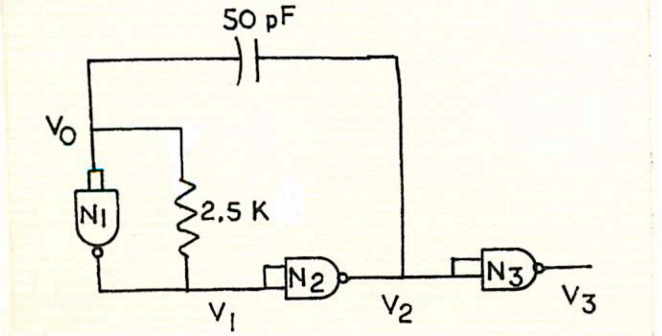

Figure 5.15 Clock Circuit.

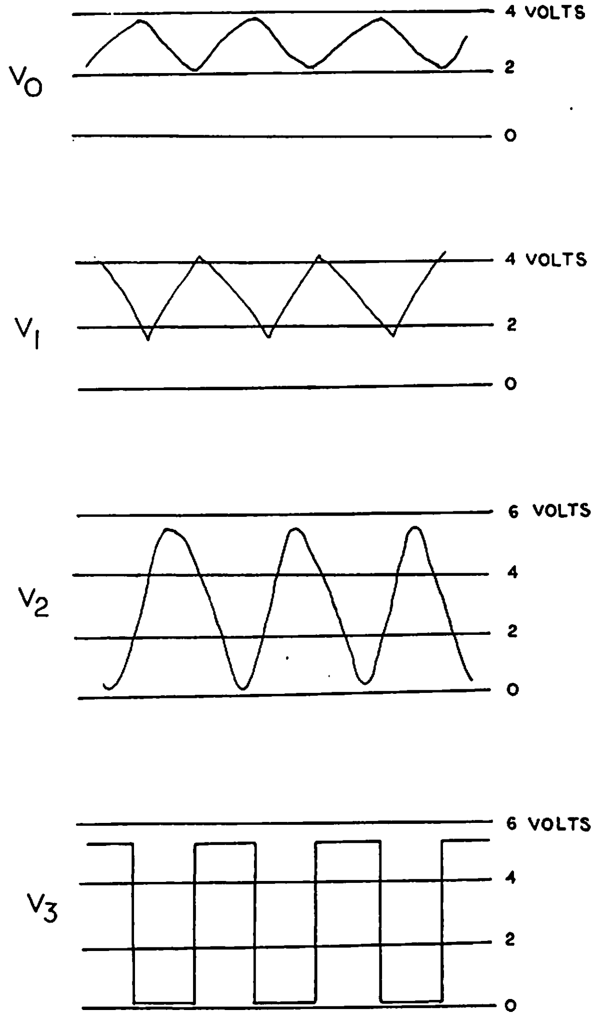

Figure 5.16 Clock Circuit Wave Forms

Consider Figure 5.15 with labelled points and Figure 5.16 which depicts the voltage waveforms as they appear at these points. Note that a NAND with inputs tied together acts as an inverter and that the third NAND gate (N3) acts to square the output of NAND gate two (N2) so that the clock output has distinct edges. N3 has no bearing on the output frequency. The voltage range of a NAND is from ground to the supply voltage (in this case the supply voltage is 5.65 volts). However, due to the 2.5K-Ohm resistor, NAND gate N1 is forced to "sit" at one or the other of its switching threshold voltages (approximately 2 and 4 volts for low-to-high and high-to-low respectively). This is evident from the inspection of voltages V0 and V1. This behavior is needed so that "small" changes in the input voltage (due to capacitance action) are amplified and passed on to N2.

The internal output resistance of gate N2 and the capacitor form a resistive-capacitive (RC) circuit and the time constant RC determines the frequency of oscillation. Table 2 gives several capacitor values (including the 50 picoFarad capacitor used in the actual clock circuit), the resulting oscillation time and the associated frequency. See [20], chapter 15 for a thorough description of such timing circuits.

