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Final Report for
Cooperative Research and Development Agreement Y1293-0207
with DSP Control Group, Inc. for
Advanced Machine Tool Accuracy Compensation

1. Introduction

Martin Marietta Energy Systems (Energy Systems) and DSP Control Group, Inc.(DSPCG) participated in an effort to demonstrate advanced machine tool compensation techniques on their existing machine control system. Machine tools exhibit mechanical inaccuracies because of gear backlash, bearing friction, inconsistent lead screw pitch, and other non-linearities. MATRIX4, the machine control system currently marketed by the DSPCG, has the capability to compensate for these errors. DSPCG requested technical assistance in measuring these errors on a test platform and developing techniques for compensation to improve machine tool accuracy. The intent of this project was to demonstrate accuracy compensation on an Energy Systems machine tool.

2. Background

DSP Control Group originally called the National Machine Tool Partnership (NMTP) hotline number for assistance in the application of machine tool accuracy compensation. The request was referred to Oak Ridge by the NMTP. After some discussion between DSPCG and Energy Systems, a statement of work was developed. This work statement defined the scope of the project and consisted of three primary objectives.

The first objective was to demonstrate normal operation of a machine tool with the DSPCG MATRIX4 controller. This included all the interfacing and system integration necessary to drive the machine with two axes of motion. Included in this objective was the tuning of the control system to insure acceptable machine dynamic response and servo loop stability.

After insuring proper operation, the next objective was to measure the positioning errors on the machine. This provided a baseline for evaluating the effectiveness of the accuracy compensation. It involved interfacing test equipment to measure machine tool errors. Energy Systems has acquired significant experienced in making measurements of this nature in the development of precision manufacturing processes at the Oak Ridge Y-12 Plant.

The third objective was to demonstrate machine tool accuracy compensation. After developing and implementing a viable compensation algorithm, the positioning error measurements were repeated. These measurements were compared to the baseline performance data to determine the magnitude of the performance improvement.

3. Experiment Design

The objective of this initiative was to demonstrate an improvement in accuracy on an existing machine tool. Due to the short duration of this project, the decision was made to concentrate on a single non-linearity. Specifically, gear backlash (or hysteresis) was selected since it is easily measured and since a machine tool was readily available that had a pronounced backlash problem.

The machine tool selected for this demonstration was originally manufactured by Moore Precision Machine Tool Company as a coordinate measuring machine. It was later modified at Energy Systems (the vertical

actuator was replaced with a horizontal spindle) and configured as a T-Base lathe. The cutting tool on this machine is mounted on a pair of stacked slides which provide motion in two directions relative to the fixed horizontal spindle. Each of these slides is driven by a lead screw which is connected to dc servo motor through a 40:1 reduction gear. This machine exhibits a significant amount of backlash (approximately 0.004 in.) due to the configuration of the mechanical drive train. The configuration of the machine tool used in this experiment is illustrated in Figure 1.

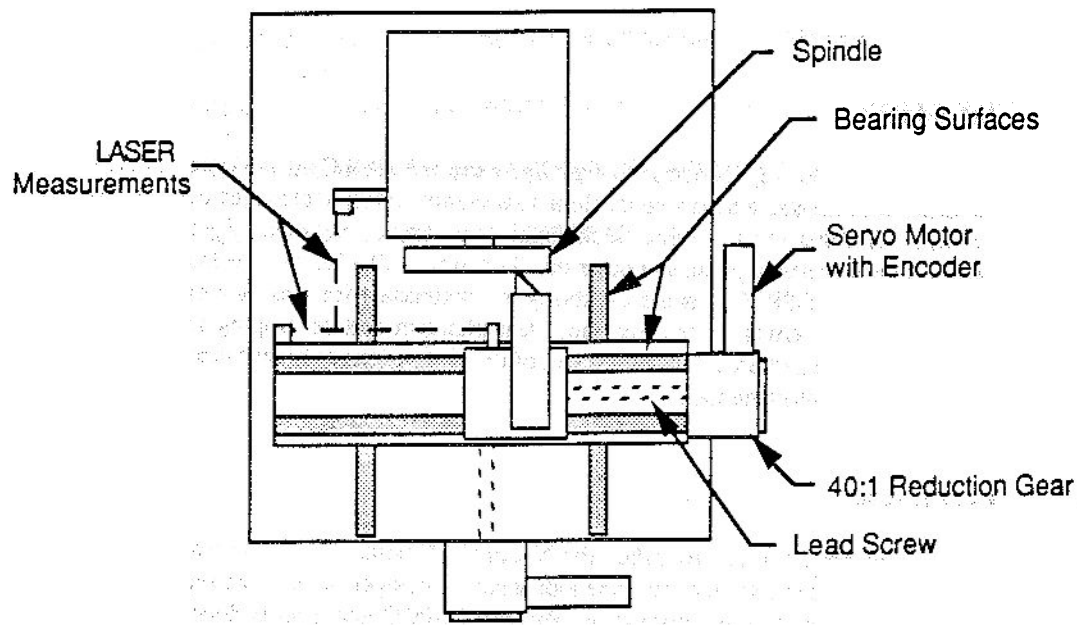


Figure 1. Machine tool layout for backlash compensation testing.

Backlash was measured by comparing the motion of the servo motors to the actual motion of the machine slides. For this experiment, the slide that moves perpendicular to the spindle axis of rotation is referred to as the x axis. The slide that moves parallel to the spindle axis is referred to as the y axis. Motor motion was measured using integral encoders in each of the servo motors. The motion of the slides was measured with a Hewlett Packard laser interferometer system and optical hardware mounted directly on the slides.

Motion control was obtained through the use of a personal computer-based MATRIX4 system manufactured by DSP Control Group. The MATRIX4 uses dual digital signal processors (DSPs) to provide the high-speed computational capability required for up to four simultaneous servo loops. This system operates in one of two primary modes. One mode performs coordinated axis moves based on a single set of input parameters to generate profiles such as straight lines, circles, etc. The other mode accepts tabular data directly from the host (personal computer) and enables the machine to follow an arbitrary trajectory. The latter mode was used in this experiment to investigate compensation for machine backlash.

The machine tool used in this experiment is normally controlled by a control system provided by another manufacturer. Since the machine was in use between parts of this experiment, it was necessary to quickly switch between the original control system and the MATRIX4 system. To facilitate this rapid changeover, an adapter was fabricated to match the MATRIX4 interface to that of the original control system. Thus, the control system was changed by simply removing a connector from the original control system and attaching it to the MATRIX4 adapter.

