# Chapter 4

Test Apparatus Assembly

The test apparatus was constructed to meet the design criteria set forth in Chapter 3. As construction progressed, systems were reevaluated and revised as necessary to provide the required performance.

4.1   Frame Construction

High yield strength (70,000 psi), low material cost, and machinability made cold-rolled steel the logical material choice for the frame, as well as the table support and the vertical rods upon which the support slides (Figure 4-1).
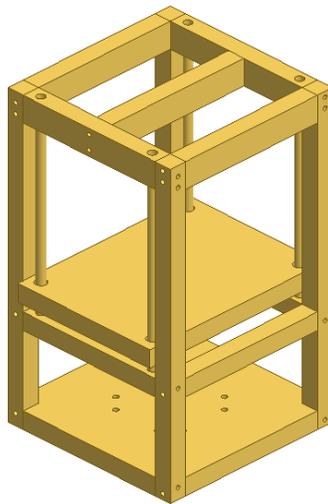
Figure 4-1. CAD drawing of the device components constructed from cold-rolled steel: the frame, table support, and vertical guide rods.

The steel was ordered in 1.5" thick plates and 1.5 x 1.5" and 1.5 x 2.5" bar stock. The bars and plates were cut to desired length and holes drilled and tapped by the machine shop (Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg, VA) to ensure easy assembly of the frame. Holes were also drilled and tapped in the bottom plate, table support, and top bars to allow attachment of the pneumatic cylinder, linear guides, and rod bearings, respectively. All frame bars and plates were fastened using 3/8" socket head bolts. Figure 4-2 shows a typical CAD

drawing given to the machine shop during construction.   All of the CAD drawings
necessary to machine and assemble the frame parts are given in Appendix A.
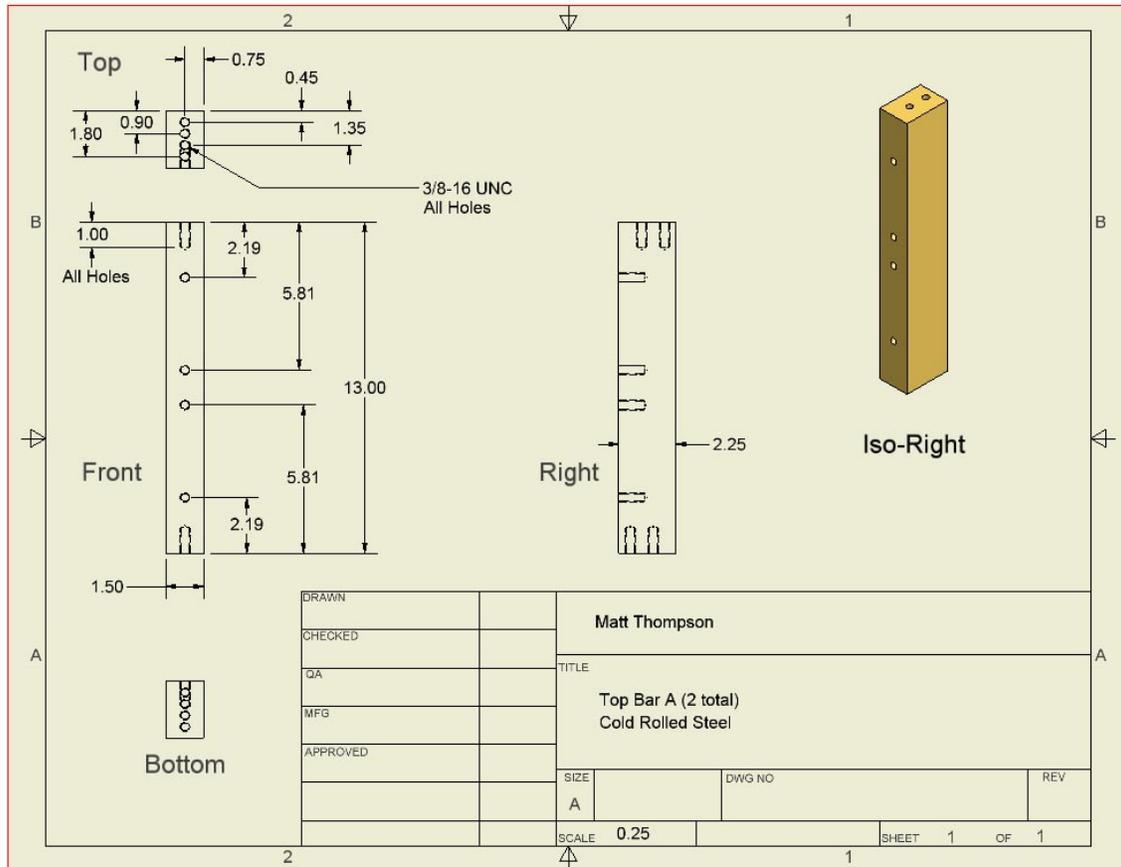
Figure 4-2. A typical CAD drawing given to the machine shop to construct the frame. This particular drawing shows the dimensions (in inches) of the two top bars that hold four of the rod bearings.

Once the frame was assembled, the table support plate was machined to accommodate the pneumatic cylinder and vertical guide rods.   Six pillow-block bearings were fastened to three of the top bars, awaiting the completion of the two F/E rods. The frame and the manner in which it was bolted together can be seen in Figure 4-3.

Figure 4-3. Photograph of the completely assembled device. The frame, the table support, and the vertical guide rods can be seen here, as well as the placement of the bolts, which fastens the components together.

4.2 Integration of Components

Assembly of the wear testing device followed completion of the frame. Although some machining was still necessary, remaining construction largely involved the attachment of the tables, the motors, and the cylinder.