Table 2

Cap Value	1 Cycle Time	Frequency
50 pFarad	12 uSec	.08 M-Hertz
76 pFarad	30 uSec	.033 M-Hertz
92 pFarad	40 uSec	.025 M-Hertz

NOTE: the MC14011 is a CMOS chip so it cannot drive a large load. For this reason, the output of the clock is passed through a 7404 TTL inverter which can drive several load lines. The output of this inverter is distributed (see the previous table) to the various IC chips in the counter circuit that use the clock.

Appendix A4. Multiplexer Board Circuit

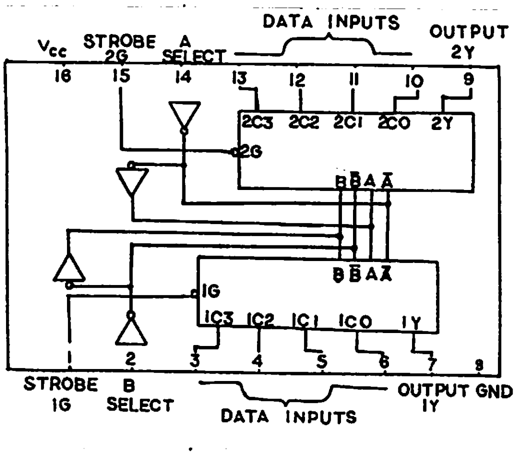

Figure 5.17 Pin Configuration for the 74LS153

Figure 5.17 shows the pin configuration for a 74LS153 dual 4-line to 1-line Data Selector/Multiplexer. The chip is given two sets of four inputs. The first set of inputs is connected to pins 6,5,4, and 3. The second set is connected to pins 10,11,12, and 13. The outputs (pins 7 and 9) are selected via a two bit binary address which is passed to pins 2 and 14 of the chip from the two Control Status Registers of the DRV11. Each output is actually one of the corresponding inputs. Suppose the binary address 10 is passed to the chip. In other words pin 2 is sent a one and pin 14 is sent a zero. Then the output on pin 7 is whatever value pin 4 has and the output on pin 9 is whatever value is on pin 12 (in other words whatever value input number 2 of each set has). The following is a table of the address selections:

Address Select Inputs			Data Inputs			Output
B	A	C0	C1	C2	C3	Y
0	0	0	x	x	x	0
0	0	1	x	x	x	1
0	1	x	0	x	x	0
0	1	x	1	x	x	1
1	0	x	x	0	x	0
1	0	x	x	1	x	1
1	1	x	x	x	0	0
1	1	x	x	x	1	1

This particular data selector was chosen from those available because there are four counters and each selector is capable of handling two sets of four inputs. Recall also that each counter circuit outputs sixteen bits. Therefore eight 74LS153's will supply the necessary selection capability. Two bits from each counter are sent to each of the data selectors as is depicted in Figure 5.18. Table 1 depicts the wire connections based on this figure (and also Figure 5.8).