All programming for this CRADA was done in Microsoft C, version 6.0. Example software provided by DSPCG was used as a starting point for the test program used in this experiment. The example program was modified to accept an arbitrary length trajectory read from a disk file instead of from a fixed length array. Other modifications were made for convenience and to support this particular application. The example program also provided access to the motor position, velocity, and following error in real time through the use of dual-port RAM in the MATRIX4.

Software was also written to read the position of the slides from the Hewlett-Packard laser interferometer system in real-time. Included in this software development effort was a module that increased the resolution of the personal computer clock. This module increased the accuracy of the time stamp that was included with each discrete measurement. The measurement of the slide position was made immediately after that of the motor position, velocity, and following error in the main program. These measurements were combined along with a time stamp and stored as a single record.

The experiment to demonstrate accuracy improvement through backlash compensation was broken into two main parts. In the first part, the machine tool was programmed to move in a 1/8 in. diameter circle at low speed. In the second part, it was programmed to move in a 4 in. diameter circle at high speed. In both experiments, position data was taken to indicate the path of the motors and the path of the slides. Each part was performed with and without backlash compensation to quantify the performance improvement. The 1/8 in. circle was selected because it provided a convenient scale such that the machine backlash is clearly visible in a plot of the entire circle. The 4 in. circle was selected because it was the largest circle that could be generated with the machine tool setup at the time of the experiment. It was also felt that the 4 in. circle was closer to a typical application on a production machine tool.

4. Backlash Compensation Algorithm

Backlash is caused by tolerances in the mechanical linkage between the motor and the slides. Each time the direction of a slide is reversed, the internal parts of the mechanism must bear against opposite ends of these tolerances. Thus, at the beginning of the slide reversal, motion of the motor results in no net motion of the slide. The backlash compensation algorithm attempts to compensate for this condition.

The algorithm used in this effort used an open-loop compensation technique. That is, real-time feedback from the laser interferometers indicating slide position was not used to correct the motion profile as it was being transmitted to the MATRIX4. Although this kind of closed-loop compensation would ultimately prove more accurate, laser interferometers are somewhat expensive for applications of this nature. In the compensation algorithm used, backlash for both axes was measured in separate tests beforehand, as it was required as input to the algorithm.

The use of laser interferometers for real time compensation is not new to DOE manufacturing operations. It has been used in high precision machining to achieve accuracy unattainable with conventional feedback techniques. A U.S. patent was issued in 1978 for a dual-loop feedback system developed at the Oak Ridge.Y-12 Plant[1].

Compensation for backlash is achieved by moving the motor an amount corresponding to the backlash each time the slide reverses direction. This moves the internal parts of the mechanical linkage to the opposite ends of their tolerances such that subsequent motion of the motor results in the desired motion of the slide. Unfortunately, as early tests indicated, this compensation move cannot be performed instantaneously due to inertia in the motor and its load. This inertia causes the

[1] U.S. Patent No. 4,128,794, "Interferometric Correction System for a Numerically Controlled Machine", issued to Robert R. Burleson for the U.S. Department of Energy, December 5, 1978.

motor to move past the desired position and causes undesired motion of the slide. A more acceptable method of compensation is to break this move into smaller moves to reduce the effect of overshoot. Compensation is incorporated by superimposing the compensation move over the motion trajectory the machine is following at the time the slide reversal takes place.

As stated previously, the MATRIX4 was given the command trajectory in the form of tabular data sent by the host computer. Due to the volume of data required, the trajectory data was stored in disk files on the host computer. Backlash compensation was implemented in software by reading data from these disk files, superimposing compensation moves as necessary, and writing the resulting data to another disk file. Compensation moves were included wherever position data for a given axis changed from increasing to decreasing or visa-versa. The program that sent the data to the host computer could accept data from the original data file or the compensated data file. This provided a convenient comparison regarding the performance of the backlash compensation algorithm.

5. Experimental Results

Parts of the experimental procedure highlighted previously were repeated several times in the process of determining the effectiveness of the error correction capability of the MATRIX4. This section provides a representative sample of the results obtained on this machine. Additional tabular data is included in an appendix to this document. The graphs presented in this section were produced using KaleidaGraph™ on a Macintosh® computer. Unless otherwise noted, all motion presented in the graphs proceeds in the counterclockwise direction.

Results from the 1/8 in. circle are presented first because the backlash phenomenon is more easily seen. Results from the 4 in. circle are then presented to show the effect of backlash on a typical size part. In all of the graphical results presented, the machine motion is in the counter-clockwise direction. Prior to each test, the machine was moved such that the backlash was removed in the direction of the initial motion.

The 1/8 in. circle profile was performed at a feed rate of 0.288 in./minute. A single revolution of the circle was executed to show the positioning errors caused by backlash. Figure 2 shows the motion of the machine without compensation. As stated previously, motion begins at the right side of the circle, proceeding in the counter-clockwise direction. The table path, measured by the laser interferometer, indicates the motion generated by the slides. A perfect circle is also plotted for comparison. The path of the motors, indicated by the encoders, was omitted to reduce clutter because it exactly coincided with the plot of the ideal circle. This figure illustrates the effect of backlash as evidenced the distortion in the measured trajectory of the slide.

Backlash is first introduced when the y slide reverses direction at the top of the circle. At this point, it can be seen that the path of the slide begins to deviate from that of the motors. The x slide reverses direction at the left side of the circle, introducing backlash in the x direction. The y slide reverses again at the bottom of the circle, repeating the backlash phenomenon. Since the circle does not continue past the starting point on the right side, the x slide reverses direction only once.