4.2.1 Linear Guides

The linear guide responsible for AP sliding was mounted to the table support using four screws. The guide used to simulate tibial rotation was fastened perpendicular to the AP sliding guide to allow cross shear during testing. To permit simple removal of the UHMWPE tray and to keep the original tray design, a support plate was mounted between the tray and the upper guide. A ½" spacer was sandwiched between the tray and the support plate to add height to the system, ensuring sufficient contact between the UHMWPE and the CoCr discs. The labeled photograph in Figure 4-4 shows these parts.
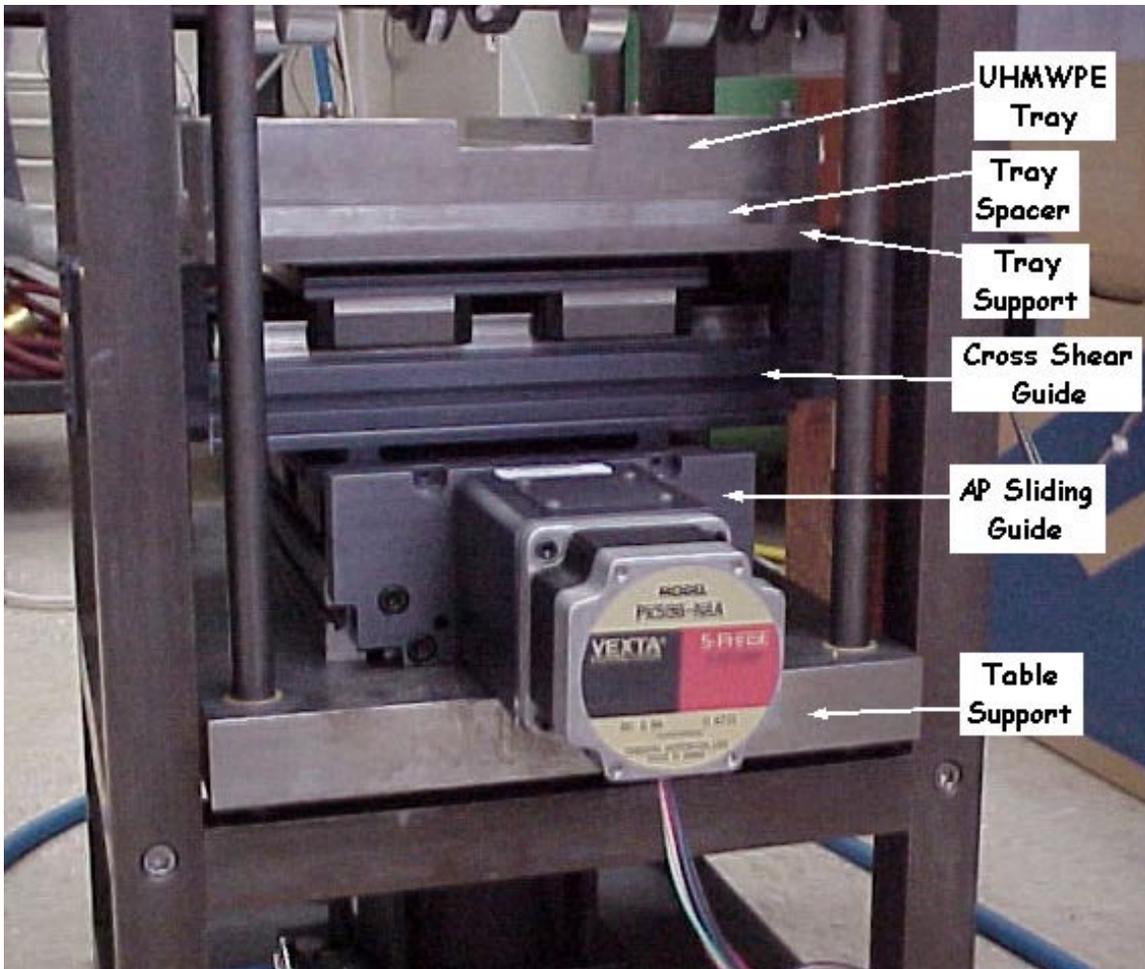
Figure 4-4. Labeled photograph showing the parts that make up the bottom, or "tibial", portion of the wear testing device.

4.2.2 UHMWPE Tray

Due to the hardness of stainless steel and the large specimen holes, the most complicated and costly machining involved that of the tray, which housed the UHMWPE. Refer to Appendix F for the cost analysis. Based upon the design previously described in Chapter 3, the tray was machined to attach atop the tray spacer and support (Figure 4-5). For testing purposes, the UHMWPE blocks (or other test materials) were press fit into the tray's counterbores to complete the bottom portion of the device.
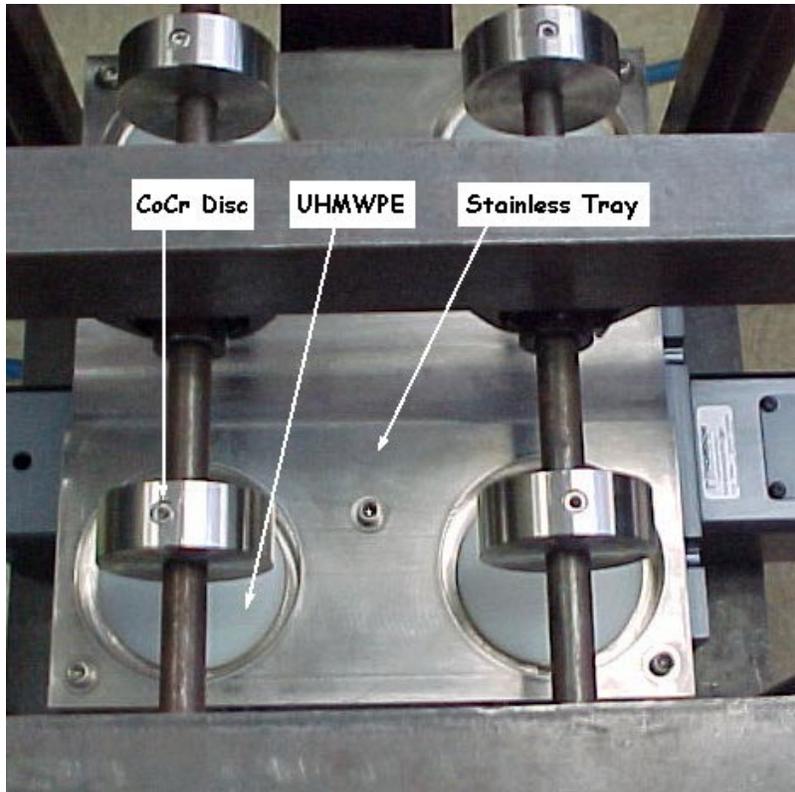
Figure 4-5. Top view of the device showing the stainless steel tray that houses the UHMWPE blocks.

### 4.2.3   CoCr Discs and F/E Rods

A 5/8" hole was drilled through the center of each CoCr disc allowing them to slide over the two cold-rolled steel F/E rods. Holes were tapped in the rods and another set of through holes drilled in the discs to permit attachment of the CoCr discs to the rods using socket head screws. The two rods were put through the six bearings, and then the bearings were tightly fastened and locked. The rods, discs, and the socket screws used to lock them together are shown in Figure 4-5.