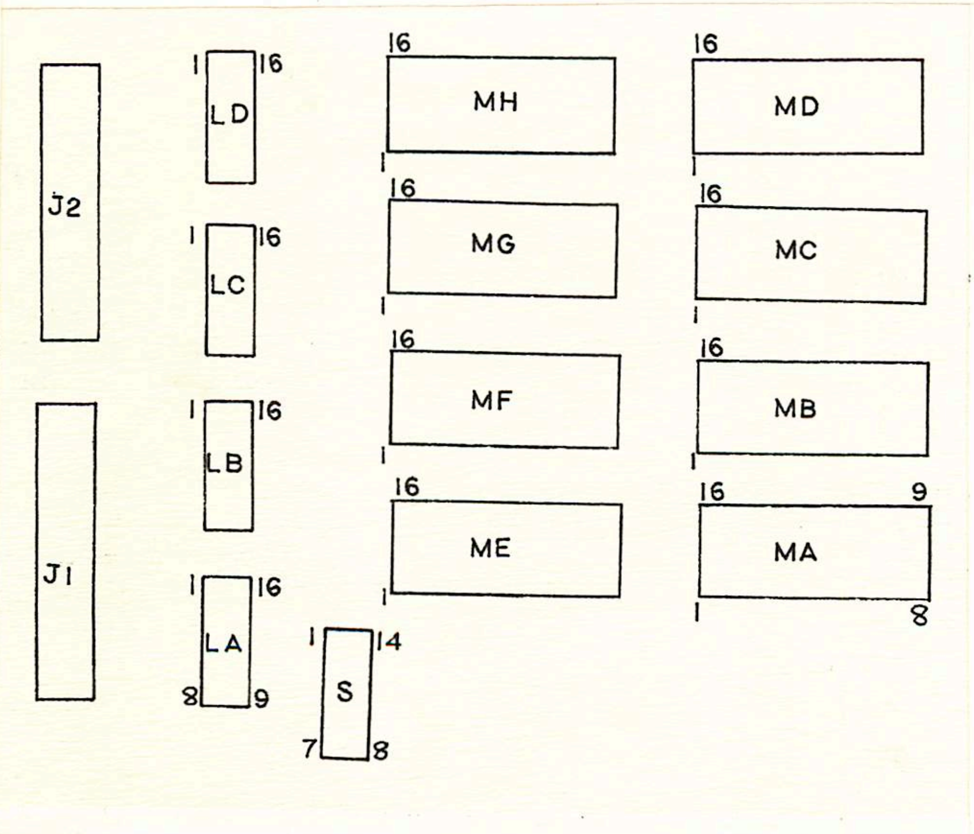

Figure 5.18 Portion of Board Depicting Multiplexers and Pin Connections.

Table 1

GENERAL COUNTER TO MULTIPLEXER CONNECTIONS:

Location	Location	Location	Location
MA6-CA,X3	MC6-CB,X3	ME6-CC,X3	MG6-CD,X3
MA5-CA,Y3	MC5-CB,Y3	ME5-CC,Y3	MG5-CD,Y3
MA4-CA,Z3	MC4-CB,Z3	ME4-CC,Z3	MG4-CD,Z3
MA3-CA,θ3	MC3-CB,θ3	ME3-CC,θ3	MG3-CD,θ3
MA10-CA,X2	MC10-CB,X2	ME10-CC,X2	MG10-CD,X2
MA11-CA,Y2	MC11-CB,Y2	ME11-CC,Y2	MG11-CD,Y2
MA12-CA,Z2	MC12-CB,Z2	ME12-CC,Z2	MG12-CD,Z2
MA13-CA,θ2	MC13-CB,θ2	ME13-CC,θ2	MG13-CD,θ2
MB6-CA,X6	MD6-CB,X6	MF6-CC,X6	MH6-CD,X6
MB5-CA,Y6	MD5-CB,Y6	MF5-CC,Y6	MH6-CD,Y6
MB4-CA,Z6	MD4-CB,Z6	MF4-CC,Z6	MH6-CD,Z6
MB3-CA,θ6	MD3-CB,θ6	MF4-CC,θ6	MH6-CD,θ6
MB10-CA,X7	MD10-CB,X7	MF10-CC,X7	MH10-CD,X7
MB11-CA,Y7	MD11-CB,Y7	MF11-CC,Y7	MH11-CD,Y7
MB12-CA,Z7	MD12-CB,Z7	MF12-CC,Z7	MH12-CD,Z7
MB13-CA,θ7	MD13-CB,θ7	MF13-CC,θ7	MH13-CD,θ7

Location	Description	Location	Description
MA16-MB16	5 Volts	MA2-MB2	B Select
MB16-MC16	5 Volts	MB2-MC2	B Select
MC16-MD16	5 Volts	MC2-MD2	B Select
MD16-ME16	5 Volts	MD2-ME2	B Select
ME16-MF16	5 Volts	ME2-MF2	B Select
MF16-MG16	5 Volts	MF2-MG2	B Select
MG16-MH16	5 Volts	MG2-MH2	B Select
MA8-MB8	GND	MA14-MB14	A Select
MB8-MC8	GND	MB14-MC14	A Select
MC8-MD8	GND	MC14-MD14	A Select
MD8-ME8	GND	MD14-ME14	A Select
ME8-MF8	GND	ME14-MF14	A Select
MF8-MG8	GND	MF14-MG14	A Select
MG8-MH8	GND	MG14-MH14	A Select