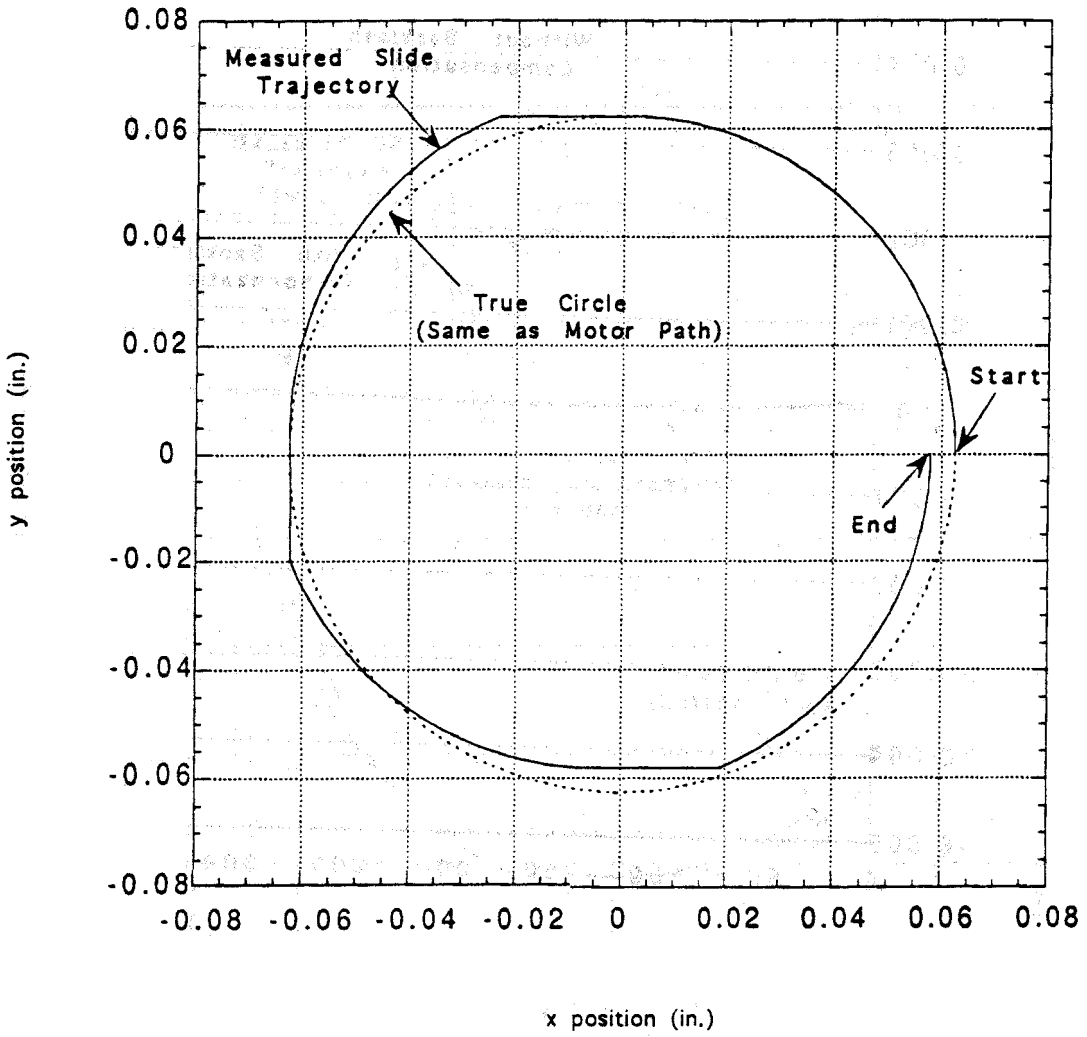


Figure 2. One-eighth in. circle without backlash compensation.

Perhaps the best measure of the effectiveness of backlash compensation for the 1/8 in. circle is the actual deviation from the desired radius. This radius error measurement was made by computing the geometric distance of each set of x and y data points from the center of the circle (where x and y are both equal to zero). Figure 3 illustrates this comparison in which results from both a compensated and uncompensated test were plotted on the same scale. Without backlash compensation, the radius error was nearly 0.005 in. With compensation, however, the radius error was less than 0.00035 in. Thus, backlash compensation yielded an improvement of more than an order of magnitude on this machine tool.

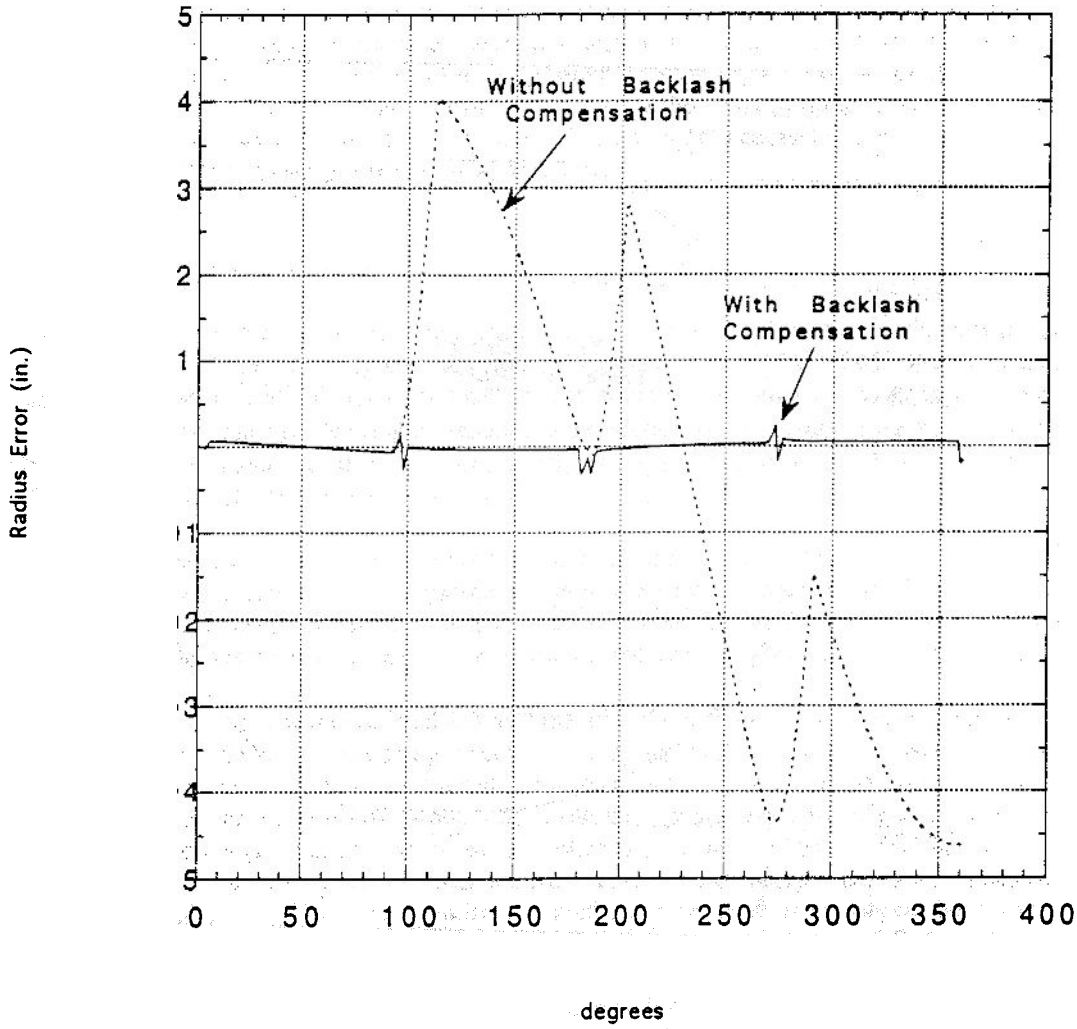


Figure 3. Radius error for 1/8 in. circle, with and without backlash compensation.