4.2.4   F/E Motor Mount

To mount the two F/E motors, a motor mount was designed and machined. The mount was designed to hold the motors firmly, as well as allow space between the rods and motor shafts for the motor couplings. To reduce cost and machining time, the mount shown in Figure 4-6 was constructed of aluminum rather than steel.   The motor mount was machined and mounted in the position shown in Figure 4-7.
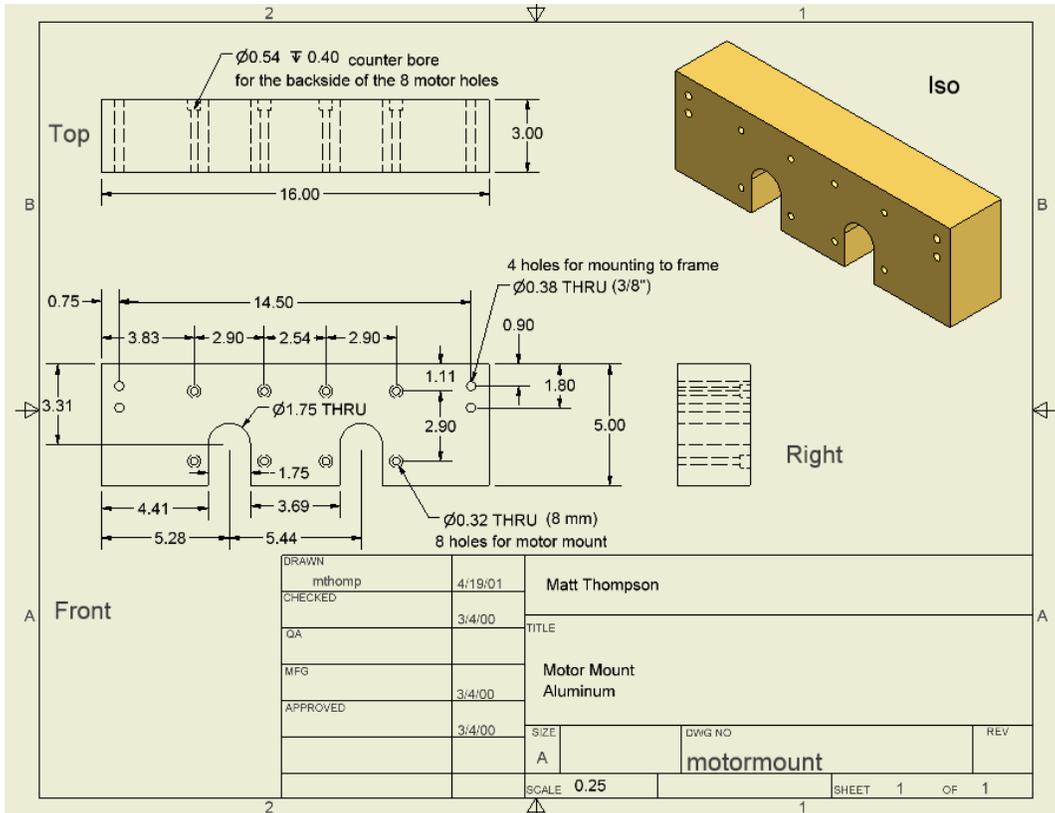
Figure 4-6. CAD representation of the F/E motor mount. The two sets of holes in the upper left and right corners allow attachment of the mount without any modifications to the frame. The two large holes in the bottom of the mount provide sufficient room for the motor couplings.
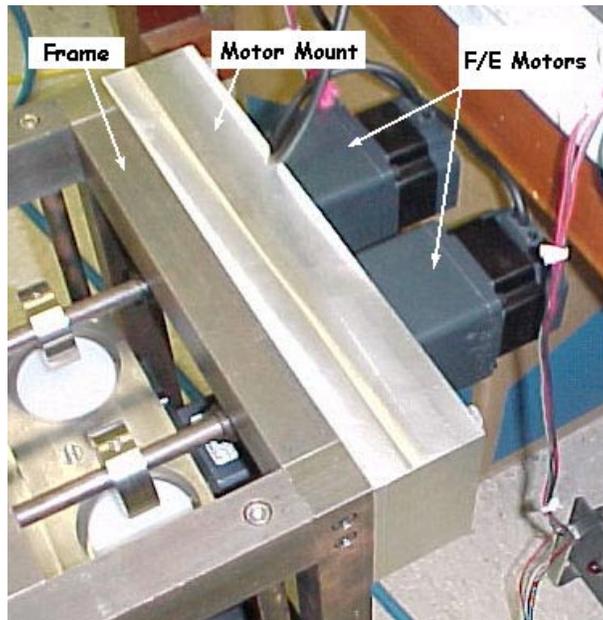
Figure 4-7. Photograph showing the motor mount attached to the apparatus frame.

65

4.2.5 Mounting the Motors

Attaching the motors to the device was simple, each motor required four bolts and a coupling. The two motors (NEMA 34) for the linear guides used ½" inner diameter (ID) to ½" ID couplings, while the F/E motors (NEMA 43) required 12 mm (0.47") ID to 5/8" ID couplings. After the motors were mounted, the couplings were tightened, and any rotation of the motors now resulted in movement within the device. Wiring of the motors to the controlling computer will be subsequently discussed.

4.3   Hardware Integration

Once all of the device's components were assembled, integration of the apparatus to the computer (Dell XPS T450, Dell Computer Corp., Round Rock, TX) followed. The task of achieving control of the apparatus by the computer mainly involved interfacing the pneumatic valve, stepper motor drivers and controllers with the computer.

4.3.1   Par-15^{TM} Valve Operation

As described in Chapter 3, the Par-15^{TM} pneumatic valve accepts a binary number from the computer between 0 and 15, and outputs a pressure between zero and the inlet pressure, in increments of $1/15^{th}$ of the inlet pressure. For connection to a wall outlet, an 115 volt (V) AC powered Par-15^{TM} valve was chosen for the apparatus. The four solenoids within this valve are opened or closed by an 115V input. To convert 5V binary output from the computer to 115V binary input into the valve, an 8 module backplane (Grayhill #70RCK8, National Instruments, Austin, TX) with four 115V output modules (OAC5A) was purchased (Figure 4-8).   The "hot" wire of a properly grounded three-pronged power cord was wired through the odd terminals of the four modules on the backplane. The four input wires of the valve (Figure 4-9) were connected to the modules' even terminals, and the common and ground from the valve were wired to the common and ground of the power cord. Lastly, a 5V power supply (APX Technologies Inc., Hicksville, NY) was connected to the backplane to power the modules. The backplane, modules, and wiring configuration are shown schematically in Figure 4-8.
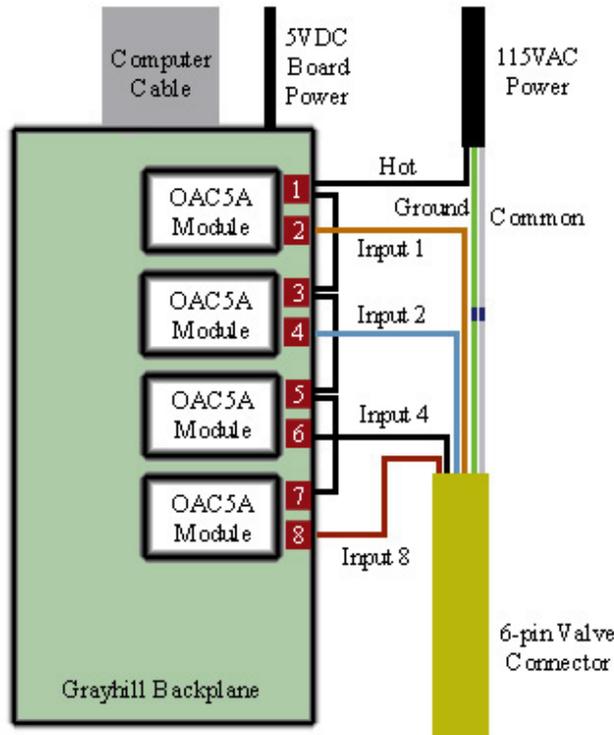
Figure 4-8. Schematic of the backplane and modules used to convert binary output from the computer into the 115V AC current necessary to activate the solenoids of the pneumatic valve. (Not to scale)

Pin	Wire Color	Function
1	Orange	Input 1
2	Blue	Input 2
3	Black	Input 4
4	White	Common
5	Red	Input 8
6	Green	Equipment Ground

Figure 4-9. Schematic of the PAR-15^{TM} pneumatic valve's 6-pin connector. (Installation Instructions, Parker Pneumatic, Richland, Michigan)

Once the valve was properly wired, 3/8" ID polyvinyl chloride (PVC) hosing was used to connect the inlet of the valve to the air tank (W. W. Grainger, Chicago, IL). For initial validation of the valve functionality, PVC hose was connected between the outlet of the valve and a pressure gauge for validation test. After the valve was determined to be functioning properly (refer to Appendix C), the gauge was removed and PVC hose was connected from the outlet of the valve to the rod end of the pneumatic cylinder. To

reduce noise and vibration, a small muffler (McMaster Carr, Atlanta, GA) was attached to the exhaust of the valve.

