CALIBRATION OF THE ARONSON 6-DOF ROBOTIC PLATFORM

NAGW-1333

by

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August 1991

CIRSSE REPORT #102

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENT

The author would like to express her gratitude to her thesis advisor, Dr. Robert Kelley, for the guidance received under his supervision. The author would also like to recognize a number of people without whom this project would not have been possible: Ken Walter and Lee Wilfinger, for their expertise in the development of the hardware and software systems, respectively; Tim Southward and Sam Charrington, for their help in the installation of hardware; and especially Dr. Steve Murphy, whose advise and encouragement at all stages of this project's development are greatly appreciated.

The author would like to thank her family and friends for their support. Lastly, the author would like to dedicate this work to the memory of her grandfather, Dr. Chao-han Lin.

ABSTRACT

This thesis is a discussion of the calibration of the Aronson six-degree-of-freedom platform. Absolute encoders are used to determine the starting positions of all six joints. The hardware implemented are described in detail. Software programs are used to calibrate the hardware and to build the look-up tables that are needed in determining the initial joint positions. The descriptions of all software routines used are given.

CHAPTER 1
INTRODUCTION

The purpose of this project is to determine the absolute position of each joint of the Aronson six-degrees-of-freedom (6 DOF) platform when high power is on. This allows the system to know where the platform joints are at with respect to the world coordinate frame. The platform consists of two carts, each with three-degrees-of-freedom (3 DOF) – translation, rotation, and tilt. The carts are situated on a common twelve foot long rail.

This project is divided into two distinct parts - hardware and software. Different position transducers are used for each of the three degrees of freedom. A linear magnetic transducer (MTS Temposonics II Linear Transducer) is used for the linear axis; a flexible magnetic transducer (MTS Temposonics I Flexible Transducer) is used for the rotating axis; and an optical transducer (R96 Series Heavy Duty Absolute Encoder) is used for the tilt axis. The Temposonics I and II transducers are manufactured by the Sensor Division of MTS Systems Corporation in North Carolina. The Absolute Optical Encoders are the product of ROBBINS & MYERS/RENCO of Goleta, California.

The software is written in C. These programs perform both system calibration and power-up calibration. System calibration involves calibrating the transducers (Temposonics I and II) and absolute encoders with respect to known zero positions in the world coordinate frame. A look-up table is then formed for each joint with the value of absolute positions that correspond to the occurrence of zero indices in the incremental encoder. Power-up calibration involves reading the absolute position from the transducer or absolute encoder then comparing it to the values in the look-up table. A torque is given to move the joint to the closest zero index. The platform is thus calibrated and ready to be used.

1.1 Purpose

The purpose in calibrating the platform is to determine the exact position of each joint when the platform is in use. Each joint is equipped with an incremental encoder. For the linear axis, the resolution is 0.00002327 meters per encoder count; for the rotating axis, 0.000020139 radians per count; and for the tilt axis, 0.000021817 radians per count. One revolution of the encoder corresponds to 0.018616 meters, 0.0161112 radians (0.9231 degrees), and 0.0174536 radians (1.000017617 degrees) respectively. It takes more than one turn of these encoders to measure the full motion of each joint. The Whedco Incremental Encoder Interface can keep track of the number of revolutions the encoders make after the power is turned on by using the index pulse of the incremental encoder. However, this information is lost when power is shut off. Therefore, a way of getting that starting position is needed.

One way to obtain reliable starting position is to move each joint to one of its two limit switches then back the joint off that limit switch to the first zero index of the incremental encoder. By knowing the exact position with respect to the world coordinate of this zero index, the initial position of the joint is determined. However, without prior knowledge of the configuration of the two PUMA arms situated on top of this platform, large motions in the joints of the platform might cause damage or collision in the system. Therefore, an approach that can accurately determine the starting positions with small movements in each joint would be a better solution. The absolute encoder and transducers are used in this case to obtain the starting position. For the linear axis, the resolution of Temposonics II transducer is 0.00005 meters per count; for the rotating axis, the resolution of Temposonics I transducer is 0.000184187 radians per count; for the tilt axis, the resolution of the Optical Absolute Encoder is 0.006135923 radians per count.

1.2 Objectives

The objectives of this project are:

1. Select and assemble the necessary hardware for all six joints.
2. Complete the path of input/output of signals from hardware to Parallel Interface/Timer Module on the VME cage.
3. Calibrate the platform with respect to limit switches (system calibration case zero).
4. Calibrate hardware with respect to known zero positions of each joint.
5. Set up a look-up table for each joint.
6. Calibrate platform at power-up.

1.3 Summary

The results of this thesis provide the Aronson platform system with the capability of determining the absolute position of each joint when the power is on.

CHAPTER 2
HARDWARE SELECTION AND DESCRIPTION

The Aronson platform consists of two carts on top of a twelve foot long rail. Each cart has three degrees of freedom - translation, rotation, and tilt. Different position transducers are used to obtain the absolute position for each joint. This chapter goes through some of the preliminary methods, designs and approaches that were considered. It also covers the final design and theory of operation of each piece of equipment in detail. First, a brief description of the existing hardware.

2.1 Platform Environment

The Aronson 6-DOF robotic platform with the two PUMA robotic arms that are currently mounted on its two carts form the CIRSSE Coordinated Assembly Testbed System. This system is capable of eighteen-degree-of-freedom motion when all joints of both PUMA arms and all joints of the platform are activated. Each cart and its corresponding robotic arm can also form a separate nine-degree-of-freedom robot.

2.1.1 Labeling Convention

There exists a uniform assignment of the coordinate frames for the 18-DOF testbed. This, together with two conventions of labeling the joints, is given in CIRSSE Technical Memorandum #1[1]. This section introduces a third convention that is used in the remaining portion of this paper and in the platform calibration software. This convention is used for the joints of the platform only. Table 2.1 shows all three conventions. The first three columns give the joint convention number, the cart and the joint type. The fourth column gives the coordinate frame number of these joints in the 18-DOF system. The last two columns show the labeling

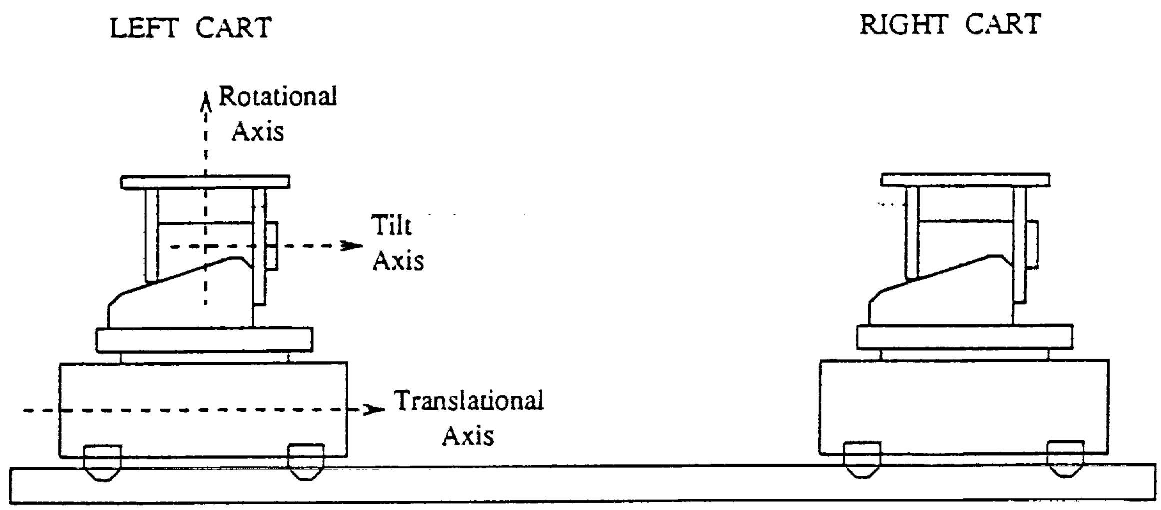

Figure 2.1: The 6-DOF Platform System

convention used for the 18-DOF system and the 9-DOF systems.

The numbering of the joints starts with the left cart (left when looked from the SUNs). Joints 1, 2 and 3 refer respectively to translate, rotate and tilt axes of the left cart, joints 4, 5 and 6 to similar joints on the right cart. A diagram of the platform system is shown in figure 2.1 with PUMA arms removed. Many details of the platform are left out to improve the clarity of the joints.

Table 2.1: Joint Numbers and Coordinate Frames

Joint Number	Cart	Joint Type	Frame Number	Global Label	Local Label
1	Left	Translate	1	G1	L1
2	Left	Rotate	2	G2	L2
3	Left	Tilt	3	G3	L3
4	Right	Translate	10	G10	R1
5	Right	Rotate	11	G11	R2
6	Right	Tilt	12	G12	R3

Table 2.2: The Range of Motion of the Platform

Joint Number	Range of	Motion
1	(-4.5, 1.79) ft	(-1.3716, 0.5456) m
2	(-150, 150) deg	(-2.618, 2.618) rad
3	(-45, 45) deg	(-0.785, 0.785) rad
4	(-1.79, 4.5) ft	(-0.5456, 1.3716) m
5	(-150, 150) deg	(-2.618, 2.618) rad
6	(-45, 45) deg	(-0.785, 0.785) rad

2.1.2 Joint Range

The two robotic carts sit on a twelve foot long rail. The base of each cart is two feet lengthwise (along the rail). With both at their respective limit switches, the edges of the carts are 2.13 meters (7 feet) apart. At minimum separation, the edges of the carts are 0.15 meters (6 inches) apart. The limit switch mechanisms for linear motion take up 0.15 meters at both ends of the track. A soft stop mechanism is placed between the two carts[2]. It is used both as a safety mechanism and as a second limit switch for the linear axes in platform system calibration. The interrupter of this mechanism extends from the left cart toward the right cart for 0.22 meters (8 $\frac{1}{2}$ inches). The linear range of motion becomes 1.92 meters (6 feet 3 $\frac{1}{2}$ inches or 6.29 feet). This range is achieved only when the cart not in motion is at its limit switch. Otherwise, the linear range of motion is less. The range of motion for the rotational axis is 300 degrees (+/- 150 degrees occur at the limit switches). The range of motion for tilt axis is 90 degrees, 45 degrees from the vertical in either direction. Table 2.2 shows the range of motion for each joint of the platform in both SI and English units.

2.1.3 Incremental Encoder with Whedco Interface

All six joints of the platform are fitted with BEI H25 Incremental Optical Encoder. Each encoder outputs two channels (A and B) of quadrature pulses and one index line. The Whedco Incremental Encoder Interface has two channels that accepts quadrature and index pulses from two BEI encoders. The interface can accumulate positions up to 4,294,967,296 counts (or +/- 2,147,483,648 counts in minus-to-plus range mode). Table 2.3 shows the conversion from encoder count to distance or angle measurement. It also gives the distance and angle measured by the encoder in every revolution.

2.2 Preliminary Approaches and Design Considerations

By using the incremental encoder, it is possible to obtain great accuracy in terms of joint positions (meters for linear axis, radians for rotate and tilt axes). However, column three of Table 2.3 shows that each revolution the encoder can only measure a small part of the total joint range. The position counter of the interface can keep track the number of counts the encoder has turned in the clockwise or counterclockwise direction. However, when the power to the platform is turned off, that count is lost. Thus, a method of getting the absolute position at power up is needed. For the additional hardware to be useful, it should be able to determine which revolution the incremental encoder is on. Thus, the hardware should have an accuracy of at least half a revolution. More detailed explanation of the theory is covered in Chapter 4.