Figure 4 shows how backlash compensation improves the trajectory of the slides on the 1/8 in. circle. Note that the trajectory followed by the motors begins to deviate from a true circle near the top where the y slide reverses direction. At this point, the backlash is removed by a linear move superimposed over the circular trajectory as described previously. It can be seen that the path traversed by the slides deviates slightly from that of a true circle near the locations where the backlash is being removed. This is caused by the fact that the backlash cannot be removed instantaneously, thus some position error is allowed during the transition. This error is small, however, compared to the errors introduced by uncompensated backlash.

To see more clearly the behavior of the system as the backlash compensation takes place, Figure 5 presents an expanded view of the top part of the circle shown in Figure 4. This region corresponds to the reversal of

the y slide. The maximum deviation from the desired trajectory occurs in the vicinity of the slide reversal. It should be noted, however, that this deviation is well below 0.001 in.

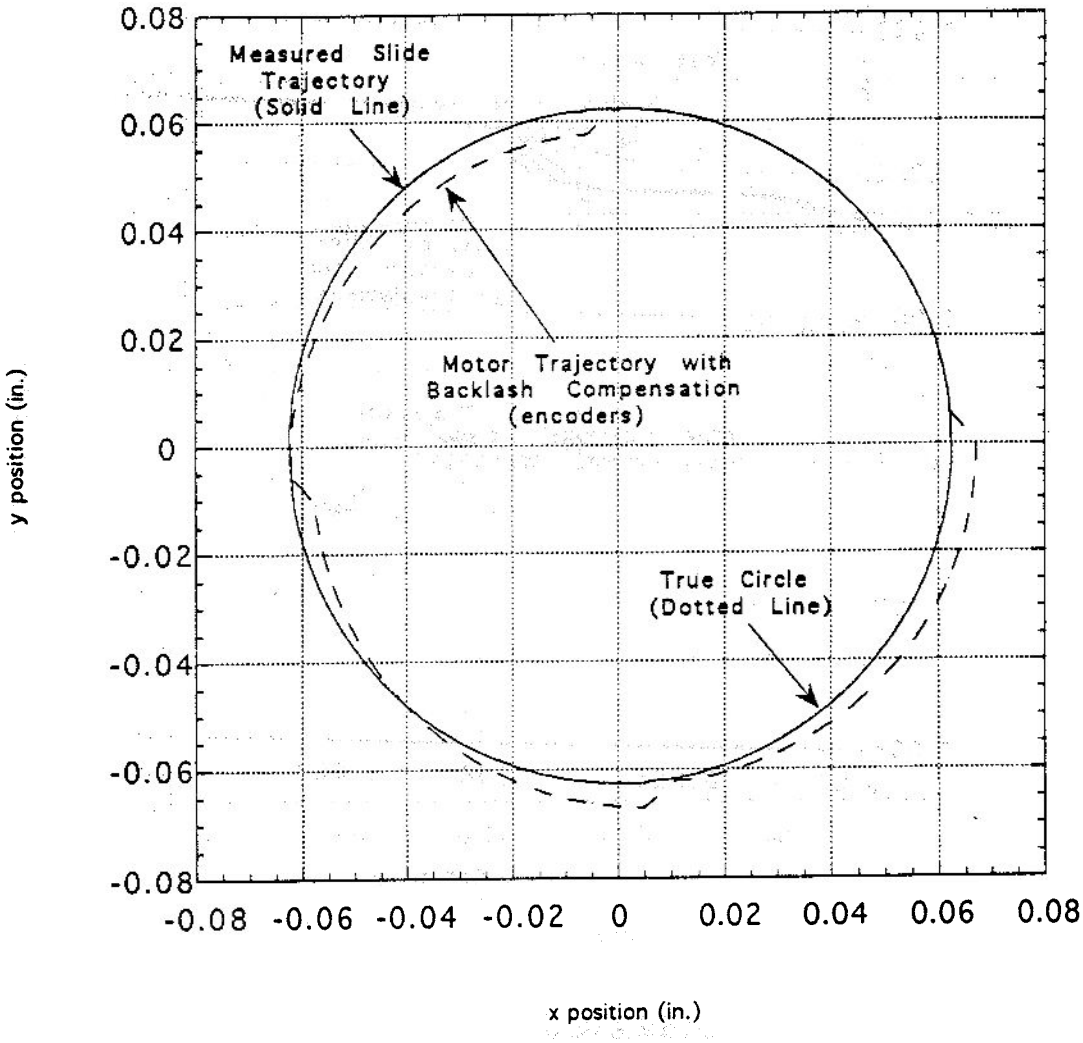


Figure 4. One-eighth in. circle with backlash compensation

Also visible in Figure 5 are the multiple traces that were produced as the machine moved through three complete revolutions of the circle. Multiple passes were made to insure the backlash compensation results were repeatable. As the figure shows, the variation in the trajectory from pass to pass was minimal.

The 4 in. diameter circle was programmed at a feed rate of approximately 5 in./min. Results from the testing performed in this configuration were generally similar to those for the 1/8 in. circle. As stated previously, the graphical results are not as clearly seen due to the difference in scale.