4.3.2   Motor Controllers and Drivers

Connection of the four stepper motors to the computer was more complicated than the wiring used for the previous setup. Since each motor came with its own driver, each driver needed to be separately wired and powered. A motion control board (National Instruments) was also necessary to provide the proper input into the drivers. The key components of the motion control hardware system are shown in Figure 4-10 and subsequently described.
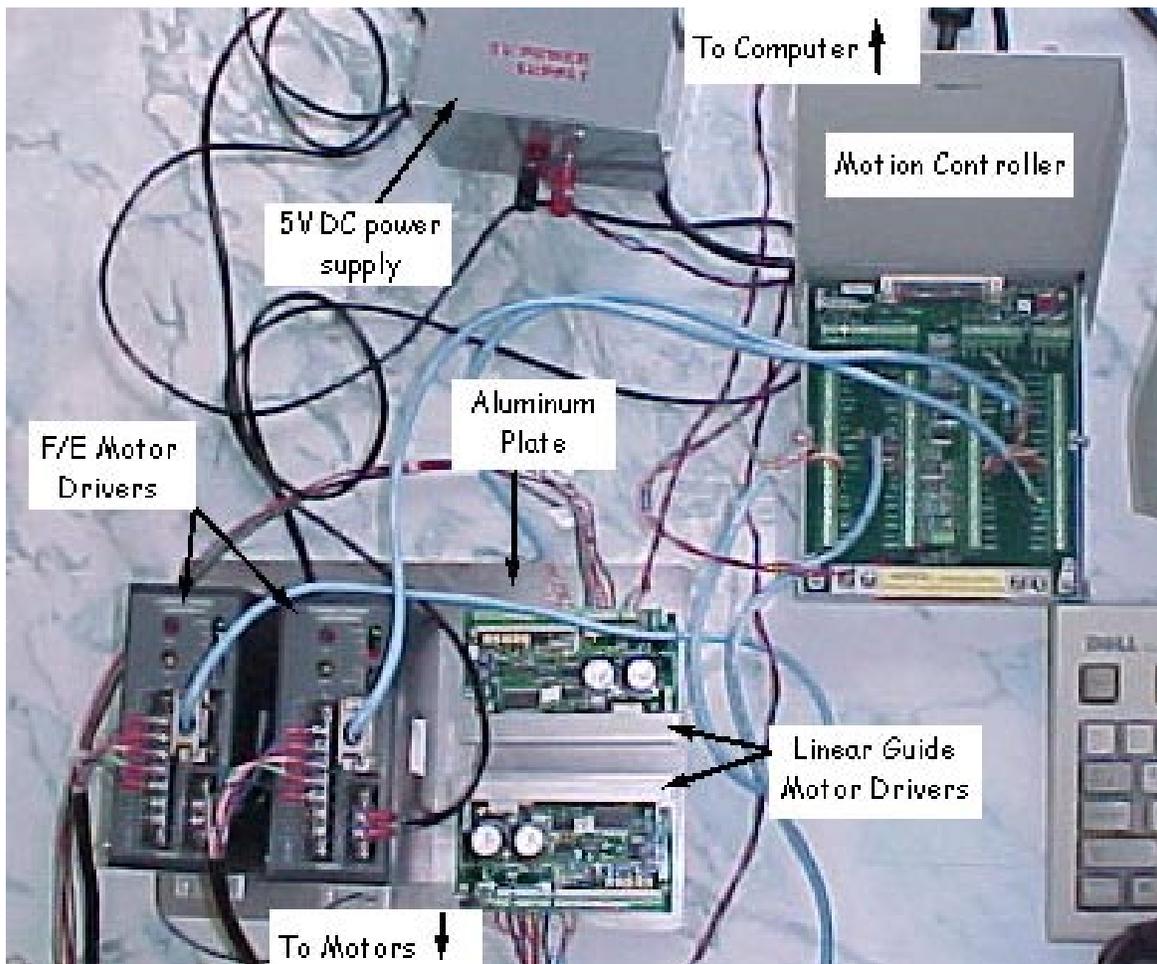

Figure 4-10. Photograph of the main components of the motion control hardware. To better understand the relationships between the parts of the motion control hardware, refer to the schematic of Figure 4-13.

4.3.2.1 PCI Motion Controller

To allow for "communication" between the computer and the motors, a motion control card and board (#7324, National Instruments, Austin, TX) were installed into an available PCI slot in the PC. The motion controller (#UMI7764, National Instruments) can operate up to four independent axes in either open or closed-loop mode, and supports full, half, and microstepping applications. The motion controller board was powered by a 5V DC power supply. The board houses a multitude of inputs and outputs for each of the four axes, but for this project only the step and direction output terminals were used. Motion control software (ValueMotion, National Instruments) was also installed to configure the controller. After the motion control card and board were properly configured, the four separate motor drivers were wired as subsequently discussed.