(Table 1 Continued)

Location	Description	Location	Description
MH1-MH15	Strobe Connect	MH15-MG1	Strobe Connect
MG1-MG15	Strobe Connect	MG15-MF1	Strobe Connect
MF1-MF15	Strobe Connect	MF15-ME1	Strobe Connect
ME1-ME15	Strobe Connect	ME15-MD1	Strobe Connect
MD1-MD15	Strobe Connect	MD15-MC1	Strobe Connect
MC1-MC15	Strobe Connect	MC15-MB1	Strobe Connect
MB1-MA15	Strobe Connect	MD15-MD8	GND for Strobes
MA8-GND Line	GND	MC8-GND Line	GND
MF8-GND Line	GND	MG8 GND Line	GND
MA7-LA10	Connection	MA9-LA12	Connection
MB7-LA14	Connection	MB9-LA16	Connection
MC7-LB10	Connection	MC9-LB12	Connection
MD7-LB14	Connection	MD9-LB16	Connection
ME7-LC10	Connection	ME9-LC12	Connection
MF7-LC14	Connection	MF9-LC16	Connection
MG7-LD10	Connection	MG9-LD12	Connection
MH7-LD14	Connection	MH9-LD16	Connection
LA9-J2TT	Count Bit 0	LA8-LA7	Connection
LA11-J2LL	Count Bit 1	LA6-LA5	Connection
LA13-J2H	Count Bit 2	LA4-LA3	Connection
LA15-J2BB	Count Bit 3	LA2-LA1	Connection
LB9-J2KK	Count Bit 4	LB8-LB7	Connection
LB11-J2HH	Count Bit 5	LB6-LB5	Connection
LB13-J2EE	Count Bit 6	LB4-LB3	Connection
LB15-J2CC	Count Bit 7	LB2-LB1	Connection
LC9-J2Z	Count Bit 8	LC8-LC7	Connection
LC11-J2Y	Count Bit 9	LC6-LC5	Connection
LC13-J2W	Count Bit 10	LC4-LC3	Connection
LC15-J2V	Count Bit 11	LC2-LC1	Connection
LD9-J2U	Count Bit 12	LD8-LD7	Connection
LD11-J2P	Count Bit 13	LD6-LD5	Connection
LD13-J2N	Count Bit 14	LD4-LD3	Connection
LD15-J2C	Count Bit 15	LD2-LD1	Connection

(Table 1 Continued)

Location	Description	Location	Description
LA9-LA8	LED	LA7-LA10	470-Ohm LED Drop Resis
LA6-LA11	LED	LA5-LA12	470-Ohm LED Drop Resis
LA4-LA13	LED	LA3-LA14	470-Ohm LED Drop Resis
LA2-LA15	LED	LA1-LA16	470-Ohm LED Drop Resis
LB9-LB8	LED	LB7-LB10	470-Ohm LED Drop Resis
LB6-LB11	LED	LB5-LB12	470-Ohm LED Drop Resis
LB4-LB13	LED	LB3-LB14	470-Ohm LED Drop Resis
LB2-LB15	LED	LB1-LB16	470-Ohm LED Drop Resis
LC9-LC8	LED	LC7-LC10	470-Ohm LED Drop Resis
LC6-LC11	LED	LC5-LC12	470-Ohm LED Drop Resis
LC4-LC13	LED	LC3-LC14	470-Ohm LED Drop Resis
LC2-LC15	LED	LC1-LC16	470-Ohm LED Drop Resis
LD9-LD8	LED	LD7-LD10	470-Ohm LED Drop Resis
LD6-LD11	LED	LD5-LD12	470-Ohm LED Drop Resis
LD4-LD13	LED	LD3-LD14	470-Ohm LED Drop Resis
LD2-LD15	LED	LD1-LD16	470-Ohm LED Drop Resis