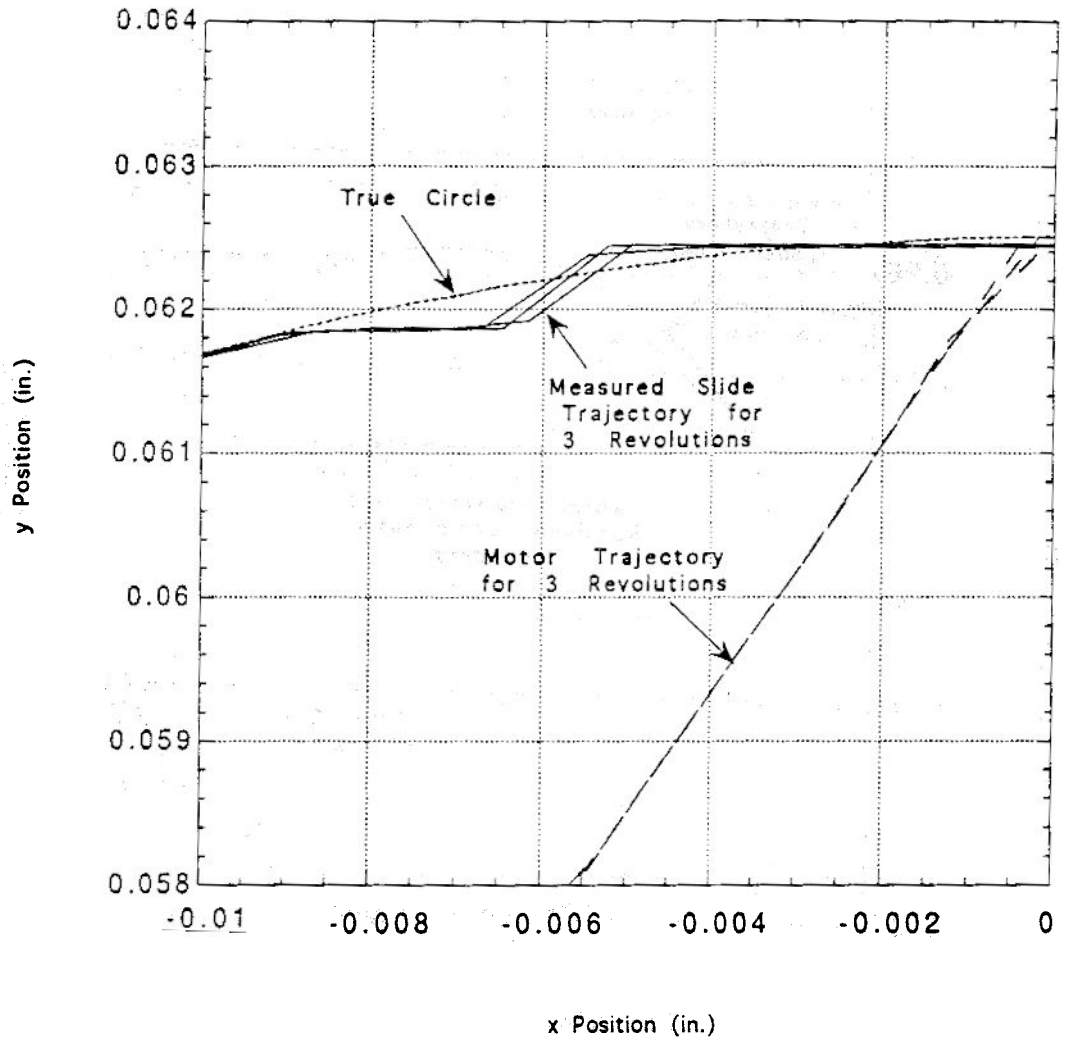


Figure 5. Detail of 1/8 in. circle with backlash compensation (3 revolutions).

Figure 6 provides an expanded view of the y slide reversal similar to that shown by Figure 5 for the 1/8 in. circle. This figure shows the minimal deviation of the slide trajectory relative to that of a true circle. Due to the larger scale of the 4 in. circle, no useful information can be obtained from a plot of the entire circle. Since the errors (even with backlash) are small compared to the 4 in. diameter, the lines are overlaid on top of each other.

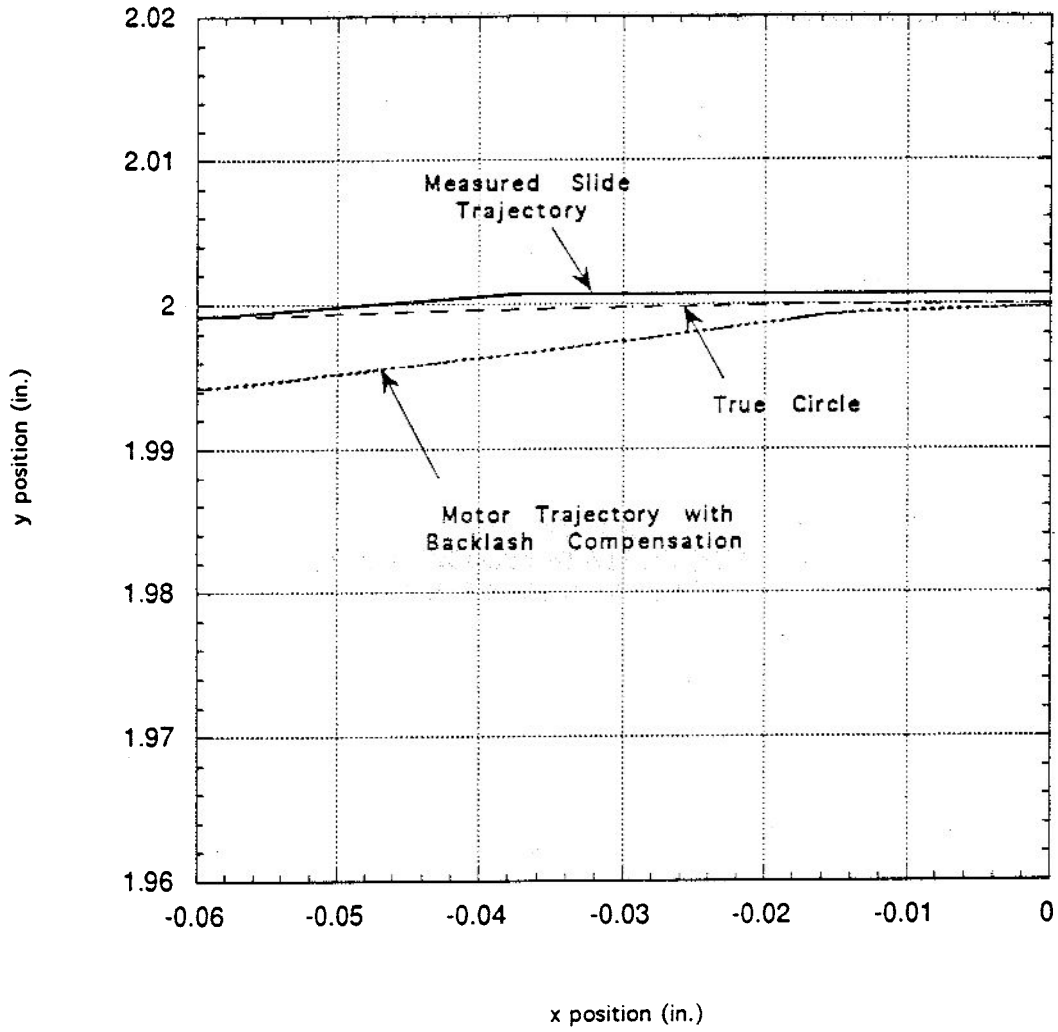


Figure 6. Detail of 4 in. circle with backlash compensation.