2.2.1 Translational Axis

The translational (linear) axis motion is used to measure the location of center of each cart along the rail. For linear motion, each revolution of the incremental encoder measures 0.018616 meters. To determine the placement of either cart, it is

Table 2.3: Incremental Encoder Count Conversions

Joint Type	Conversion	Per Encoder Revolution
Translate	0.00002327 m/count	0.018616 m
Rotate	0.000020139 rad/count	0.0161112 rad
Tilt	0.000021817 rad/count	0.0174536 rad

necessary to be able to tell where the starting point is. The hardware has to have an accuracy of 0.009308 meters or less. This permits the correct identification of the revolution of the encoder.

A linear potentiometer assembly using Nichrome wire was considered. A 3.658 meters (12 foot) long Nichrome wire placed along the backside of platform approximately 0.13 meters (5 inches) above the floor acts as the conductor. Two mechanisms, one for each cart, placed at the center backside of each cart would be used to measure the movement of the center of the carts. When the request for absolute position is initiated, the correct mechanism (either right or left) would be activated. Then by using the voltage divider rule, the placement of the center of the cart with respect to the full rail can be calculated. The major disadvantage of this system is the low accuracy and low precision of its output.

Another approach was the multi-turn potentiometer. Each cart is driven by the servo motor with a 12:1 motor-to-joint reduction ratio. The pinion situated on the bottom of each cart rotates and moves the cart left and right. By aligning the center of potentiometer with the center of the pinion, it is then possible to keep track of the absolute position of the linear axis. The pinion turns 8.87 times as the cart moves down the rail, therefore, a 9 turn potentiometer is needed. This idea is not practical since the carts are both in place with PUMA arms already attached. At this time, it is not possible to take the system apart and invert the carts to drill holes that are needed to install the equipment.

2.2.2 Rotational Axis

For the rotational axis, each turn of the incremental encoder measures 0.0161112 radians (slightly less than 1 degree) per revolution. Therefore, hardware for this joint needs to be able to resolve less than half of a degree.

For this axis, a 10-bit optical absolute encoder is required. To accurately measure the angles, it is necessary to access the center of the rotating axis. Unfortunately, the center is purposely left open for pulling cables through. Thus, it is not possible to get to the center. To access the center from the bottom brings up the implementation problem. Gear reduction assembly to obtain the one to one turn ratio of the rotating axis was considered. This however introduces the problems of backlash, and the placement of the gears assemble both inside and on top of the rectangular cart.

A potentiometer was also considered. A gear assembly is also needed even though a one to one turn ratio is not essential. Similar mechanical problems exist for this implementation as for an optical absolute encoder.

2.2.3 Tilt Axis

For the tilt axis, each turn of the incremental encoder measures 0.0174536 radians (approximately 1 degree). The hardware has to resolve at least a half of a degree. A 10-bit optical absolute encoder is used. It has an accuracy of 0.35 degree.

2.3 Final Design

For the final design, a Temposonics II Linear Transducer is used for the linear axis, a Temposonics I Flexible Transducer for the rotate axis, and an Optical Absolute Encoder for the tilt axis.

2.3.1 Translational Axis

The Temposonics II Linear Displacement Transducer System with Digital Output is produced by the Sensor Division of MTS Systems Corporation. This system contains a Linear Displacement Transducer Waveguide, a Digital Interface Box, and a Digital Counter Card. The transducer senses the position of a pair of external electromagnets. This is used to measure displacements of the linear joint to a high degree of resolution. The resolution of the transducer is factory set to 0.025 millimeters per count. This system measures the time interval between an interrogation pulse and a return pulse. The interrogation pulse is transmitted through the transducer waveguide. The return pulse is generated by two electromagnets at the displacement to be measured.

2.3.1.1 Linear Displacement Transducer Operation

The interrogation pulse travels the transducer by a conducting wire inside the hollow of the waveguide. This waveguide is spring loaded inside the transducer rod. It exhibits the physical property of magnetostriction. When the magnetic field of the interrogation pulse interacts with the stationary magnetic field of the external electromagnet, a torsional strain pulse (or twist) is produced in the waveguide. This strain pulse travels up and down the rod, away from the magnet. At the end of the waveguide, the strain pulse is damped inside a dead zone. This zone is 0.06 meters (2.5 inches) long for the Temposonics II. At the head of the transducer, there are two magnetically coupled sensing coils. These coils are attached to strain sensitive tapes which translates the strain pulses into an electrical return pulse. The coil voltage is amplified by the electronics in the head of the transducer before it is sent to the interface box.

Figure 2.2 gives a visual representation of the waveguide interactions. For the linear rail application, two electromagnets are used in place of the permanent

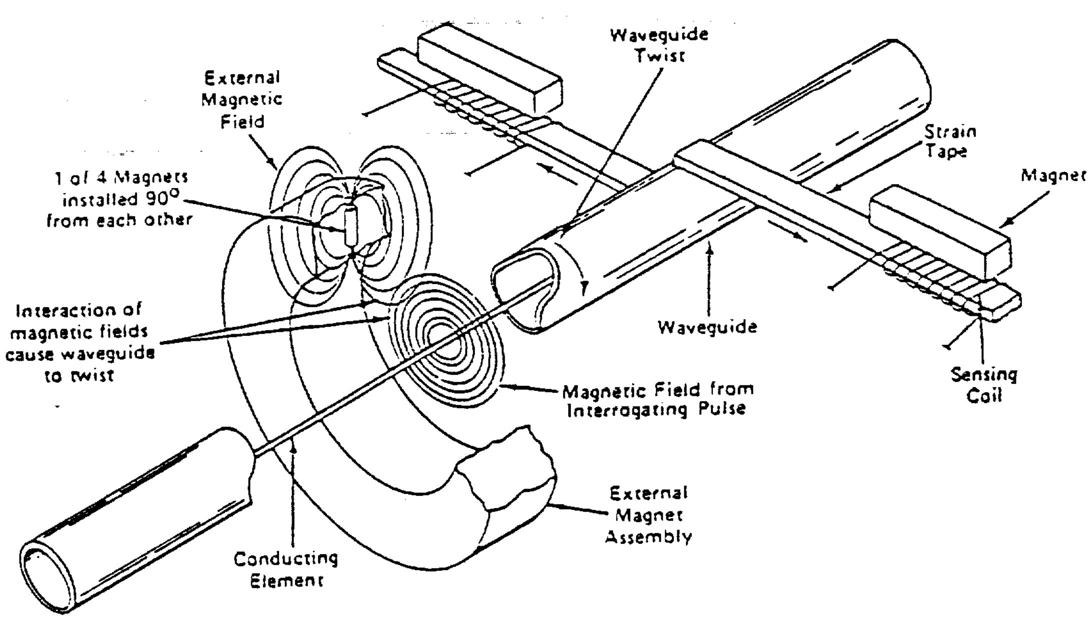

Figure 2.2: Waveguide Interaction

magnet. The twist is produced in the same manner when the electromagnet pair is activated. The electromagnet pairs are chosen for this application since the absolute position of both carts are determined by the same transducer. Thus, when calibrating the left cart, the left pair is activated, similarly for the right cart. This way, only one pair of electromagnets is on at any one time. Therefore, the transducer is not confused by signals from two locations.

2.3.1.2 Digital Interface Box

The Digital Interface Box contains the intelligence for sensing the interrogation and return pulses. The frequency for the interrogation pulse comes preset from the factory to allow sufficient time for return pulse sensing based on recirculation (factory preset) and the stroke length. The interrogation pulse turns on a flip-flop. The return pulse switches the flip-flop off. The elapse time is directly proportional to the position of the electromagnet pair. The on time of the flip-flop is sent to the counter card as the pulse duration signal.

2.3.1.3 Digital Counter Card

The digital counter card measures the time interval of the pulse duration signal from the interface box. The leading edge of this pulse enables the counter register. The trailing edge triggers a latch pulse that downloads the count into the output registers. This latch pulse is normally low for the receiver device to interpret as data valid. Its frequency is the same as the interrogation frequency with the duration of 1 microsecond.

For more details, see the manual for Temposonics II transducer[3].

2.3.2 Rotational Axis

The Temposonics I Flexible Transducer is used for the rotational axis. The direct digital output system consists of a Flexible Linear Displacement Transducer Waveguide, a Digital Interface Box, and a Digital Counter Card.

The description of the working of each item is the same as that for the Temposonics II transducer with a couple of differences. The transducer waveguide is flexible so it can be bent to measure circular distances. Since one transducer is used for each cart, a permanent magnet is used. The dead zone is 8 inches.

For more detail, see the manual for Temposonics I transducer[4].

2.3.3 Tilt Axis

The tilt axis use the R96 Heavy Duty Absolute Encoder from ROBBINS & MYERS/RENCO. This encoder outputs 10-bit gray code for 1024 unique positions. It is accurate up to $\pm\frac{1}{2}$ count. Clockwise rotation of shaft produces ascending count.

See the technical manual for Absolute Encoder for more detail[5].

2.4 Summary

This chapter gave a brief overview of the platform environment and the existing incremental encoders and the Whedco Incremental Encoder Interface that are available for determining positions. It also covered some of the design considerations and several preliminary designs that were considered for obtaining the absolute joint position. Lastly, the final hardware configuration was described in detail.

CHAPTER 3
HARDWARE INSTALLATION AND INFORMATION FLOW

This chapter covers the installation of the hardware. Since the sensing device for each motion is different, special supports are designed to place each transducer at the required locations. The flow of the signals is traced from the hardware to the computer. The output from each hardware is piped through the CIRSSE multiplexer then onto MVME340A Parallel Interface/Timer (PIT) Module. Finally, the calibration of equipment is discussed.

3.1 Equipment Supports

The hardware used for platform calibration are one Temposonics II Linear Transducer, two Temposonics I Flexible Transducer, and two Absolute Optical Encoder. The description of installation of each piece is given below.

3.1.1 Linear Transducer

One linear transducer is used to determine the position of both the left and right carts. As mentioned previously, only one pair of electromagnets is allowed to be on at one time, otherwise, the digital interface box would get confused. As shown in Figure 3.1, the nominal distance between the transducer rod and the electromagnet is 1.588 millimeters ($\frac{1}{16}$ inches). The two coils are mounted 180 degrees apart to produce a sufficient magnetic field. The center line of the magnetic poles has to pass through the center line of the transducer rod. Electromagnet supports and transducer supports are designed to ensure the alignment of the center lines.

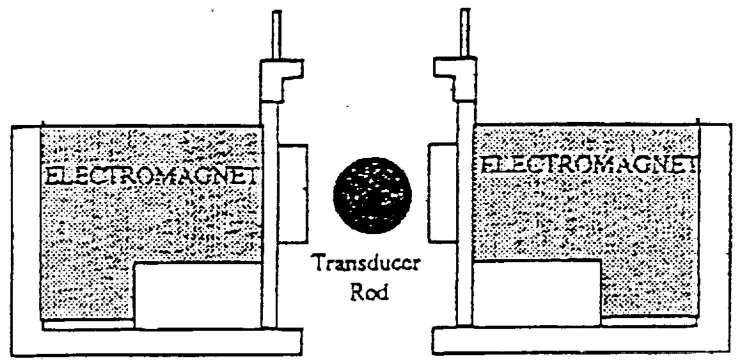

Figure 3.1: The Configuration of the Temposonics Transducer and the Electromagnets

3.1.1.1 Electromagnet Support

An L shaped bracket was designed to keep the magnets in place. Figure 3.2 shows the top view of the bracket with the dotted line showing the placement of the electromagnet pair.

3.1.1.2 Linear Transducer Supports

Another L shaped support is designed for the transducer itself. Figure 3.3 shows all three views of the support with the dimensions. A small post is also used to hold the transducer rod further up on the L support. The significance of this post will be explained later. Since the transducer works on using magnetic fields, non-ferrous material (brass shim) is used to hold the transducer rod onto the post. All the supports except for the brass shim are made of aluminum.