Location	Description
CD,θ10-J1U	θ Counter Load Line from DRV11
CD,Z10-J1NN	z Counter Load Line from DRV11
CD,Y10-J1K	y Counter Load Line from DRV11
CD,X10-J1C	x Counter Load Line from DRV11
MF14-J2K	Low order bit of 2-bit axis selection address
MF2-J1DD	High order bit of 2-bit axis selection address
J1NN-MB8	Ground Connection for DRV11
J1U-S5	Connection for x axis load line
J1K-S2	Connection for y axis load line
J1C-S1	Connection for z axis load line
J1NN-S7	Connection for θ axis load line
S11-MH8	Ground for Load Line noise filter capacitors
S14-MH16	5 Volts for Load Line Resistors

(Table 1 Continued)

Location	Description
S13-S11	Connection
S11-S9	Connection
S7-S6	Connection
S5-S4	Connection
S3-S2	Connection
S13-S11	Connection
S11-S9	Connection
S9-S8	Connection
S1-S14	Load Line Pullup Resistor
S2-S13	Load Line Pullup Resistor
S3-S12	Load Line noise filter capacitor
S4-S11	Load Line Pullup Resistor
S5-S10	Load Line noise filter capacitor
S6-S9	Load Line Pullup Resistor
S7-S8	Load Line noise filter capacitor

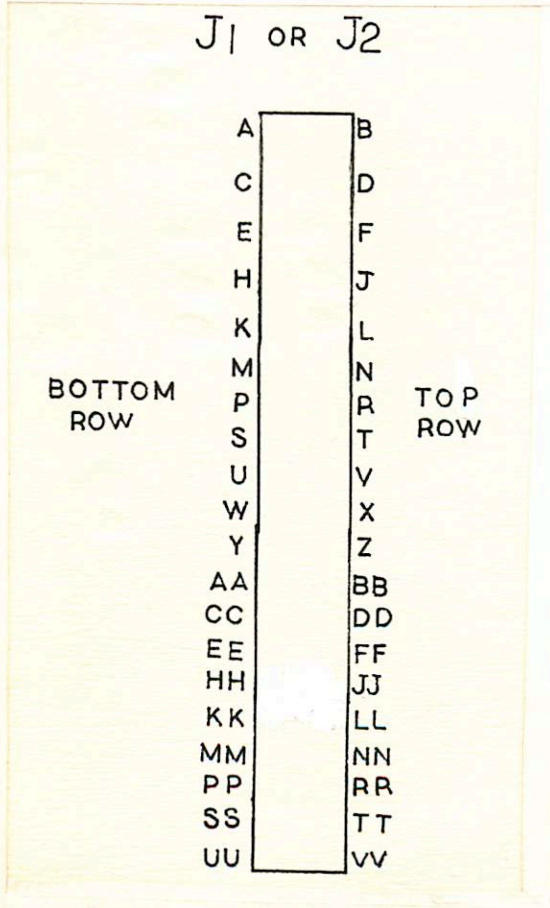

Figure 5.19 DRV11 Ribbon Connector Layout (J1 and J2)

Appendix A5. Trouble Shooting

This appendix describes symptoms of various system component failures, possible causes, and procedures for determining and correcting those causes.

Because of the complexity of the machine interfaces and the "delicate" nature of the PC boards used for these interfaces, a certain number of problems may possibly arise. For example, loss of power to one of the boards may be due to several different malfunctions. If one of the boards is not working correctly loss of power should be checked first. Most of the boards have LEDs connected to the power lines which should be lit when the board itself has power. In debugging, each power connection should be checked with the DMM (Digital Multimeter) first to determine that each IC chip is receiving power. For example, each IC chip will have a power pin (for instance the 74LS191 has a power connection on pin 8). Similarly, all ground connections should be checked.

In general, seemingly large problems are often caused by a loose wire-wrap connection which is easily replaced. Using the configurations and circuit diagrams given, possible signal failures can be traced and corrected. Broken soldered leads (for example to the potentiometer pins on the comparator borads) can cause a bad connection. Once found, the wire needs only to be restripped and resoldered. The screws on the barrier strips must be tight and should be checked when trying to trace signals through the machine.