4.3.2.2 Linear Guide Motor Drivers

Each motor used with the two linear guides came with its own driver package, also from Oriental Motors (motor driver package #CSK596-NATA). The drivers accept the pulse, direction, and step angle signals from the motion controller, and then output the desired signal to the 5 phase stepping motors. As denoted in Figure 4-11, each driver is powered by a 24V power supply (Lambda Power, San Diego, CA) (not pictured in Figure 4-10). Also, as seen in Figure 4-11, multiple inputs and outputs are possible with the drivers. To simplify wiring and operation, it was initially decided that closed loop feedback was not necessary. Hence, only the pulse and direction signals from the two linear guide axes, numbers 3 and 4, on the controller were wired. The two linear guide motor drivers were mounted to a ¼" thick aluminum plate (Figure 4-10), which functioned as a ground and heat sink for all four drivers.
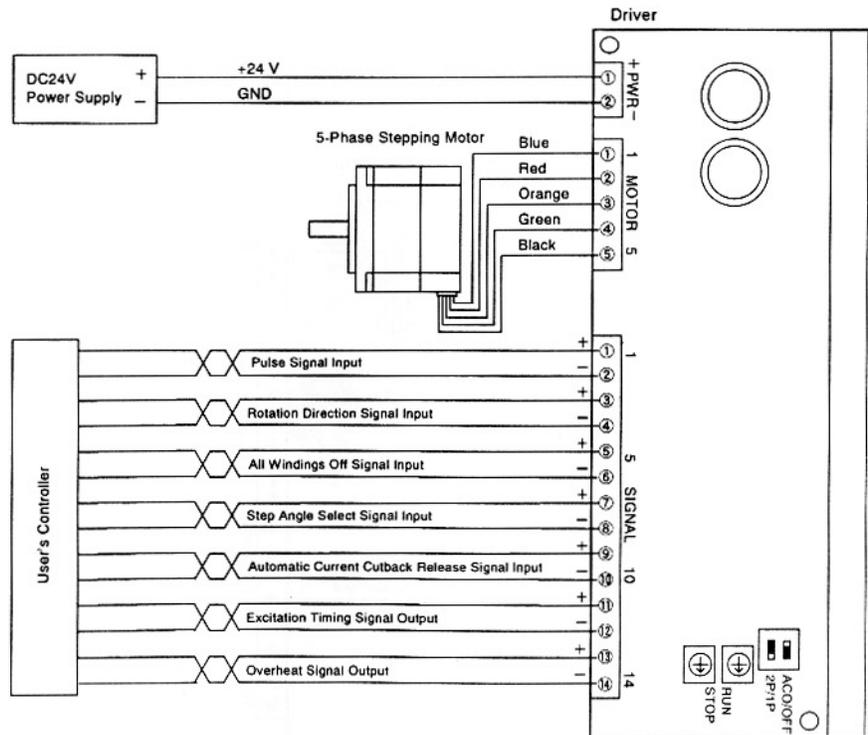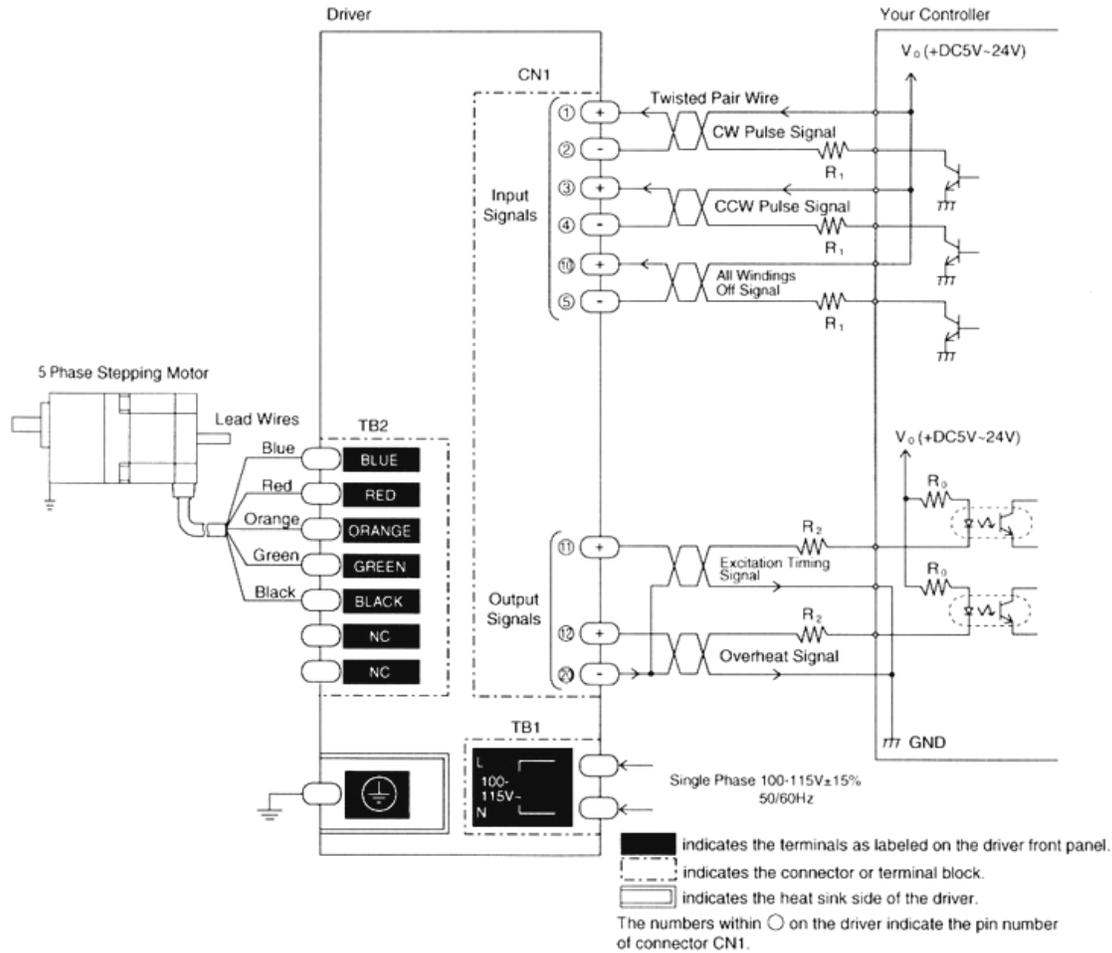
Figure 4-11. Wiring diagram for the linear guide motor drivers. Only signal terminals 1 through 4 were used for the designed apparatus. (Oriental Motors)

4.3.2.3 Flexion/Extension Motor Drivers

To drive the high torque geared F/E motors, the two F/E motor drivers (motor driver package #UPK596AW-T20, Oriental Motors) have a built in 80V DC power supply. Consequently, powering the F/E motor drivers only required connection to an 115V AC wall outlet. The wiring diagram for the F/E motor drivers is shown in Figure 4-12. Unlike the screw terminals of the linear guide drivers, a 20-pin I/O signal connector on the F/E drivers accepts signals from the controller. Eight of the twenty pins were wired and soldered, but like with the other two drivers, only the step and direction signals were wired to the controller (axes 1 and 2).

Figure 4-12. Wiring diagram for the F/E motor drivers. Only input signals 1 through 4 were used here as well. (Oriental Motors)

Connection of the motor wires completed the link between the PC and the four motors. A schematic showing the integration of all of the devices parts, from the motors and drivers to the valve and backplane, is given in Figure 4-13. Programming of the motions and loading curves for the motors and valve will be discussed in Section 4.4.
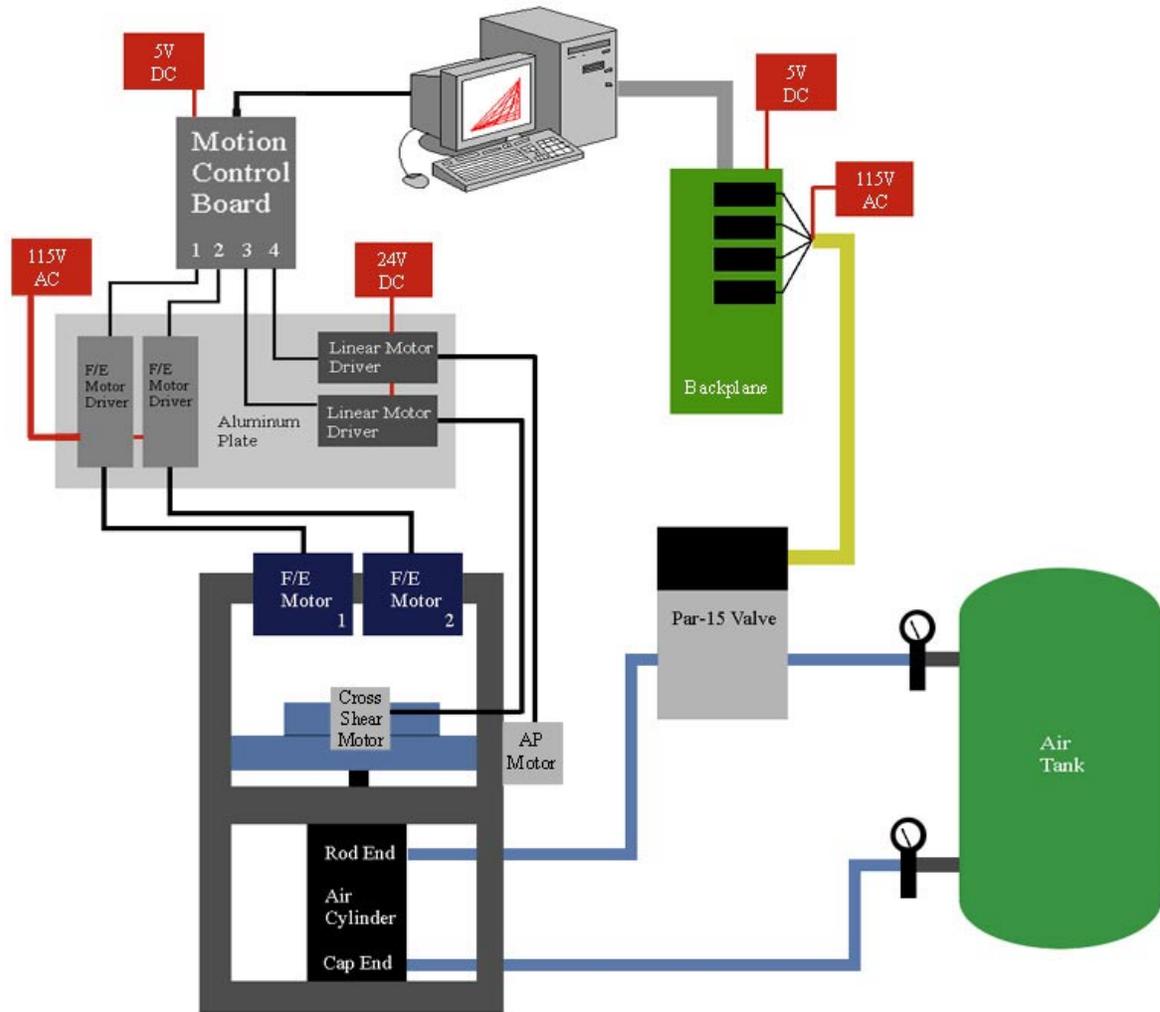
Figure 4-13. Schematic showing the integration of the device's key components. (Not to scale)