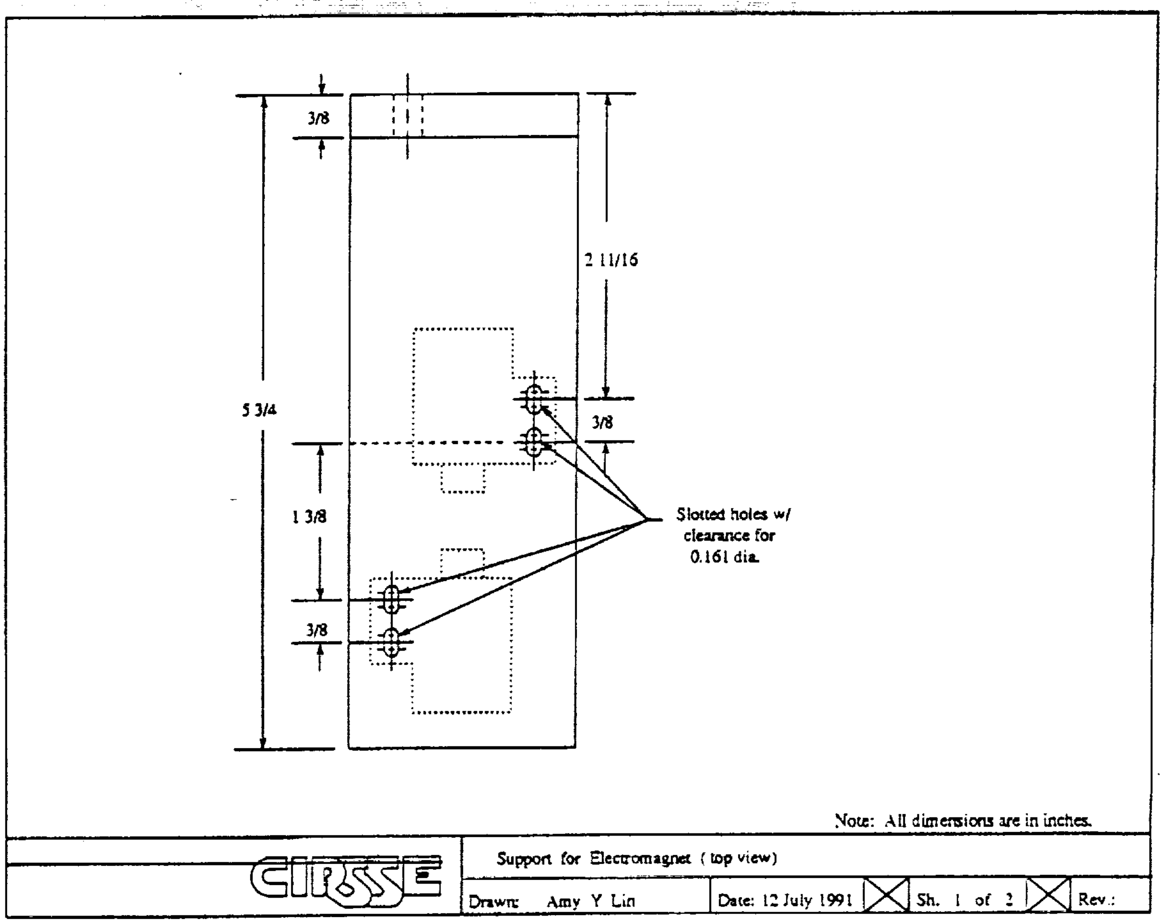

Figure 3.2: The Electromagnet Support

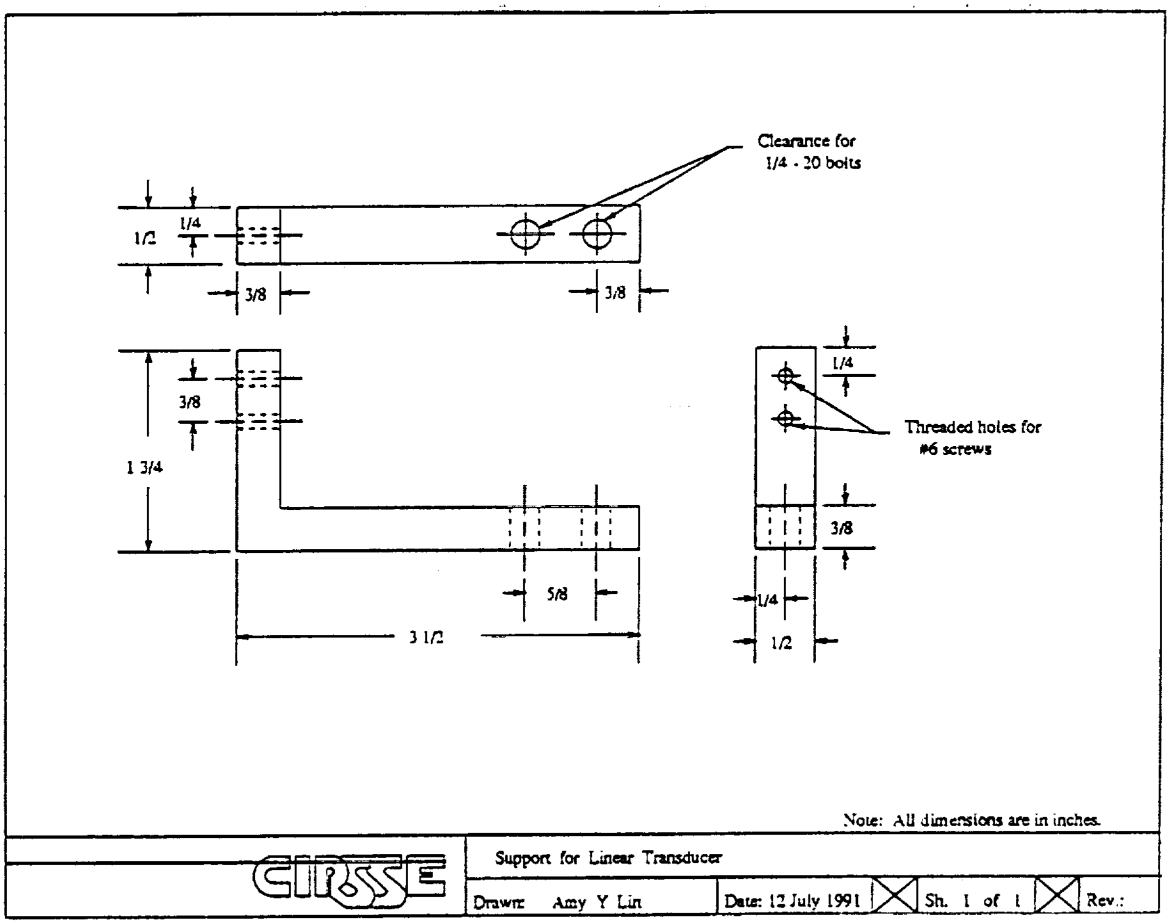

Figure 3.3: The Linear Transducer Support

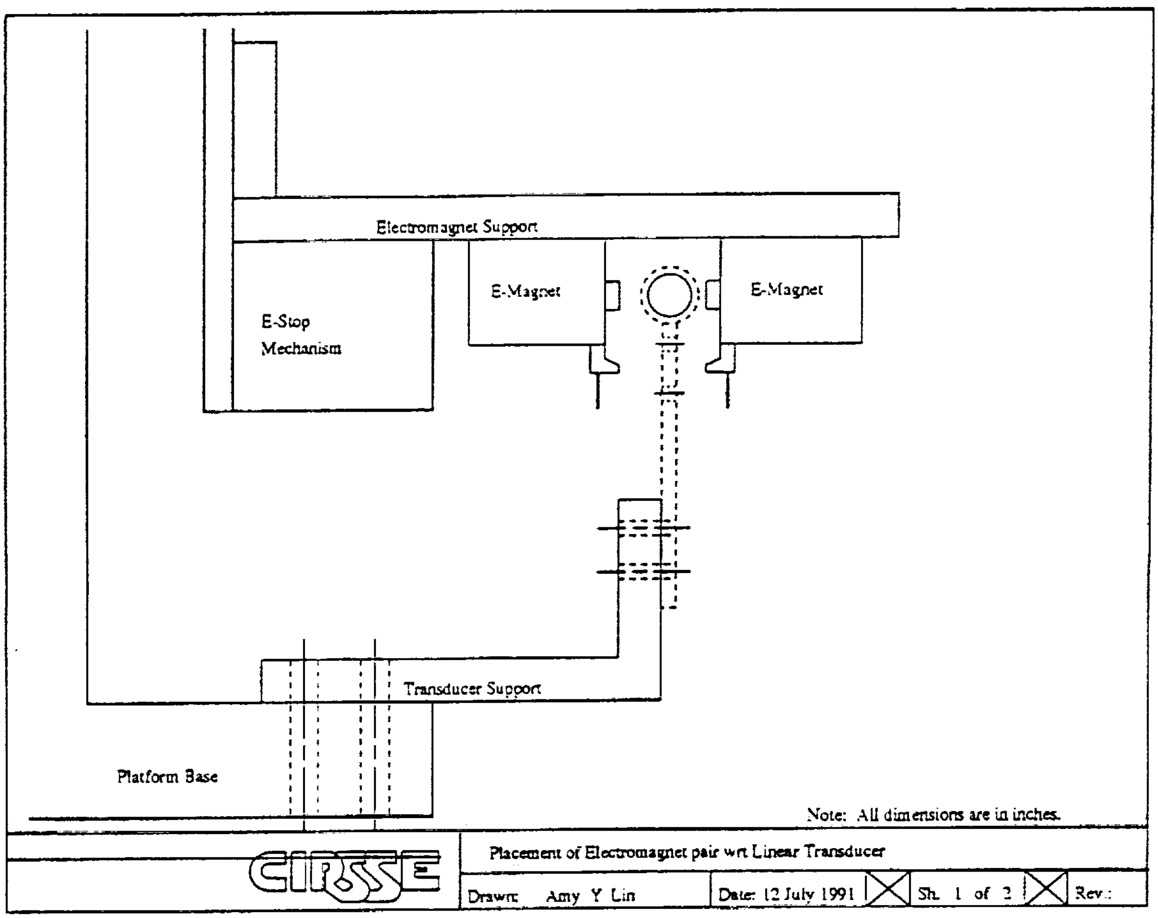

Figure 3.4: The Linear Transducer Assembly

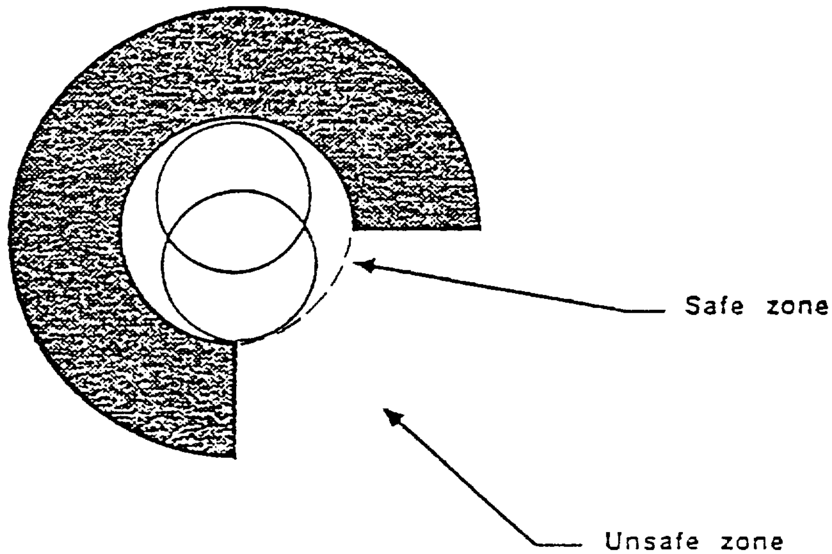

Figure 3.5: The Transducer Rod Position within an Open Magnet

3.1.1.3 Support Assembly

Figure 3.4 shows the placement of the electromagnet pair with respect to the transducer rod. It also shows where all the supports are located. Notice that if the L shaped transducer support had extended further up to the rod itself, it would have hit the electromagnet located next to the emergency stop mechanism. Nine sets of transducer support, post and brass shim are used to hold up the linear transducer.