Symptoms and Likely Causes:

Encoder Output Faulty:
- → Phototransistors burned out...must be replaced
- → Power or Ground connection to encoder is loose
- → Encoder block misaligned (See [8])

Voltage Comparator output does not switch:
- → Pullup resistors not connected (in this case slight switching behavior will occur, but over a very small voltage range)
- → Reference voltage potentiometer needs adjusting
- → Reference voltage potentiometer solder lead is broken off
- → Encoder output faulty

Counter does not count correctly:
- → Try connecting the input lines (from the first comparator board) to another counter. This will indicate whether it is the counter malfunctioning or the comparator board or encoder

Continual zero count on counter:
- → DRV11 ribbon cable loose
- → Comparator not switching
- → Load line grounded

Counter cannot be reset:
- → DRV11 ribbon cable loose
- → Bad connection on load line so that line is always pulled high by load line pullup resistors.

Limit Sensing Board Does not Switch:

(Can be checked by passing a piece of paper through the sensor and measuring the voltage on the input connector on the axis comparator board.)

- → Two incorrect diode reponses can arise, causing no switching:
  - † Forward bias on diode is 0 volts → diode is shorted: check connections (forward bias should be 1.3 volts)
  - † Forward bias on diode is 6 volts → diode is burned out...must be replaced

NOTES:

☞ Do not check circuit connections with power applied to the circuit

☞ Resistors should not be measured while connected to other circuit components...otherwise erroneous values result