4.4   Software Development

After the components of the apparatus were appropriately wired, establishing a link of communication between the PC and the components was initiated. Labview™ (National Instruments) was chosen as the programming language because of its compatibility with the National Instruments hardware and its user-friendly graphical interface. The motion control software that came with the motor controller included some Labview™ Virtual Instruments (VIs), which were modified for our device, but the valve VI was written in its entirety.

4.4.1 Valve Software

The specifications for the Par-15 ^{TM} pneumatic valve were previously described in Chapter 3. The valve accepts a binary number from the PC between 0 (0000) and 15 (1111), and outputs a pressure between zero and the inlet pressure, in increments of 1/15th of the inlet pressure. The primary goal of the designed software was to input the valve inlet pressure along with a physiologically-correct loading curve, and output the correct sequence of binary numbers to the backplane. The valve only supplies the rod end of the cylinder. The cap end of the cylinder was kept at a constant pressure equal to the inlet of the valve. With the net pressure and resulting cylinder force of primary interest, the VI was programmed to ensure that the force applied by the cylinder matched the loading curve. A sequence of pressures representing points on the Seireg loading curve was imported from a Microsoft Excel spreadsheet as a list of 50 numbers. Because the valve supplied the rod end of the cylinder, the imported curve was inverted in the spreadsheet. Therefore, when the loading curve was at a maximum, the valve was actually supplying a minimum pressure to the rod end, maximizing the force applied to the device by the cap end of the cylinder.

To better illustrate this phenomenon, consider the following example: Suppose the valve inlet and cap end pressures were 75 psi and the first desired peak of the loading curve occurred at 0.4 of the maximum peak. To invert the curve, each point was subtracted from 1. For the example given, the peak on the curve was now 0.6, which was multiplied by 15 (increments of the valve) to get 9. The number 9 was then converted to its binary number, 1001, which was sent to the backplane. Also, consider that the valve solenoids were normally-open, which meant that a 115V signal closed them. However, the backplane was normally-on, which meant when a module of the backplane was pulsed with a voltage from the PC, the module was turned off, which resulted in opening its corresponding valve solenoid. Therefore, the valve actually acted as if it was normally-closed, since a signal from the PC turned off the module and opened the solenoid. Following the truth table for a normally-closed valve (Figure 4-14), the binary number 1001 opened inputs 1 and 8 (Figure 4-9), outputting a pressure equal to 9/15 of the inlet pressure (Figure 4-14), or 45 psi, to the rod end. With the cap end at 75 psi, the

net pressure was 30 psi, or 0.4 of the maximum pressure. This process was repeated for each of the 50 points of the loading curve

PAR™-15 Valve

Truth Table

Normally Closed Valves/ Solenoids	Normally Open Valves/ Solenoids	Proportion of Inlet Pressure	PSIG Output @ 75 PSIG Inlet ††	PSIG Output @ 90 PSIG Inlet
Binary Input* 8 4 2 1 Pin Number † 5 3 2 1	Binary Input* 8 4 2 1 Pin Number † 5 3 2 1			
0 0 0 0	1 1 1 1	0	0	0
0 0 0 1	1 1 1 0	1/15	5	6
0 0 1 0	1 1 0 1	2/15	10	12
0 0 1 1	1 1 0 0	3/15	15	18
0 1 0 0	1 0 1 1	4/15	20	24
0 1 0 1	1 0 1 0	5/15	25	30
0 1 1 0	1 0 0 1	6/15	30	36
0 1 1 1	1 0 0 0	7/15	35	42
1 0 0 0	0 1 1 1	8/15	40	48
1 0 0 1	0 1 1 0	9/15	45	54
1 0 1 0	0 1 0 1	10/15	50	60
1 0 1 1	0 1 0 0	11/15	55	66
1 1 0 0	0 0 1 1	12/15	60	72
1 1 0 1	0 0 1 0	13/15	65	78
1 1 1 0	0 0 0 1	14/15	70	84
1 1 1 1	0 0 0 0	15/15	75	90

Figure 4-14. Truth table for the Par-15™ Valve. Notice that a binary input of 1001 corresponds to a pressure 9/15 of the inlet pressure. (Installation Instructions, Parker Pneumatic)

The time it took the valve to cycle through the loading curve was dependent on the frequency response of the valve and the modules. The frequency response of the modules was insignificant in comparison to that of the valve (approximately 20 milliseconds per pressure change). Thus, cycling through 50 points at about 20 ms per point would take approximately 1 second. However, since the valve was only capable of changing pressure in increments of $1/15^{th}$ of the inlet pressure, many adjacent points on the curve were within the same pressure range, or on the same "step". Although frequencies higher than 1 Hz were theoretically possible by decreasing the resolution of the loading curve, the acceptable design specification previously established was 1 Hz.