The shaft of the electromagnet coil was loose. The motion of the cart could shift it out of its housing. Thus, Epoxy adhesive was used to keep it in place. This does not affect the performance of the coil. Washers are used to lower the electromagnets from the L shaped bracket for the final alignment of the center of the transducer rod with the center of electromagnets.

3.1.2 Flexible Transducer

The flexible transducer is used to obtain the absolute position of the rotational axis. The center of the cross section of the flexible transducer is placed at 38.1 millimeters (1.5 in) from the side of the turn table. Since the range of motion is 5.236 radians (300 degrees), it is necessary to shape the flexible transducer to a perfect circle for at least 5.236 radians.

A permanent magnet is used in this application to create the strain pulse. Figure 3.5 shows the safe zone and the unsafe zone for the transducer. The two sample placement of the transducer rods are inside the safe zone. The permanent magnet support and the flexible transducer supports are designed to keep the transducer in shape and within the safe zone.

3.1.2.1 Flexible Transducer Supports

Figure 3.6 shows the three views of the design of the flexible transducer support. It places the center of the transducer 69.85 millimeters ($2\ \frac{3}{4}$ inches) above the top of the rectangular cart. Again, a brass shim is used to keep the transducer in place.

3.1.2.2 Permanent Magnet Support

Figures 3.7 and 3.8 show both parts of the assembly that is used to keep the permanent magnet in place. The magnet is placed close to the zero degree mark of the rotating axis (the limit switches are at +/- 150 degrees). The screws and nuts used to keep the permanent magnet in place are brass to minimize interference with the magnetic field.