6. Conclusions

Three objectives were set forth in the as metrics for this cooperative research and development agreement. As stated in the earlier in this report, these were to demonstrate standard operation of a machine tool with the MATRIX4 controller, measure positioning errors, and to demonstrate accuracy compensation.

The first objective was met in the uncompensated operation of the machine tool as shown in Figure 2. A significant accomplishment in implementing this objective is the fact that control could be interchanged from the existing system to the MATRIX4 in a few minutes.

The second objective was met by interfacing the Hewlett-Packard laser interferometer system to the machine tool to measure the exact position of the slides. This system provided a measurement resolution of less than one micro-inch. As stated previously, the maximum positioning error measured (due to backlash) was approximately 0.0045 in. This was shown graphically in Figures 2 and 3.

The third objective was met by demonstrating machine tool backlash compensation using the MATRIX 4. Figure 3 shows that backlash was reduced by more than an order of magnitude using a simple error correction algorithm. While these results are impressive, it should be noted that no attempt was made to fine-tune the control parameters or the correction algorithm. With continued emphasis in these areas, it seems likely that the machine tool accuracy would be improved even further.

APPENDIX A
1/8 INCH UNCOMPENSATED TEST DATA
(ALL UNITS IN INCHES)

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
0	44	0.062500	0.0000	0.0000	0.0000	0.062500	0.0000	0.062500	0.0000	0.0000
1	45	0.062494	0.00067700	-1.0000e-06	0.00019400	0.062499	0.00064900	0.062488	0.0012271	2.3712e-06
2	46	0.062471	0.0020320	-7.0000e-06	7.6000e-05	0.062500	0.0020160	0.062452	0.0024537	3.2506e-05
3	47	0.062417	0.0033260	-8.0000e-06	2.6000e-05	0.062475	0.0032940	0.062392	0.0036794	6.1778e-05
4	48	0.062339	0.0045590	-6.0000e-06	6.0000e-06	0.062398	0.0045350	0.062307	0.0049037	6.2583e-05
5	49	0.062233	0.0058290	-8.0000e-06	9.0000e-06	0.062293	0.0057900	0.062199	0.0061261	6.1506e-05
6	50	0.062107	0.0070460	-6.0000e-06	3.0000e-06	0.062165	0.0070280	0.062067	0.0073461	6.1010e-05
7	51	0.061958	0.0082590	-5.0000e-06	-8.0000e-06	0.062016	0.0082460	0.061911	0.0085633	6.1815e-05
8	52	0.061777	0.0095170	-6.0000e-06	2.0000e-06	0.061836	0.0094940	0.061731	0.0097772	6.0587e-05
9	53	0.061575	0.010748	-7.0000e-06	3.0000e-06	0.061632	0.010732	0.061527	0.010987	5.9406e-05
10	54	0.061348	0.011973	-7.0000e-06	2.0000e-06	0.061405	0.011952	0.061299	0.012193	5.7368e-05
11	55	0.061097	0.013194	-7.0000e-06	2.0000e-06	0.061153	0.013157	0.061048	0.013394	5.2345e-05
12	56	0.060828	0.014386	-4.0000e-06	-9.0000e-06	0.060879	0.014376	0.060773	0.014590	5.3353e-05
13	57	0.060534	0.015573	-4.0000e-06	-9.0000e-06	0.060584	0.015562	0.060475	0.015781	5.0756e-05
14	58	0.060186	0.016869	-4.0000e-06	-7.0000e-06	0.060238	0.016847	0.060153	0.016965	4.9485e-05
15	59	0.059845	0.018043	-9.0000e-06	7.0000e-06	0.059895	0.018028	0.059809	0.018143	4.9340e-05
16	60	0.059473	0.019232	-9.0000e-06	7.0000e-06	0.059526	0.019211	0.059441	0.019314	4.9238e-05
17	61	0.059086	0.020392	-9.0000e-06	7.0000e-06	0.059135	0.020384	0.059050	0.020477	4.9627e-05
18	62	0.058667	0.021566	-7.0000e-06	1.0000e-06	0.058719	0.021547	0.058637	0.021632	4.7537e-05
19	63	0.058234	0.022710	-3.0000e-06	-9.0000e-06	0.058282	0.022693	0.058201	0.022779	4.4094e-05
20	64	0.057770	0.023867	-3.0000e-06	-9.0000e-06	0.057823	0.023836	0.057742	0.023918	4.3218e-05
21	65	0.057292	0.024991	-4.0000e-06	-7.0000e-06	0.057339	0.024977	0.057262	0.025047	4.2878e-05
22	66	0.056783	0.026129	-4.0000e-06	-8.0000e-06	0.056834	0.026105	0.056759	0.026166	4.2583e-05
23	67	0.056261	0.027234	-1.0000e-05	5.0000e-06	0.056306	0.027214	0.056234	0.027276	3.7729e-05
24	68	0.055695	0.028373	-3.0000e-06	-8.0000e-06	0.055735	0.028355	0.055688	0.028374	3.3161e-05
25	69	0.055119	0.029478	-3.0000e-06	-8.0000e-06	0.055161	0.029455	0.055120	0.029462	3.2655e-05
26	70	0.054532	0.030549	-1.1000e-05	4.0000e-06	0.054574	0.030529	0.054531	0.030539	3.2720e-05
27	71	0.053911	0.031631	-1.0000e-05	5.0000e-06	0.053956	0.031605	0.053921	0.031604	3.1003e-05
28	72	0.053283	0.032679	-7.0000e-06	-1.0000e-06	0.053320	0.032661	0.053290	0.032656	2.8098e-05
29	73	0.052621	0.033735	-6.0000e-06	-1.0000e-06	0.052662	0.033708	0.052639	0.033696	2.6118e-05
30	74	0.051951	0.034758	-7.0000e-06	0.0000	0.051986	0.034739	0.051967	0.034723	2.4734e-05
31	75	0.051248	0.035787	-1.0000e-06	-1.0000e-05	0.051288	0.035757	0.051275	0.035737	2.2174e-05
32	76	0.050538	0.036783	-2.0000e-06	-8.0000e-06	0.050571	0.036763	0.050564	0.036737	2.1552e-05
33	77	0.049765	0.037821	-6.0000e-06	-1.0000e-06	0.049807	0.037787	0.049833	0.037722	1.8756e-05
34	78	0.049016	0.038787	-6.0000e-06	-2.0000e-06	0.049047	0.038775	0.049082	0.038693	2.2867e-05