Considering the limitations of the valve, a Labview™ VI was written to import the prescribed loading curve and repeatedly output the desired binary sequence. The VI was also capable of adjusting the frequency by varying the delay between points on the loading curve. A screen shot of the valve VI is shown in Figure 4-15.
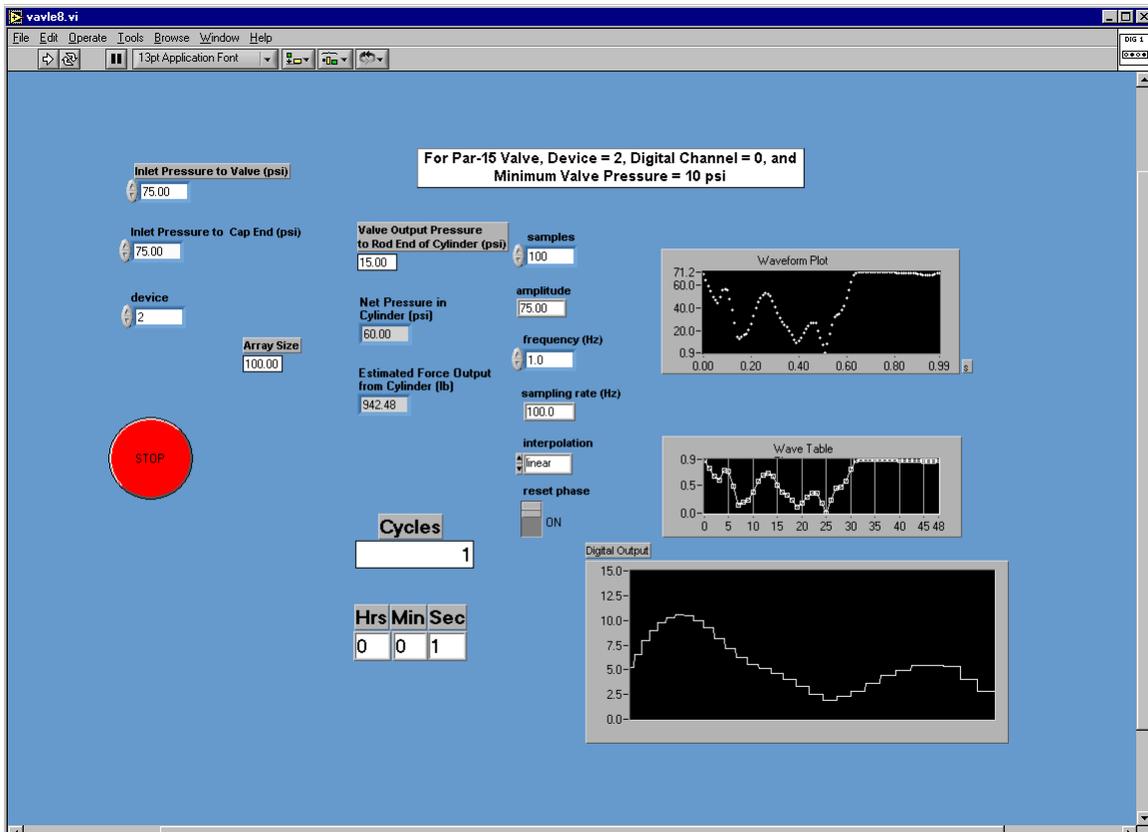
Figure 4-15. Screen shot of the Labview^{TM} VI responsible for controlling the pneumatic valve. The plot on the top right shows the inverted loading curve, while the plot on the bottom right shows the real time binary output.

Once the valve VI was working properly, the VI was combined with the motor VIs to synchronize the loading curve with the motor motions. Synchronization of the VIs is explained further in Section 4.4.3.
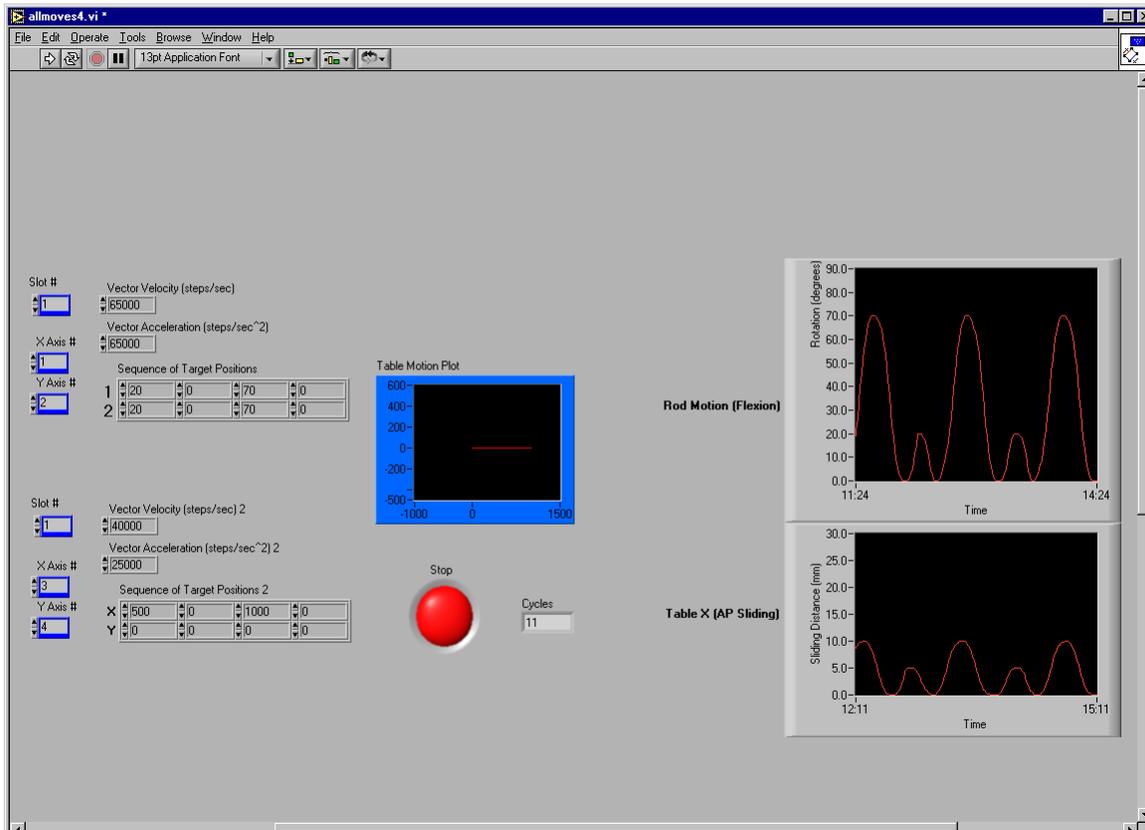
4.4.2 Motion Control Software

The software (ValueMotion, National Instruments) included with the motion control hardware contained several example VIs for stepper motors. The most useful VI accepted a sequence of target positions and ran the motors through those positions, plotting the positions in real time. Although it was originally hoped that the motor VI would function like the valve VI, importing the motion curve and driving the motors through multiple positions at a specified frequency, this was not the case. To overcome this difficulty with LabView^{TM} and due to time constraints, an example VI was modified which required only four positions be programmed. Recall that the AP sliding and F/E

curves (refer to Section 2.1.2) are similar to a sine wave with two peaks of different amplitude. By modifying the example VI, only the two maximums and the beginning and end positions were necessary inputs for LabView[TM] to approximate the points in between with a sine wave.   The AP and F/E curves are shown on the screen shot of Figure 4-16.

It was also possible to produce cross-shear within the UHMWPE by programming a figure-eight or bow-tie pattern for the two linear guides. The screen shot of Figure 4-17 shows the bow-tie pattern on the Table Motion Plot.