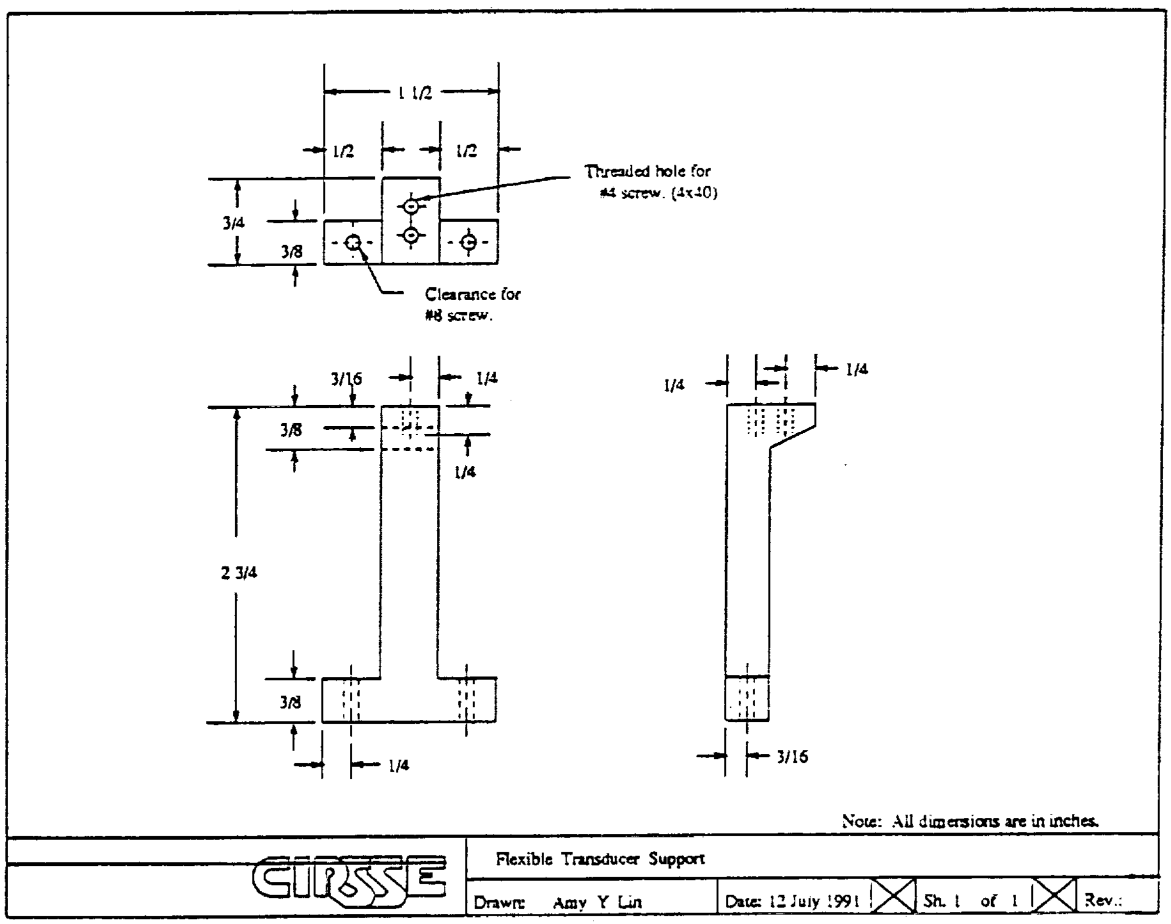

Figure 3.6: The Flexible Transducer Support

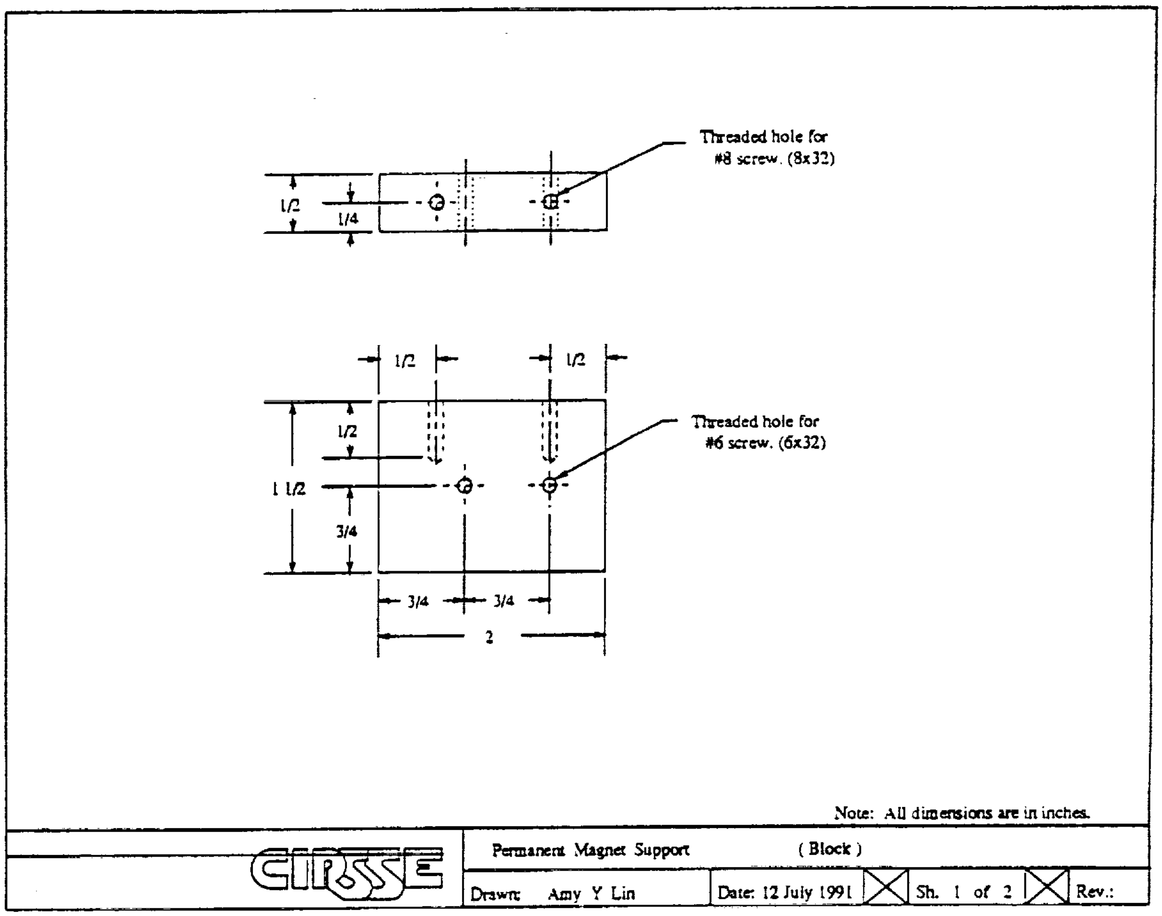

Figure 3.7: The Permanent Magnet Support – Part I

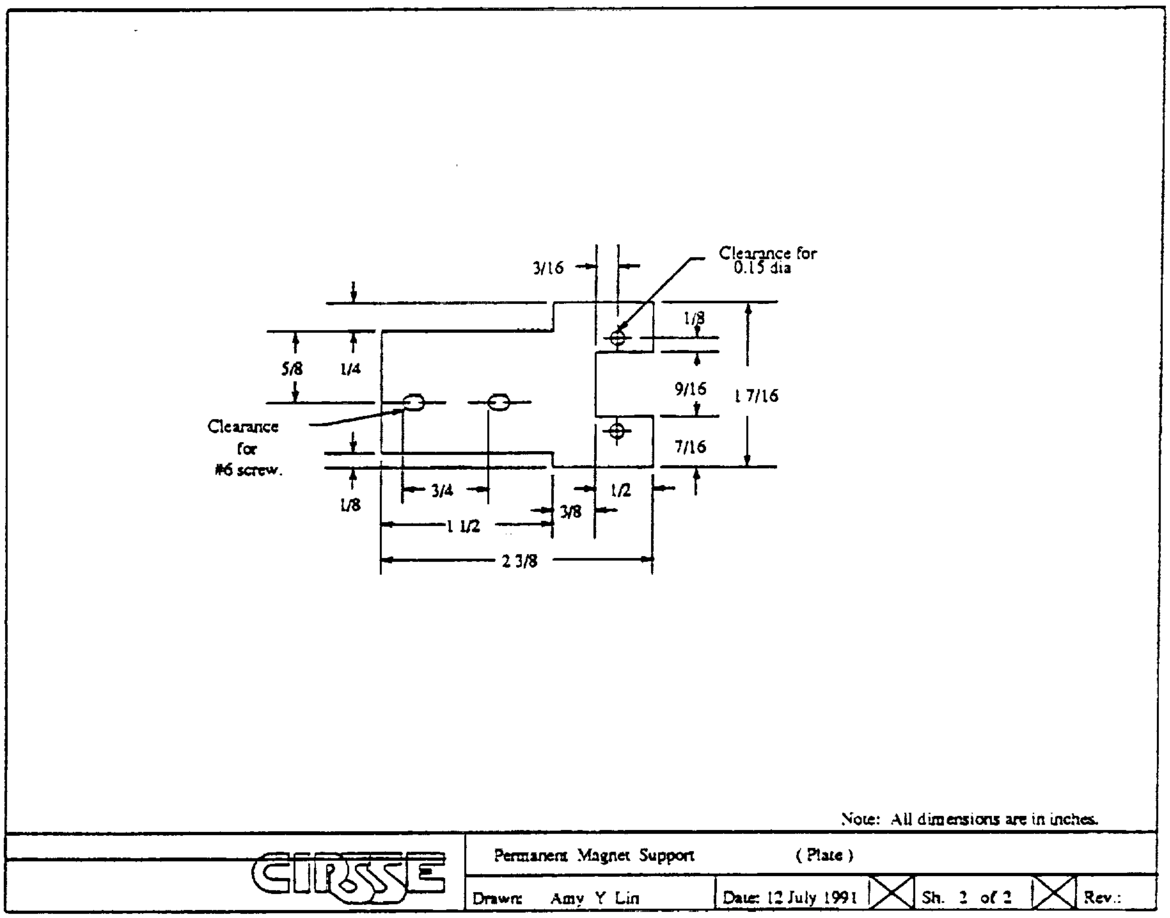

Figure 3.8: The Permanent Magnet Support – Part II

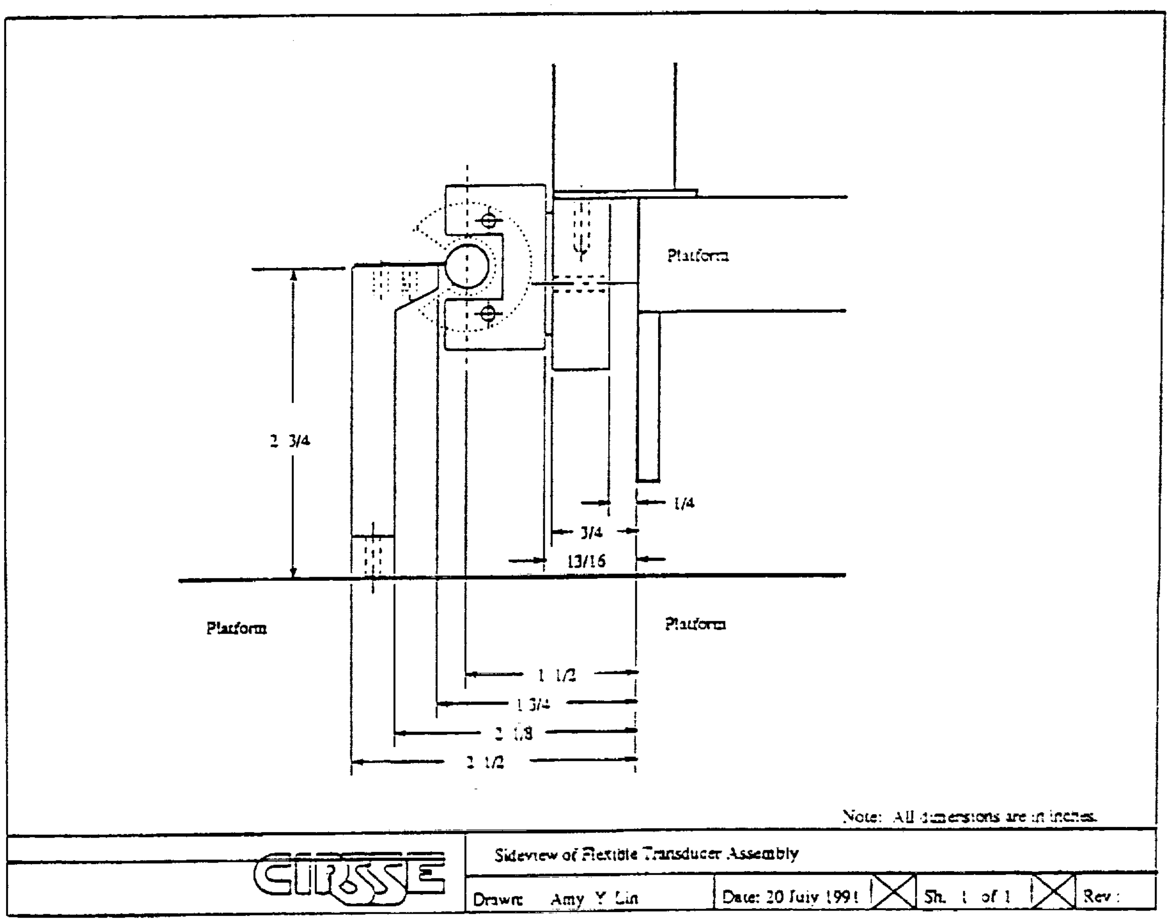

Figure 3.9: The Flexible Transducer Assembly

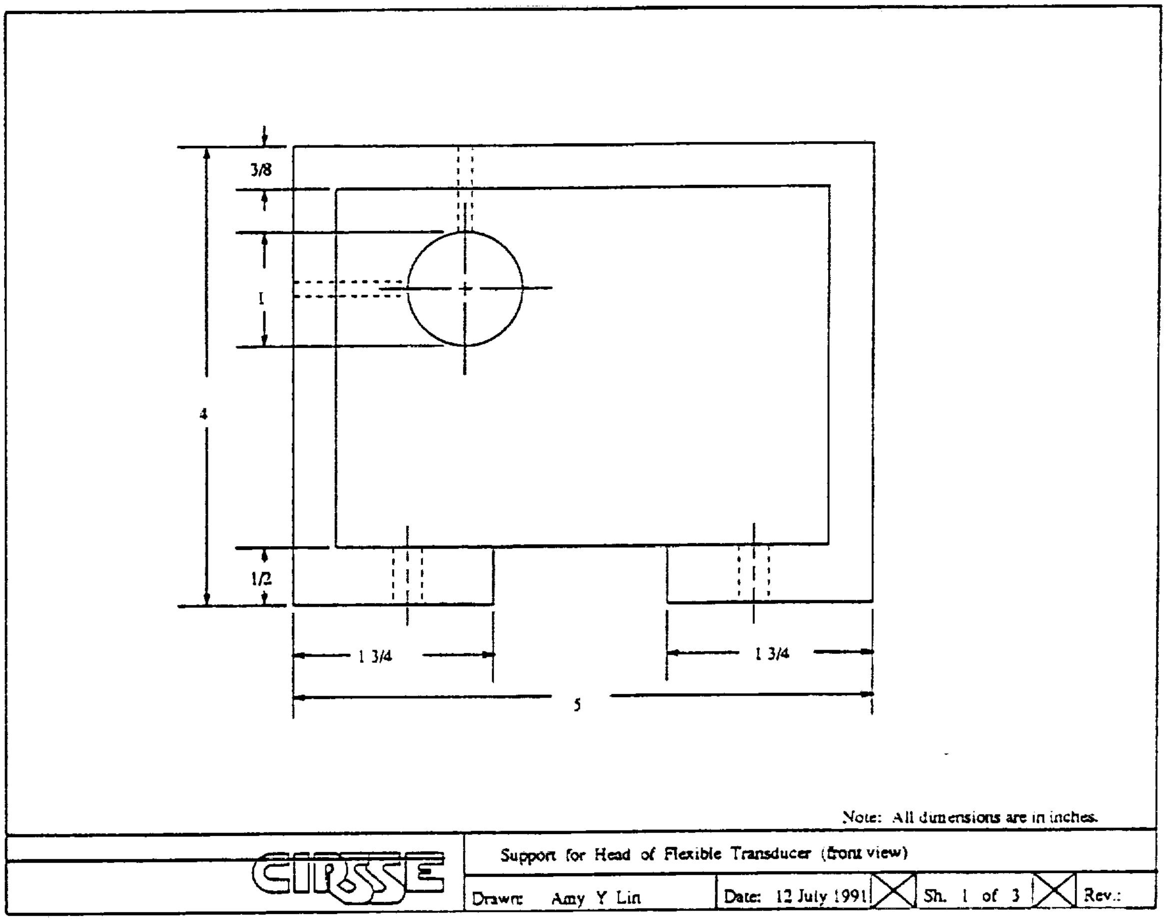

Figure 3.10: The Support for the Head of the Flexible Transducer

3.1.2.3 Support Assembly

The sideview of the magnet assembly and the transducer support is shown in Figure 3.9. This figure also shows the location of each supports. Ten sets of aluminum support and brass shim are used to keep the circular form of the flexible transducer. The head of the transducer is clamped in place. Figure 3.10 shows the front view of this clamp.

3.1.3 Absolute Encoder

An absolute encoder is used to determine the absolute position of the tilt axis. The encoder is placed such that its shaft is aligned with the center of rotation of the tilt axis. Figure 3.11 shows the support that holds the encoder in place. A center piece made of aluminum was used to turn the shaft of the encoder (Figure 3.12). During installation, it was found that an aluminum piece is not the best choice. A 9.5 millimeters ($\frac{3}{8}$ inch) steel bolt is used for the tilt axis of the right cart. The unthreaded part is kept at 6.35 millimeters (1 $\frac{1}{4}$ inch) to maintain the original design specifications. A Helical Coupling (AC100-12-12) is used to clamp the shaft of the encoder to the stationary center piece.

3.2 Interconnection Box

This box contains the electronics for the calibration hardware. The digital interface box and digital counter card for each transducer resides here. The power supply for the system is also included. The 18-bit signals from the transducers are converted in this box to 16-bit digital output. The most significant bit (MSB) is not used since the count for both Temposonics I and II never goes that high. The least significant bit (LSB) is also not connected. This changes the resolution of the transducers from 0.025 millimeters per count to 0.05 millimeters per count. The