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
35	79	0.048233	0.039756	0.0000	-9.0000e-06	0.048268	0.039724	0.048313	0.039650	1.2365e-05
36	80	0.047446	0.040693	-1.0000e-06	-9.0000e-06	0.047475	0.040668	0.047525	0.040591	1.2093e-05
37	81	0.046626	0.041630	-1.0000e-06	-8.0000e-06	0.046664	0.041604	0.046719	0.041516	1.7372e-05
38	82	0.045786	0.042552	-2.0000e-06	-8.0000e-06	0.045824	0.042519	0.045895	0.042425	1.1632e-05
39	83	0.044945	0.043439	-1.1000e-05	2.0000e-06	0.044980	0.043411	0.045053	0.043318	1.1723e-05
40	84	0.044069	0.044326	-1.1000e-05	2.0000e-06	0.044112	0.044291	0.044194	0.044194	1.0490e-05
41	85	0.043194	0.045179	-5.0000e-06	-3.0000e-06	0.043224	0.045152	0.043318	0.045053	6.1383e-06
42	86	0.042303	0.046016	-6.0000e-06	-3.0000e-06	0.042327	0.045994	0.042425	0.045895	6.1836e-06
43	87	0.041359	0.046866	-1.2000e-05	1.0000e-06	0.041382	0.046842	0.041516	0.046719	3.1440e-06
44	88	0.040415	0.047681	-6.0000e-06	-3.0000e-06	0.040445	0.047649	0.040591	0.047525	-1.9836e-07
45	89	0.039458	0.048478	-6.0000e-06	-3.0000e-06	0.039497	0.048440	0.039650	0.048313	1.5710e-06
46	90	0.038501	0.049241	3.0000e-06	-9.0000e-06	0.038534	0.049206	0.038693	0.049082	-1.2031e-06
47	91	0.037531	0.049984	2.0000e-06	-9.0000e-06	0.037549	0.049955	0.037722	0.049833	-6.5654e-06
48	92	0.036527	0.050723	1.0000e-06	-8.0000e-06	0.036555	0.050688	0.036737	0.050564	-5.6707e-06
49	93	0.035528	0.051427	-1.1000e-05	-1.0000e-06	0.035549	0.051399	0.035737	0.051275	-5.2915e-06
50	94	0.034495	0.052125	-1.1000e-05	0.0000	0.034523	0.052091	0.034723	0.051967	-7.5235e-06
51	95	0.033449	0.052803	-1.1000e-05	0.0000	0.033481	0.052758	0.033696	0.052639	-1.4929e-05
52	96	0.032368	0.053471	2.0000e-06	-8.0000e-06	0.032401	0.053428	0.032656	0.053290	-1.4993e-05
53	97	0.031317	0.054094	1.0000e-06	-8.0000e-06	0.031334	0.054059	0.031604	0.053921	-1.6444e-05
54	98	0.030232	0.054708	-1.1000e-05	-1.0000e-06	0.030258	0.054670	0.030539	0.054531	-1.5159e-05
55	99	0.029156	0.055289	-1.1000e-05	-1.0000e-06	0.029173	0.055253	0.029462	0.055120	-1.8339e-05
56	100	0.028048	0.055859	-5.0000e-06	-4.0000e-06	0.028072	0.055822	0.028374	0.055688	-1.6940e-05
57	101	0.026951	0.056397	2.0000e-06	-8.0000e-06	0.026968	0.056364	0.027276	0.056234	-1.6615e-05
58	102	0.025820	0.056924	4.0000e-06	-9.0000e-06	0.025843	0.056888	0.026166	0.056759	-1.7162e-05
59	103	0.024701	0.057418	3.0000e-06	-8.0000e-06	0.024719	0.057382	0.025047	0.057262	-2.0221e-05
60	104	0.023553	0.057898	3.0000e-06	-7.0000e-06	0.023574	0.057857	0.023918	0.057742	-2.4679e-05
61	105	0.022393	0.058357	3.0000e-06	-8.0000e-06	0.022424	0.058311	0.022779	0.058201	-2.5937e-05
62	106	0.021226	0.058791	3.0000e-06	-8.0000e-06	0.021241	0.058751	0.021632	0.058637	-2.7126e-05
63	107	0.020048	0.059203	4.0000e-06	-8.0000e-06	0.020069	0.059162	0.020477	0.059050	-2.6751e-05
64	108	0.018864	0.059591	3.0000e-06	-8.0000e-06	0.018893	0.059545	0.019314	0.059441	-2.9588e-05
65	109	0.017694	0.059948	-1.1000e-05	-3.0000e-06	0.017716	0.059899	0.018143	0.059809	-3.6036e-05
66	110	0.016496	0.060289	-1.1000e-05	-4.0000e-06	0.016529	0.060238	0.016965	0.060153	-3.5414e-05
67	111	0.015313	0.060601	-3.0000e-06	-6.0000e-06	0.015330	0.060557	0.015781	0.060475	-3.2735e-05
68	112	0.014102	0.060894	-4.0000e-06	-5.0000e-06	0.014132	0.060846	0.014590	0.060773	-3.4415e-05
69	113	0.012908	0.061158	6.0000e-06	-7.0000e-06	0.012920	0.061114	0.013394	0.061048	-3.5233e-05