Appendix A6. FORTH Code

```
 ******************  BLOCK   1000     *******************

 ( Servo Routine Variables                        GCP  5/16/83 )
 4 ARRAY Desire.Pos         ( The desired position for all 4 axis)
 4 ARRAY State              ( The state of each axis )
 4 ARRAY MaxVel             ( The maximum velocity of each axis )
 4 ARRAY Velocity           ( The current velocity of each axis )
 4 ARRAY Increment          ( Velocity increment for each axis )
 4 ARRAY 0-Vel              ( Zero Velocity output for each axis )
 4 ARRAY Command.Status     ( 1=Command executing/0=Idle )
 4 ARRAY Delay.Left         ( Amount of time left for next adapt)
1704400 CON VelOut           ( Starting address of the output D/A)
1677700 CON CntOut           ( Address to write to counter )
1677740 CON CntIn            ( Address to read from counter )
      5 VAR Range            ( Error range for stopping )
     30 VAR Delay            ( Delay between adapt. steps )
0 CON Stop 1 CON Move        ( Internal states for servo routine)
      0 VAR Dir              ( Direction of move )     -->


******************  BLOCK   1001     *******************

( Servo Routine Macros                           GCP    4/7/83 )
: Save-Regs   ( <>-<>, Save used registers on return stack )
    ASSEMBLER
          RP -)  R0   MOV,   ( Save R0 )
          RP -)   T   MOV,   ( Save T  )
          RP -)   W   MOV,   ( Save W  )
    FORTH  ;

: Restore-Regs  ( <>-<>, Restore registers from return satck )
    ASSEMBLER
          W   RP )+  MOV,   ( Restore  W )
          T   RP )+  MOV,   ( Restore  T )
         R0   RP )+  MOV,   ( Restore R0 )
    FORTH  ;


                                                -->


******************  BLOCK   1002     *******************

(  Stop?
: Stop? ( <>-<>,  Test for stop point )          GCP 4/7/83  )
  ASSEMBLER

  BEGIN,                      R0 CLR,   ( Init. loop counter )

                            T  R0 MOV,   ( Determine table ... )
                                T ASL,   ( ... byte offset )
     W  Desire.Pos  T I)  MOV,   ( Get desired position )
         CntOut  @#  R0  MOV,   ( Select axis position )
               W  CntIn @# SUB,   ( How far away? )
    MI IF,

    THEN,                     W  NEG,   ( Get absolute value )


                                                -->
```

```
******************  BLOCK   1003     *******************

( Stop? cont.                              GCP 5/16/83 )
                Range @#  W  CMP,   ( Within range of Des. Pos.)
    LT IF,                          ( Yes )
      VelOut T I) 0-Vel T I) MOV,   ( Stop Axis Movement )
         State  T I)  Stop # MOV,   ( Set axis state to stop )
               Velocity T I) CLR,   ( Update velocity table )
         Command.Status T I) CLR,   ( Command completed )
    ELSE,                           ( No )
         State  T I)  Move # MOV,   ( Set axis state to move )
    THEN,
                          R0 INC,   ( Increment counter )
                      4 # R0 CMP,   ( Finished? )
  GE END,                           ( Yes if greater or equal )
  FORTH ;

                                                -->
```

```
******************  BLOCK   1004     *******************

( Change.Speed?                           GCP 4/7/83    )
: Change.Speed?  ( <>-<>, Test for speed change & do it )
 ASSEMBLER                R0 CLR,  ( Initialize loop counter )
  BEGIN,
                        T R0 MOV,  ( Determine table ... )
                           T ASL,  ( ... byte offset )
          State T I)  Stop # CMP,  ( Is axis stopped ? )
    NE IF,                         ( No )
           W Desire.Pos T I) MOV,  ( Get desired position )
               CntOut @# R0  MOV,  ( Select axis position )
                  W CntIn @# SUB,  ( How far away? )
      MI IF,
                           W NEG,  ( Get absolute value )
                 Dir @# -1 # MOV,  ( Set negative direction )
      ELSE,
                  Dir @# 1 # MOV,  ( Set pos. dir. )  -->
```

```
******************  BLOCK   1005     *******************

( Change.Speed cont.                    GCP  5/18/83 )
      THEN,
          Command.Status T I) TST,   ( Idle ?)
      EQ IF,                         ( Yes )
              Delay.Left T I) DEC,   ( Decrement time remaining)
        EQ IF,                       ( Ready for next adapt )
     Delay.Left T I) Delay @# MOV,   ( Reset time remaining )
            0-Vel T I) Dir @# ADD,   ( Adapt for zero offset )
        THEN,
      THEN,
          Velocity   T I)  W  CMP,   ( Distance left <  Vel )
      LT IF,                         ( Yes )
              Velocity T I) W MOV,   ( Update velocity table )
                       Dir @# TST,   ( Which direction ?)
        MI IF,                       ( Negative direction )
                            W NEG,   ( Set for sub. )  -->
```

```