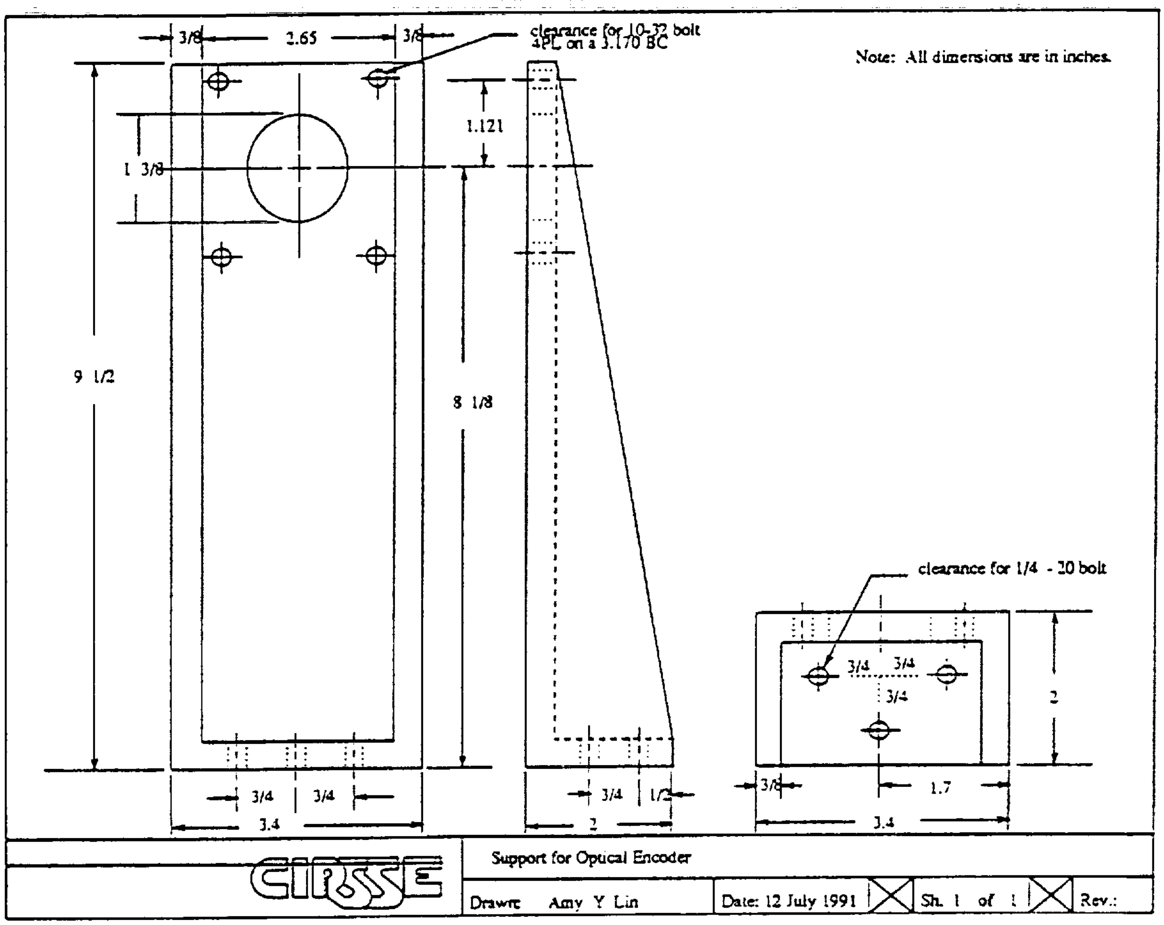

Figure 3.11: The Optical Encoder Support

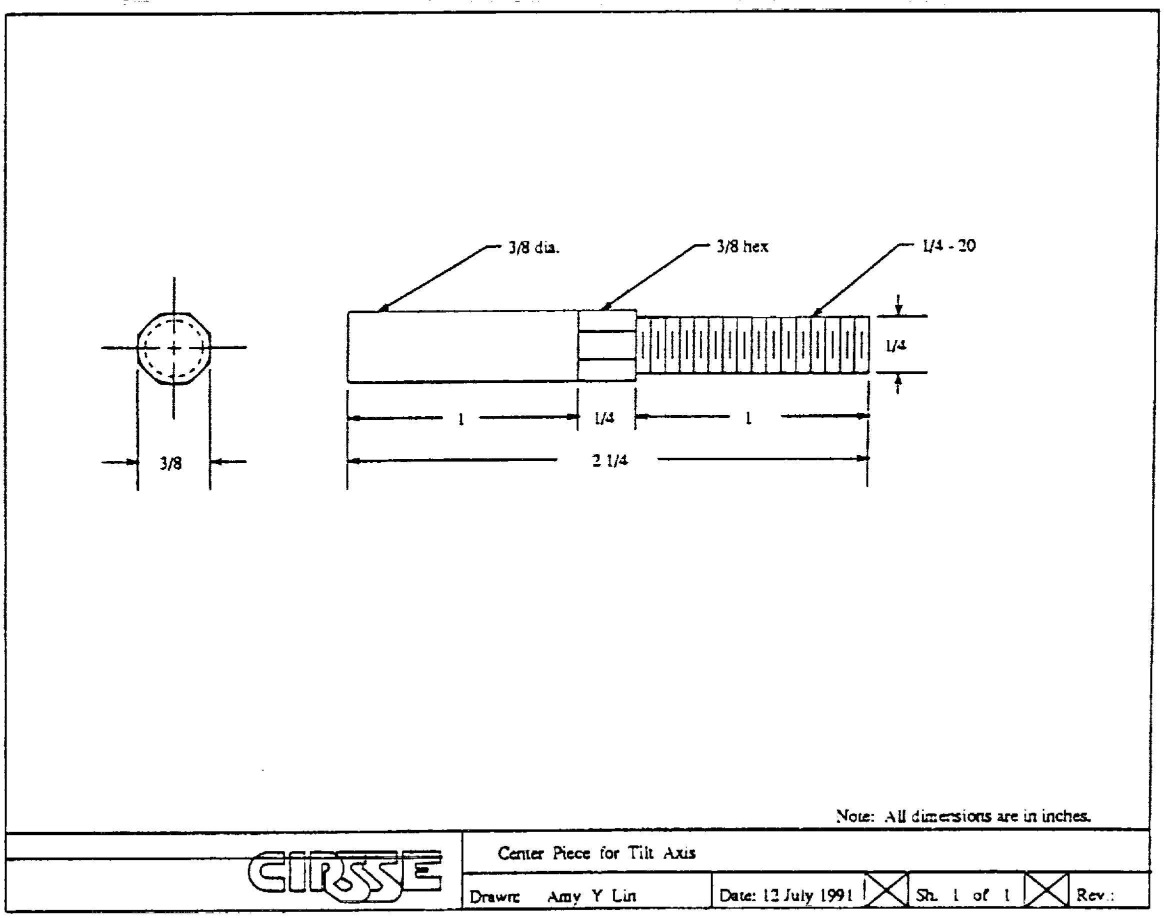

Figure 3.12: The Center Piece for the Tilt Axis

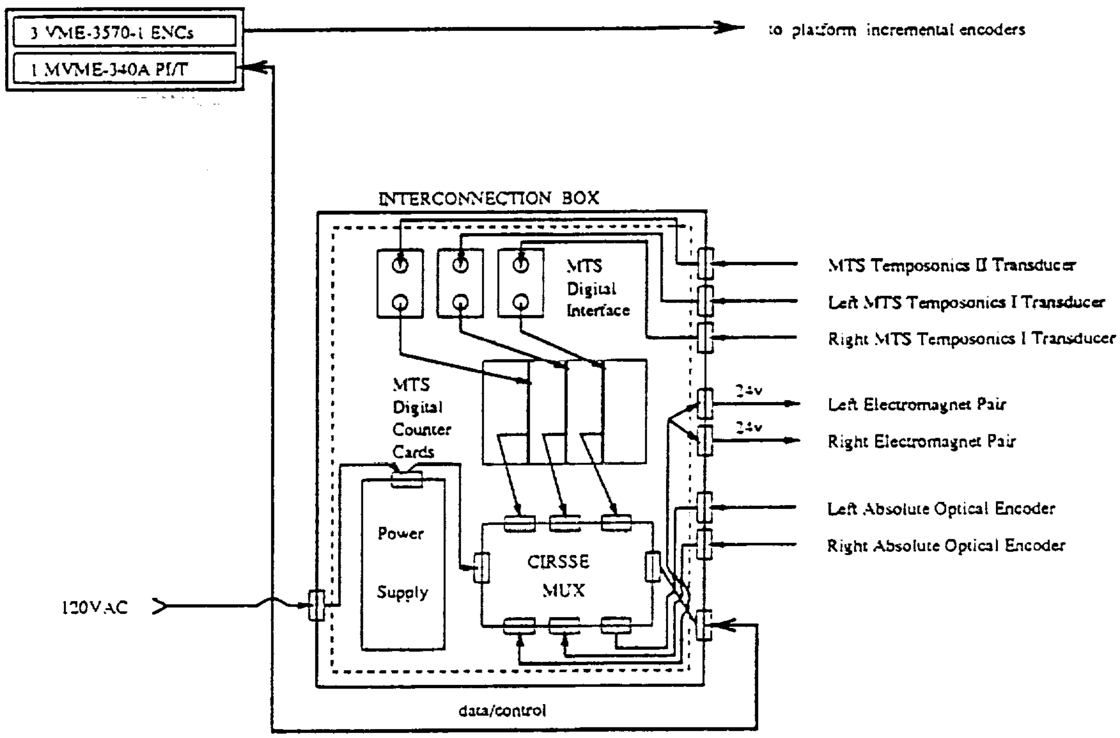

Figure 3.13: The Interconnection Box with Signal Flow

10-bit signals from the encoders and the 18-bit signals (now 16-bit) from the transducers are piped through a multiplexer (MUX) and out of the box to the Parallel Interface/Timer (PIT) board. Both the MUX and the PIT will be described further in the next two sections. Figure 3.13 shows the block diagram of the interconnect box showing the signal flow.

3.3 CIRSSE Multiplexer

The purpose of the CIRSSE multiplexer is to route the signal from the selected transducer or encoder to the PIT board. When accessing the MUX, a command needs to specify which transducer or encoder and electromagnet pair to activate. A 6-bit command is used to define the combination. Table 3.1 shows the commands used to specify the transducer. Table 3.2 shows the commands for the electromagnet

Table 3.1: Commands for Activating Transducer or Absolute Encoder

Transducer Select	Activate Transducer
0 0 0	No Selection
0 0 1	Linear Transducer
0 1 0	Left Flexible Transducer
0 1 1	Right Flexible Transducer
1 0 0	Left Absolute Encoder
1 0 1	Right Absolute Encoder
1 1 0	No Selection
1 1 1	No Selection

pair selection. Two pairs of electromagnets (one for the linear motion of the left cart and one for the right cart) are connected. The multiplexer is designed to handle up to four pairs electromagnets. Only two pair are needed to determine the absolute positions of the linear axes, therefore, the third and fourth ones are not used.

A 50 pin ribbon cable is used for getting signals out of the MUX. Most of the even pins are connected. The odd numbered ones are not used (grounded). Pins 2 through 12 are used for the specification of the transducer/encoder and magnet pairs. Pins 14 through 44 are used to output the 16-bit data to the PIT. Table 3.3 describes the function of each pin.

Table 3.2: Commands for Activating Electromagnet Pair

Transducer Select	Activate Electromagnet Pair	Joint Type
0 0 0	No Selection	
0 0 1	Electromagnet Pair #1	Left Translate
0 1 0	Electromagnet Pair #2	Right Translate
0 1 1	Electromagnet Pair #3	Not Used
1 0 0	Electromagnet Pair #4	Not Used
1 0 1	No Selection	
1 1 0	No Selection	
1 1 1	No Selection	

Table 3.3: Pin Connections for Signals between Multiplexer and Parallel Board

MUX Pin	MUX Signal	PIT Pin	PIT Signal
2	Transducer Select 0 (LSB)	C8	PB14
4	Transducer Select 1	C6	PB15
6	Transducer Select 2 (MSB)	C4	PB16
8	Electromagnet Select 0 (LSB)	C16	PB10
10	Electromagnet Select 1	C14	PB11
12	Electromagnet Select 2 (MSB)	C12	PB12
14	Transducer Data 0 (LSB)	A31	PA20
16	Transducer Data 1	A29	PA21
18	Transducer Data 2	A27	PA22
20	Transducer Data 3	A25	PA23
22	Transducer Data 4	A23	PA24
24	Transducer Data 5	A21	PA25
26	Transducer Data 6	A19	PA26
28	Transducer Data 7	A17	PA27
30	Transducer Data 8	A15	PA10
32	Transducer Data 9	A13	PA11
34	Transducer Data 10	A11	PA12
36	Transducer Data 11	A9	PA13
38	Transducer Data 12	A7	PA14
40	Transducer Data 13	A5	PA15
42	Transducer Data 14	A3	PA16
44	Transducer Data 15 (MSB)	A1	PA17
46	Not Connected		
48	Not Connected		
50	Not Connected		

Table 3.4: Commands for Activating Transducer and Electromagnet Pair

Platform Joint	Transducer/E-magnet Select	Command
1	0 0 0 1 0 0 0 1	0x11
2	0 0 1 0 0 0 0 0	0x20
3	0 1 0 0 0 0 0 0	0x40
4	0 0 0 1 0 0 1 0	0x12
5	0 0 1 1 0 0 0 0	0x30
6	0 1 0 1 0 0 0 0	0x50

3.4 Parallel Interface/Timer Module

The MVME340A Parallel Interface/Timer Module is the gateway for the software and hardware. C programs send out commands to activate the hardware through the PIT board. Signals from the hardware are also read from the PIT board.

The parallel board is configured for device-parallel 16-bit input/output. Port A for both chip 1 and 2 is used for the signal (input) while Port B of chip 1 is used for the command (output). Port B of chip 2 is not connected to the MUX. The command send to the parallel port is 8-bits wide. while the input to the MUX is 6-bits wide. By not connecting bit 7 and 3 of the signal going to MUX and setting them to be zero, the commands used (shown in Table 3.4) are realized. The last column shows the command in hexadecimal. The connections for the input/output signals to the PIT are shown in the last two columns of Table 3.3.

For more information on the PIT, see the user's manual[6].

3.5 Hardware Calibration

The calibration of each piece of hardware is done during system calibration. A known zero position for each joint is used to offset the absolute encoder position. The zero position of each joint is defined as the zero meter or zero radian mark in the range of motion. More detail is given in Chapter 4.

3.6 Summary

This chapter presented the installation of the hardware and the designs of the supports that are required to keep each piece of equipment in place. It also covered the interconnection box that is used to supply the power and to house the electronics of the transducers. Finally, hardware calibration was briefly mentioned.