The desired frequency of the movements, velocities, and accelerations for the four motors were then adjusted. Unfortunately, frequency adjustment was mainly done by trial and error. Although the four motors always started each cycle at the same time, adjustments were necessary to reach the desired frequency and ensure the motors completed their patterns simultaneously. Synchronization of the motions and loading curve are subsequently discussed.
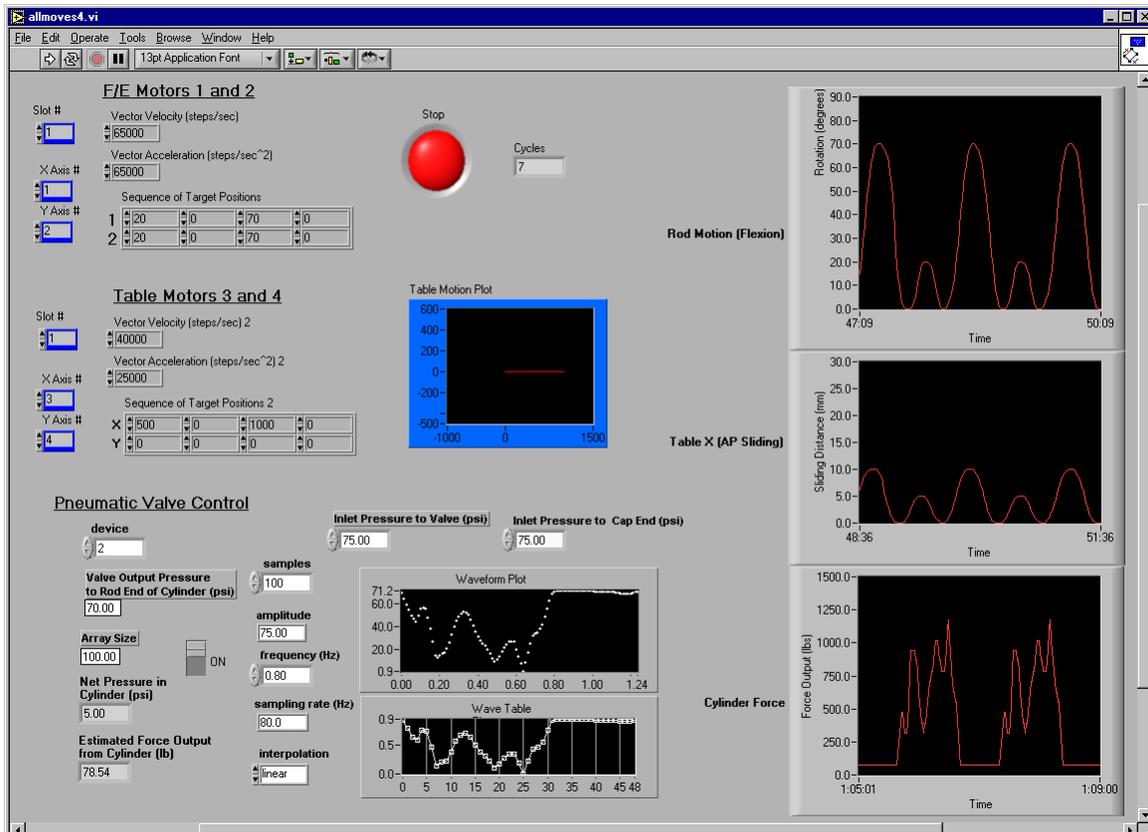

Figure 4-16. Screen shot of the motion control software.   Without an import file to define the motion curves, adjustments to the frequency, flexion angles, and sliding distances were made right on the user interface.
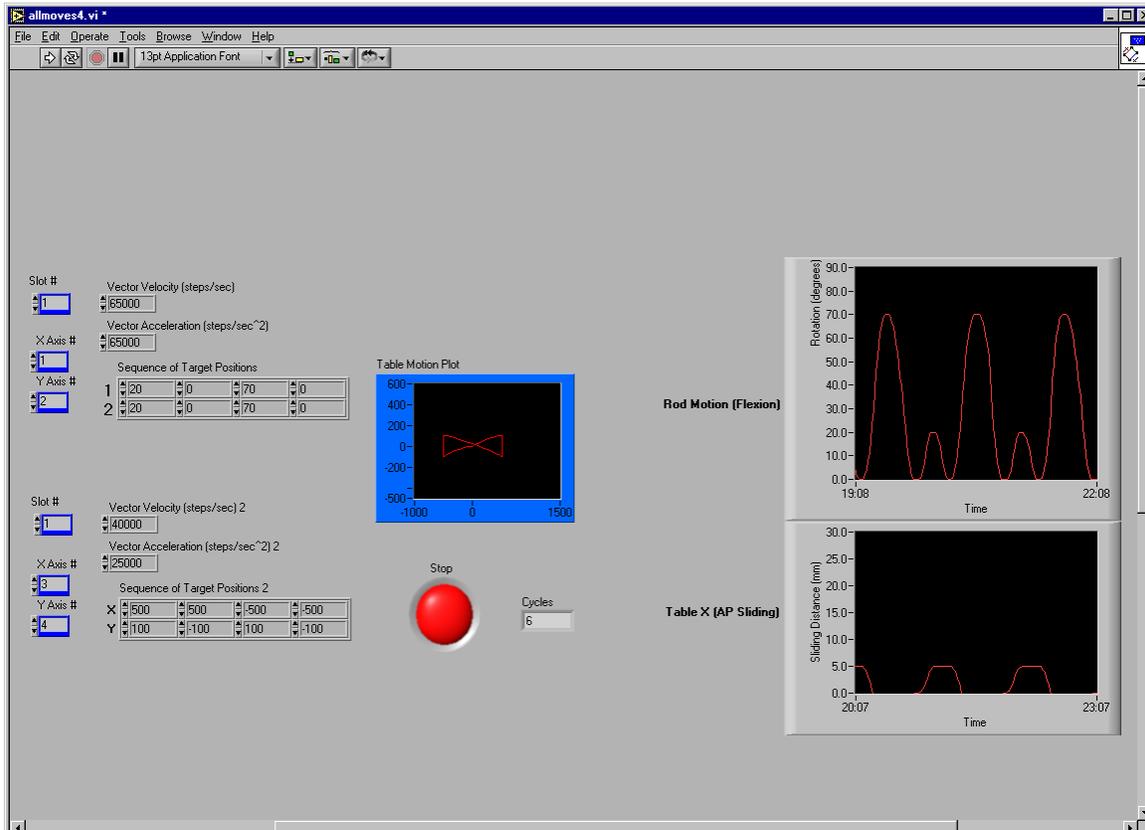
Figure 4-17. Screen shot of the motion control software, showing the capability of programming cross-shear into the device (i.e., the bowtie of the Table Motion Plot).

4.4.3 Synchronizing the VIs

Ensuring that each cycle of the loading curve, AP sliding curve, and F/E curve all began at the same instant was simple. Each VI was put within the same while loop and a counter was setup to keep track of the number of cycles. Unfortunately, there was no way of guaranteeing that each cycle would end at the same time. Consequently, adjustments were made to the motor velocities and accelerations, as well as to the delay between points on the loading curve to reach the desired frequency and synchronize all of the curves. Any change in desired frequency meant adjustments by trial and error of these variables. After time and minor modifications to the VI, synchronizing the motions for a desired frequency became easier, and the final controlling VI (Figure 4-18) was completed. The source code, or VI diagram, for the wear testing device's VI is given in Appendix B.

Figure 4-18. Screen shot of the final VI, which could control, synchronize and output all motions, including F/E, AP sliding, cross shear, and the loading curve.

Once all components were assembled and appropriately interfaced with the PC as described in this chapter, validation of the designed wear testing apparatus was started. This aspect of the project is described in Chapter 5.