******************  BLOCK   1006      *******************

( Change.Speed? cont.                   GCP 4/7/83 )
        THEN,
                  W 0-Vel T I) ADD,  ( Add offset )
                 VelOut T I) W MOV,  ( Output new vel. )
      ELSE,                          ( Distance left > Max Vel)
     MaxVel T I) Velocity T I) CMP,  ( Increase Velocity ? )
        LT IF,                       ( Yes )
  Velocity T I) Increment T I) ADD,  ( Increase Vel by Inc.)
        ELSE,
     Velocity T I) MaxVel T I) MOV,  ( Set velocity to Max )
        THEN,
               W Velocity T I) MOV,  ( Copy vel. for output )
                        Dir @# TST,  ( Which Direction ?)
          MI IF,                     ( Negative Direction ?)
                             W NEG,  ( Yes )
          THEN,                                -->


******************  BLOCK   1007      *******************

( Change.Speed? cont.                   GCP 5/18/83 )
            W 0-Vel T I) ADD,  ( Add Offset )
           VelOut T I) W MOV,  ( Output Velocity )
       THEN,
     THEN,
                      R0 INC,  ( Increment counter )
                 4 #  R0 CMP,  ( Finished?  )
  GE END,                      ( If >= to 4 )
  FORTH  ;


(   Extra space for expansion of routines  )

                                               -->


******************  BLOCK   1008      *******************

( Interrupt.Servo, Install.Int.Servo, Enable & Disable Int.     )
CODE Interrupt.Servo  ( <>-<>,  Interrupt servo routine )
    Save-Regs  Stop?  Change.Speed?  Restore-Regs RTI,
: Install.Int.Servo  ( <>-<>,  Install the servo routine )
    0 1775460 !     ( Disable Clock interrupt )
    ' Interrupt.Servo 1000 !  3400 1020 !  ( Install interrupt )
    1000 1775460 !     ( Enable interrupt )  ;

0 VAR Proc.Status
CODE Restore.Processor  ( <>-<>, Restore old processor status )
   Proc.Status @# MTPS,      ( Set Processor status )
              NEXT,          ( Sequence  )
CODE Disable.Interrupts ( <>-<>, Disable all Interrupts    )
   Proc.Status @# MFPS,      ( Save old Processor Status )
          3400 # MTPS,       ( Disable all interrupts )
              NEXT,          ( Sequence )             -->
```

```
******************  BLOCK   1009     *******************

( Read.Counter, Zero.Array, Abs.Move.Single   GCP     5/16/83 )
: Read.Counter  ( <int1>-<int2>, read axis int1 position )
     Disable.Interrupts
     CntOut !  CntIn @
     Restore.Processor  ;

: Zero.Array  ( <array>-<>, Zero out the array )
   DUP 2DUP  4 0 DO I 2 * + 0 SWAP ! LOOP ;

: Abs.Move.Single ( <pos,axis>-<>, Absolute single axis move )
     Disable.Interrupts
     DUP ROT SWAP 2* Desire.Pos + !    ( Set Desire Position)
     2* Command.Status + 1SET           ( Set Command Status)
     Restore.Processor  ;

                                                   -->
```

```
******************  BLOCK   1010     *******************

( Position and Velocity setting words     GCP 5/16/83      )
: Max.Vel.Single ( <vel,axis>-<>, Set velocity for axis )
   2 * MaxVel + ! ;

: Abs.Move ( <x,y,z,t>-<>, Absolute move on all four axes )
   0 3 DO I Abs.Move.Single -1 +LOOP ;

: Max.Vel ( <x,y,z,t>-<>, Set all four Velocities )
   0 3 DO I Max.Vel.Single -1 +LOOP ;

: Rel.Move.Single ( <Rpos,Axis>-<>, Relative single axis move )
   DUP 2* Desire.Pos + @ ROT + SWAP Abs.Move.Single ;

: Rel.Move ( <x,y,z,t>-<>, Relative move on all axes )
   0 3 DO I Rel.Move.Single -1 +LOOP ;          -->
```

```
******************  BLOCK   1011     *******************

( Array Intialization words                    GCP 4/11/83 )
: Clear.All.Arrays  ( <>-<>, Initialize all arrays )
    Desire.Pos Zero.Array    State Zero.Array
    MaxVel Zero.Array        Velocity Zero.Array
    Command.Status Zero.Array  ;

: Initialize.Counter ( <>-<>, Intialize the counter )
   CntOut 2+ DUP 0 SWAP ! 15 SWAP ! ;

: Initialize.Zero.Velocities ( <>-<>, Init 0-Vel Array )
  40010 0-Vel !   40010 0-Vel 2+ !    40520 0-Vel 4 + !
  40000 0-Vel 6 + !     ;

: Set.Increments  ( <>-<>, Init Increment Array )
  3 DUP DUP DUP Increment ! Increment 2+ ! Increment 4 + !
  Increment 6 + ! ;                              -->
```

```
******************  BLOCK   1012     *******************

( Set.Up.Robot, Move.Complete               GCP   5/18/83 )
: Set.Delay ( <>-<>, Initialize Delay for Adapt. routine )
  Delay @ 4 0 DO DUP Delay.Left I 2* + ! LOOP DROP ;

: Set.Up.Robot ( <>-<>, Set up Arrays and Enable Servo Rtn. )
  Clear.All.Arrays              Initialize.Counter
  Initialize.Zero.Velocities    Set.Increments
  300 300 300 0 Max.Vel         Set.Delay
  Install.Int.Servo  ;


: Move.Complete? ( <>-<>, Waits for completion of a command
                        move on x, y, and z axes only )
  BEGIN
    3 0 DO I 2* Command.Status + @ LOOP OR OR 0=
  END  ;                                         ;S
```

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