CHAPTER 4
PLATFORM CALIBRATION

This chapter covers the purpose of platform calibration. It defines the terms system calibration, and power-up calibration and then goes over the steps that were taken to accomplish each.

4.1 Purpose

As mentioned previously, the purpose of calibration is to determine the position of each joint of the platform when the high power is on. The incremental encoders that came with the Aronson Platform are capable of measuring a small section of the joint range very accurately. With a Whedco Dual Channel Incremental Encoder Interface, the system is capable of tracking the number of times the encoders rotate clockwise or counterclockwise from a starting position at power-up. The Whedco interface gives the relative change of location of each joint. However, without the knowledge of the starting point, the system is unaware of the absolute joint position. This is where absolute position calibration of the platform comes in. By using absolute encoders to determine the initial positions, the system is then able to tell where the starting position is for each joint in the world coordinate frame.

4.2 System Calibration

System calibration of the platform is used to set up look-up tables (header files) each containing a list of absolute encoder positions and a second list with the corresponding joint positions. There is one header file for each of the platform joint. Each absolute encoder position in that table occurs at the zero index mark (when index pulse is high) of the corresponding incremental encoder. It is essential to know the absolute encoder position at each zero index since the look-up table will

Table 4.1: Absolute Encoder/Transducer Count Conversions

Joint Type	Conversion
Translate	0.00005 m/count
Rotate	0.000184187 rad/count
Tilt	0.006135923 rad/count

be used by the power-up calibration as a ruler. Each list contains all the possible zero indices the joint will encounter as it moves from one limit switch to the other.

This calibration should be done periodically (e.g., every six month) or whenever the calibration hardware has been moved.

The incremental encoder position given by *platPosSRead* of *platLib.c* (software program in platform library) is in meters for the linear axis and radians for the rotating and tilt axes. To keep the units consistent, the outputs from transducers and absolute encoders are converted accordingly. The conversions factors are shown in Table 4.1.

4.2.1 Calibration Procedure

This section describes the procedure used to system calibrate the platform. The ideal way to do the calibration is to move each joint from one of its limit to the other one and stop at each zero index mark to read and store the absolute encoder position. However, due to the momentum of platform and the simplicity of the velocity controller that is used, it is not possible to stop the joints exactly at the zero index mark. After the command of freeze joint motion is given, each joint drifts a bit before it comes to a full stop. To stop a joint more exact on the zero index position, a PID controller should be considered. Table 4.2 shows the range of stopping distance when the command of moving to the first zero index off the limit switch then stop (*platcalFirstZeroIndex*) is given. This drift of distance is taken into

Table 4.2: Stopping Distances from the Zero Indices

Joint	Limit	Minimum Position	Maximum Position
1	left	0.002527 m	0.025889 m
2	cw	0.008196 rad	0.010814 rad
2	ccw	-0.001973 rad	-0.022998 rad
3	cw	0.004188 rad	0.005977 rad
3	ccw	-0.000589 rad	-0.002203 rad
4	right	-0.007562 m	-0.023851 m
5	cw	0.006907 rad	0.010109 rad
5	ccw	-0.002618 rad	-0.012063 rad
6	cw	0.002661 rad	0.010297 rad
6	ccw	-0.002748 rad	-0.003534 rad

account in both calibration procedures. The joints are calibrated one at a time.

For system calibration, the test pendant is used to move a joint to some position off the limit switch. This distance is chosen to be about 0.1745 radian (10 deg) for the rotation and tilt axes and 0.45 meters (1.5 ft) for the translation axis. The software controller then takes over to bring the joint to the limit switch. The reason for using the test pendant to move a joint is to save time. This is particularly noticeable when calibrating the rotational axes. The software controller is designed to move the joint toward its limit switch slowly. This way, the joint will not hit more than one zero index after the limit switch is reached. The joint is placed at a sufficient distance away from the limit to allow the motion of the joint to become smooth and slow enough. Because of static friction, all platform joints need a kick start. In essence, the required starting torque is a lot higher than the moving torque.

The joint is then backed off from the limit switch to the first zero index and stopped. A feature of the Whedco Interface, find zero index then set the position count to zero, is used. Both absolute encoder position (*init_abs_pos*) and incremental encoder position (*init_pos*) are recorded. The joint is then moved to its zero position with the test pendant. Again, the absolute encoder position (*zero_abs_pos1*) and incremental encoder position (*zero_pos1*) are stored. This process is repeated with the limit switch on the other extreme. The positions are stored in *final_abs_pos* and *final_pos* and then *zero_abs_pos2* and *zero_pos2* respectively. Figure 4.1 shows the location of each of these positions with respect to one another. *zero_pos2* can also occur on the other side of *zero_pos1*.

The movement of each joint is performed so that the incremental position count increases as it moves from the first limit switch to the second while the absolute position count decreases. Since *init_pos* is taken at the zero index and *zero_pos1* is the positional difference between the zero index and the zero position a joint, *init_pos* is assigned the value of $-1 *$ *zero_pos1* while *zero_pos1* is assigned the value of 0.0. A similar relationship exists between *final_pos* and *zero_pos2*. However, instead of setting the value of negative *zero_pos2* to *final_pos*, the difference between *zero_pos1* and *zero_pos2* also needs to be accounted for. There is some error between the two zero positions due to human error in lining up the joint with a mark at the zero position using the test pendant. The difference can be compensated for by using the difference between the two absolute encoder zero positions. Thus *final_pos* $= -1 *$ *zero_pos2* $-$ (*zero_abs_pos2* $-$ *zero_abs_pos1*).

The locations of the first and the last zero indices are known. The distance between successive zero indices is also known for the incremental encoder. The number of zero indices a joint goes through (including the first and last ones) are determined. The increment between successive zero indices for the absolute encoder positions is then calculated.

Before the increment of the absolute position can be calculated, the drift in each joint has to be taken into account. (The drift is the overshoot of the joint after the stopping command is given.) Since the absolute position reading is taken when a joint has stopped fully, there is some difference between the zero index position and where the reading is actually taken. This can be compensated for by using the

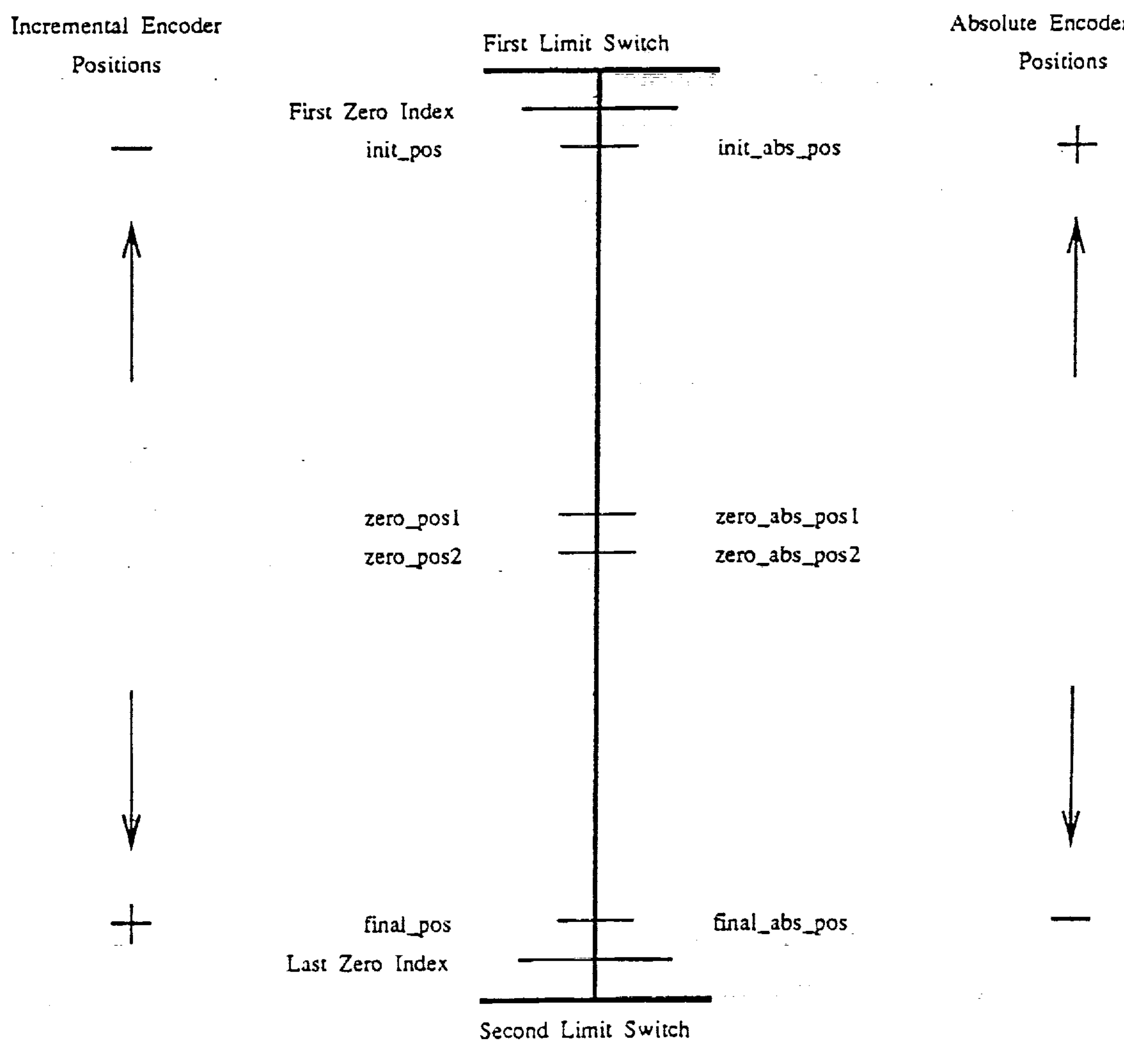

Figure 4.1: The Locations of Critical Points in System Calibration

incremental position readings. The position given by Whedco Interface keeps track of the distance between the the zero index and the point where the joint stopped. *init_pos* is taken when the joint has fully stopped, at some position very close to the zero index. Since the position of a joint is set to zero when a zero index is encountered, *init_pos* can be use to correct *init_abs_pos*. This is done before *init_pos* takes the value of $-1 * zero\_pos1$. Similar process is used for the final position readings.

Using the number of zero index count, the increment in absolute position, the increment in incremental encoder, and the initial and final positions a look-up table is formed. This table contains a list of absolute encoder positions that occur at all the zero index of that joint. It also contains a list of incremental encoder positions that corresponds to these absolute encoder positions. The table is stored in a C header file that is included in any future programs that require joint position informations. There is one header file for each joint.

The zero position of the tilt axis is defined at the midpoint between the +0.785 radians (+45 degrees) and -0.785 radians limit switches when the base for PUMA is parallel to the ground. For the linear axis, the zero position is defined at a point for which the center of either cart lines up with the center of the rail. This is where zero location of the zero coordinate frame is defined. The zero position of the rotate axis is defined at the midpoint between the +150 degrees and -150 degrees limit switches.

4.3 Power-up Calibration

Power-up calibration of the platform is used to determine the initial position of each joint after high power is turned on. This should be run before any joint is to be moved.

The first step in power-up calibration is to read the absolute encoder position from the PIT. That value is then compared to the list in the correct look-up table which is created during system calibration. The closest zero index is determined. A torque is then applied to the joint to move it to that index. A second feature of the Whedco interface is used here - find zero index then set position count to a specified value. The incremental position that corresponds to the absolute position (at the closest zero index) is set onto the Whedco Interface. From that point on, the Whedco Interface is able to keep track of where the joint is with any increment or decrement of position.

4.4 Summary

This chapter presented the theory of system and power-up calibration. It also stepped through the procedures for each calibration.

CHAPTER 5
SOFTWARE DESCRIPTION

This chapter lists the routines used for both system calibration and power-up calibration. The parameters and returns for each routines are given. A short description of the purpose of each routine is also included. Lastly, the calibration programs and the header files are described.

5.1 Description of Functions

There is one library, *platcalLib*, which includes all the routines used in both system and power-up calibration. *platcalPit.c* includes routines used to initialize, release, read, and write from the Parallel Interface/Timer Module. *platcalLib.c* holds routines that initialize the correct hardware, move the platform to limit switches and zero indices, get absolute encoder positions, create header files, and release hardware.

5.1.1 platcalPit.c

The routines in this program are called by the routines in *platcalLib.c* to obtain the absolute position count of each joint.

Routine: *platcalPitInit*

Parameter: None.

Return: PLATCALPITOK - indicates successful PIT initialization.

Purpose: Configures PIT board to receive 16-bit data from the CIRSSE multiplexer and to send 8-bit command for the selection transducer and electromagnet pair.

Routine: *platcalPitRelease*

Parameter: None.

Return: None.

Purpose: Resets registers on PIT board.

Routine: *platcalPitClear*

Parameter: direction - specifies whether the read registers or the write registers are to be cleared.

Return: PLATCALPITOK - indicates registers cleared successfully.

Purpose: Clears the selected PIT registers before next read or write command.

Routine: *platcalPitWrite*

Parameter: command - specifies which channel of the multiplexer is to be activate.

Return: PLATCALPITOK - write success.

Purpose: Writes a command to port B of chip 1 of the PIT board to specify the transducer/absolute encoder and electromagnet pair to activate.

Routine: *platcalPitRead*

Parameter: location - 16-bit absolute position count.

Return: PLATCALPITOK - read success.

Purpose: Obtains the absolute position count of a specified joint from port A of both chip 1 and chip 2.

The header file *platcalPit.h* defines the hexadecimal command used to specify the encoder/transducer and electromagnet pair. It does the forward declaration of all the function in this library. The macros for identifying the Parallel Interface/Timer board and the two chips that are presently being used are also defined. The return code for each function is also specified.

5.1.2 platcalLib.c

This program contains the routines required for both system calibration and power up calibration.

Routine: *platcalInit*

Parameter: None.

Return: PLATCALOK - success.

Purpose: Initializes the required hardware and turns high power off.

Routine: *platcalMoveToLimit*

Parameter: joint - joint of platform to be moved.

limit - direction the platform is to move in.

position - pointer to position of joint.

Return: PLATCALOK - success.

PLATCALERROR - hardware not responding correctly.

Purpose: Moves a joint to the specified limit switch.

Routine: *platcalFirstZeroIndex*

Parameter: joint - joint of platform to move.

limit - direction the platform is to move in.

mode - specify to set Whedco Interface position count zero or a specified value.

position - pointer to position of joint.

Return: PLATCALOK - success.

PLATCALERROR - hardware not responding correctly.

Purpose: Moves a joint toward a specified limit switch and stop the joint at the first zero index encountered.

Routine: *platcalRelease*

Parameter: None.

Return: PLATCALOK - success.

Purpose: Releases hardware after calibration is done.

Routine: *platcalAbsPosition*

Parameter: joint - joint of platform to find absolute position of.

abs_position - pointer to absolute position of a joint.

Return: PLATCALOK - successfully reads the position.

Purpose: Writes a command to specify encoder/transducer and electromagnet pair then reads absolute position from PIT board; gives the absolute position of joint in meters or radians.

Routine: *platcalSetTable*

Parameter: init_pos[ ] - initial position vector for incremental encoder.

zero_pos1[ ] - first zero position vector of each joint.

zero_pos2[ ] - second zero position vector of each joint.

final_pos[ ] - final position vector for incremental encoder.

init_abs_pos[ ] - initial position vector for absolute encoder.

zero_abs_pos1[ ] - first absolute zero position of each joint.

zero_abs_pos2[ ] - second absolute zero position of each joint.

final_abs_pos[ ] - final position vector for absolute encoder.

Return: PLATCALOK - success.

Purpose: Uses incremental and absolute encoder positions to make a look-up table (stored as a C header file) for each joint. This function is called after all the positions (incremental and absolute) have been obtained.

The header file *platcalLib.h* contains the macro for joint identification. It does the forward declaration of all the routines in *platcalLib.c*. A couple of timer constants are also defined. These timers are used by the velocity controller inside the routines *platcalMoveToLimit* and *platcalFirstZeroIndex*. The conversion factor for absolute encoder are given in *platcalLib.c*.

5.2 Calibration Programs

The program, *platSysCal.c*, is used for system calibration. It initializes the hardware. It defines the limit switches for each joint. It directs the user to move the joint to a specified position off the limit switch starting with joint one. *platcalMove-ToLimit* then moves the joint to the limit. *platcalFirstZeroIndex* backs the joint off the limit switch and stops the joint at the first zero index. The incremental encoder and absolute encoder positions are obtained by using *platPosSRead* (a function from *platLib.c*) and *platcalAbsPosition* respectively. This process is repeated for the limit at the other extreme. When all the positions from all six joints are obtained. *plat-calSetTable* is called to set up header files. Lastly, *platcalRelease* is used to reset the hardware.

The program *platPowerCal.c* is used for power-up calibration. It initializes the hardware. It defines the limit switches for each joint. Two pointers, *absPtr* and *incPrt*, are used to point to the absolute position and incremental position arrays in the look-up table. This program then reads the absolute encoder of a joint starting with joint one. This absolute encoder position is compared with the values in absolute position array. The closest zero index is determined. The incremental encoder position corresponds to that zero index is loaded into the Whedco Interface. This is done by using the second feature of the interface (find zero index then set position count to a specified value). The joint position is set to the incremental encoder value from the look-up table when the zero index is detected. As in system calibration, *platcalRelease* is used to reset the hardware.

5.3 Header Files

The header files are written by *platcalSetTable*. The name of each header files is *platcalJoint* $*$ *.h* ($*$ is a number from 1 to 6). ZERO_INDEX_COUNT* is the number of zero index joint * has. The two arrays inside the header files are abs_enc_pos*[ZERO_INDEX_COUNT*] and inc_enc_pos*[ZERO_INDEX_COUNT*]. All six header files are included in the power-up calibration.

5.4 Summary

This chapter reviewed the routines used in both platform calibration and power up calibration. The purpose of each routine was described. System calibration and power-up calibration programs were also mentioned.

CHAPTER 6
CONCLUSION AND FUTURE WORK

The goal of this project is to determine the position of the joints of the platform when it is in use. Absolute encoders and Temposonics transducers are used to determine the joint position at start up. Software programs are written to do system calibration (calibrate the hardware and set up header files) and power-up calibration (find the starting position).

The hardware (Temposonics I Flexible Transducer, Temposonics II Linear Transducer and Absolute Optical Encoders) is installed. The electronics are also in place. Software programs for system calibration (*platSysCal.c*) and power-up calibration(*platPowerCal.c*) have already been written. System calibration will be done as soon as the diagnostic for the hardware is run.

Before signals from the absolute encoders become available, the absolute positions of all six joints at the first zero indices need to be measured by hand and hard coded into the system calibration program. This then requires the power-up calibration to be done off the limit switches.

The results of *platPowerCal.c*, the joint positions, are stored in an array. These positions are printed out on the monitor. It is possible to pass the position information to a program which requires the knowledge of starting position of the joints. A simple program that calls the power-up calibration will be use to test the availability of this information.

The follow still need to be accomplished:

1. Run the diagnostic on the hardware.
2. Run case zero of the system calibration.
3. Calibrate the system with *platSysCal.c*.

4. Test *platPowerCal.c.*

5. Modify *platPowerCal.c* for more general usage.

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APPENDIX A
SOFTWARE UPDATE

This appendix describes all the important programs in the *platcalLib* directory. Some of them has already been mentioned in Chapter 5. Thus, the changes made in those programs are also given.

A.1 platcalPit.c

As mentioned before, the routines in *platcalPit.c* are used to initialize, release, read and write from the Parallel Interface/Timer Module. The read and write routines are called by *platcalAbsPosition* located in *platcalLib.c*. *platcalPitRead* is used to obtain a specified absolute encoder position. *platcalPitWrite* is used to select the correct absolute encoder with its corresponding electromagnet pair. *platcalPitInit* and *platcalPitRelease* are called by *platcalInit* and *platcalRelease* respectively.

The description of all four of these functions has been given in Chapter 5.

A.2 platcalPit.h

This header file is includes in all the programs that require the knowledge of the macros defined in it.

A.3 platcalLib.c

This program contains the routines required for platform calibration. The description of the functions has already been given in Chapter 5. Two changes were made in the parameters of *platcalSetTable*. The first is the addition of the parameter, *joint*. The second is the change of the positions passed in from arrays to pointers. This is done so it is be possible to calibrate the platform one joint at a time.

 # ifndef and *# ifdef* are put in to activate and deactivate the diagnostic print lines in the routines, respectively. Only one set should be use at one time.

The functions in this routines are called by the calibration programs.

A.4 platcalLib.h

Aside from the forward declaration of the *platcalLib.c*, the ones for both *platPowerCal0.c* and *platPowerCal.c* are also included. A structure type, *PLATCALCONSTTYPE*, is defined here. It is used to define the constants that are used by all the routines.

A.5 platcalConst.c

This program contains an array *abs_consts[PLATNUMJOINTS+1]*. Each element of this array is a structure of *PLATCALCONSTTYPE* type. The conversion factor from absolute encoder readings to radians or meters is given. The command for activating the correct combination of absolute encoder and electromagnet pair is included. In addition, the limit switch and the initial torque required to move the joint in that direction is also given. This array is used in all the calibration programs.

A.6 ZeroIndexPosTest.c

This program is used to determine the location of the first zero index for each joint. The result of this program is used to hardcode the absolute position in *platPowerCal0.c* (case 0 of power-up calibration).

A.7 platPowerCal0.c

This program contains two routine, *platPowerCal0* and *platPowerCal0All*. They are used to calibrated the platform manually at power-up. *platPowerCal0* is called to calibrate a specified joint. *platPowerCal0All* is used to calibrated all six joints at one time. The descriptions of the functions are given below.

Routine: *platPowerCal0*

Parameter: joint - the joint to be calibrated.

pos - pointer to the calibrated position of a joint.

Return: None.

Purpose: Determine the position of the first zero index of a joint with respect to the world coordinate frame.

Routine: *platPowerCal0All*

Parameter: pos[ ] - position vector.

Return: None.

Purpose: Determine the position of the first zero index of all joints.

A.8 PowerCal0Test.c

This is a test program that calls *platPowerCal0All.* It then prints out the position of each joint with respect to the world coordinate frame.

A.9 platSysCal.c

platSysCal.c is used to calibrate the hardware with respect to known zero positions. It then sets up look-up tables (header files) for power-up calibration. This program asks the user to specify the joint, it then walk the user through the calibration procedure. Lastly, it sets up the header file for that joint.

A.10 platPowerCal.c

This program contains two routine, *platPowerCal* and *platPowerCalAll.* They are used to calibrated the platform at power-up. *platPowerCal* is called to calibrate a specified joint. *platPowerCalAll* is used to calibrated all six joints at one time.

Routine: *platPowerCal*

Parameter: joint - the joint to be calibrated.

pos - pointer to the calibrated position of a joint.

Return: None.

Purpose: Determine the position of the first zero index of a joint with respect to the world coordinate frame.

Routine: *platPowerCalAll*

Parameter: pos[ ] - position vector.

Return: None.

Purpose: Determine the position of the first zero index of all joints.

A.11 load.sh

This program is used to load the required objet (.o) files onto the VME cage. To execute the following programs, *PowerCal0Test.c*, *platPowerCal0.c*, *ZeroIndexPosTest.c*, *platSysCal.c*, *platPowerCal.c*, just type in the name of the program without the *.c*.