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
70	114	0.011686	0.061403	6.0000e-06	-8.0000e-06	0.011714	0.061356	0.012193	0.061299	-3.5797e-05
71	115	0.010436	0.061628	-3.0000e-06	-6.0000e-06	0.010448	0.061582	0.010987	0.061527	-3.7985e-05
72	116	0.0092290	0.061821	7.0000e-06	-8.0000e-06	0.0092360	0.061776	0.0097772	0.061731	-3.7387e-05
73	117	0.0079940	0.061992	6.0000e-06	-7.0000e-06	0.0080050	0.061943	0.0085633	0.061911	-4.1893e-05
74	118	0.0067560	0.062139	6.0000e-06	-7.0000e-06	0.0067820	0.062086	0.0073461	0.062067	-4.4680e-05
75	119	0.0055390	0.062259	5.0000e-06	-6.0000e-06	0.0055560	0.062203	0.0061261	0.062199	-4.9360e-05
76	120	0.0042980	0.062358	5.0000e-06	-6.0000e-06	0.0043220	0.062299	0.0049037	0.062307	-5.1262e-05
77	121	0.0030770	0.062430	-9.0000e-06	-6.0000e-06	0.0030800	0.062370	0.0036794	0.062392	-5.3998e-05
78	122	0.0018320	0.062478	-9.0000e-06	-5.0000e-06	0.0018550	0.062415	0.0024537	0.062452	-5.7440e-05
79	123	0.00060900	0.062503	-3.0000e-06	-6.0000e-06	0.00061600	0.062439	0.0012271	0.062488	-5.7963e-05
80	124	-0.00063700	0.062503	-3.0000e-06	-7.0000e-06	-0.00061400	0.062446	3.8269e-18	0.062500	-5.0983e-05
81	125	-0.0019070	0.062476	-9.0000e-06	-7.0000e-06	-0.0018890	0.062448	-0.0012271	0.062488	-2.3438e-05
82	126	-0.0031530	0.062426	-9.0000e-06	-7.0000e-06	-0.0031280	0.062448	-0.0024537	0.062452	2.6290e-05
83	127	-0.0043730	0.062353	-3.0000e-06	-6.0000e-06	-0.0043670	0.062448	-0.0036794	0.062392	0.00010051
84	128	-0.0056150	0.062253	-1.0000e-06	-6.0000e-06	-0.0055970	0.062448	-0.0049037	0.062307	0.00019832
85	129	-0.0068320	0.062131	8.0000e-06	-5.0000e-06	-0.0068250	0.062445	-0.0061261	0.062199	0.00031687
86	130	-0.0080690	0.061982	9.0000e-06	-5.0000e-06	-0.0080580	0.062443	-0.0073461	0.062067	0.00046078
87	131	-0.0093040	0.061809	8.0000e-06	-4.0000e-06	-0.0092910	0.062443	-0.0085633	0.061911	0.00063043
88	132	-0.010511	0.061615	9.0000e-06	-4.0000e-06	-0.010507	0.062443	-0.0097772	0.061731	0.00082081
89	133	-0.011737	0.061393	6.0000e-06	-4.0000e-06	-0.011731	0.062443	-0.010987	0.061527	0.0010354
90	134	-0.012912	0.061158	-2.0000e-06	-7.0000e-06	-0.012908	0.062442	-0.012193	0.061299	0.0012622
91	135	-0.014129	0.060888	-1.0000e-06	-7.0000e-06	-0.014114	0.062443	-0.013394	0.061048	0.0015182
92	136	-0.015341	0.060594	-1.0000e-06	-6.0000e-06	-0.015321	0.062443	-0.014590	0.060773	0.0017951
93	137	-0.016523	0.060282	8.0000e-06	-4.0000e-06	-0.016518	0.062443	-0.015781	0.060475	0.0020908
94	138	-0.017722	0.059941	1.0000e-05	-4.0000e-06	-0.017708	0.062443	-0.016965	0.060153	0.0024053
95	139	-0.018913	0.059575	8.0000e-06	-3.0000e-06	-0.018896	0.062443	-0.018143	0.059809	0.0027395
96	140	-0.020075	0.059194	8.0000e-06	-4.0000e-06	-0.020074	0.062443	-0.019314	0.059441	0.0030903
97	141	-0.021251	0.058781	7.0000e-06	-4.0000e-06	-0.021243	0.062443	-0.020477	0.059050	0.0034575
98	142	-0.022419	0.058346	7.0000e-06	-4.0000e-06	-0.022398	0.062441	-0.021632	0.058637	0.0038366
99	143	-0.023556	0.057897	-6.0000e-06	-9.0000e-06	-0.023541	0.062226	-0.022779	0.058201	0.0040301
100	144	-0.024751	0.057396	9.0000e-06	-3.0000e-06	-0.024734	0.061737	-0.023918	0.057742	0.0040074
101	145	-0.025889	0.056892	1.0000e-05	-3.0000e-06	-0.025858	0.061240	-0.025047	0.057262	0.0039754
102	146	-0.026998	0.056374	9.0000e-06	-3.0000e-06	-0.026991	0.060713	-0.026166	0.056759	0.0039423
103	147	-0.028116	0.055825	7.0000e-06	-3.0000e-06	-0.028102	0.060167	-0.027276	0.056234	0.0039063
104	148	-0.029223	0.055253	7.0000e-06	-3.0000e-06	-0.029197	0.059602	-0.028374	0.055688	0.0038691

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
105	149	-0.030319	0.054659	8.0000e-06	-3.0000e-06	-0.030291	0.059012	-0.029462	0.055120	0.0038322
106	150	-0.031383	0.054056	-5.0000e-06	-9.0000e-06	-0.031368	0.058401	-0.030539	0.054531	0.0037920
107	151	-0.032454	0.053419	-4.0000e-06	-1.0000e-05	-0.032436	0.057766	-0.031604	0.053921	0.0037496
108	152	-0.033513	0.052762	-5.0000e-06	-1.0000e-05	-0.033487	0.057110	-0.032656	0.053290	0.0037037
109	153	-0.034619	0.052043	1.0000e-06	-6.0000e-06	-0.034603	0.056386	-0.033696	0.052639	0.0036570
110	154	-0.035649	0.051343	2.0000e-06	-6.0000e-06	-0.035625	0.055688	-0.034723	0.051967	0.0036082
111	155	-0.036666	0.050621	1.0000e-06	-6.0000e-06	-0.036640	0.054967	-0.035737	0.051275	0.0035595
112	156	-0.037649	0.049894	9.0000e-06	-1.0000e-06	-0.037634	0.054234	-0.036737	0.050564	0.0035125
113	157	-0.038636	0.049134	9.0000e-06	0.0000	-0.038615	0.053479	-0.037722	0.049833	0.0034630
114	158	-0.039591	0.048369	9.0000e-06	-1.0000e-06	-0.039578	0.052706	-0.038693	0.049082	0.0034116
115	159	-0.040547	0.047570	8.0000e-06	-1.0000e-06	-0.040533	0.051907	-0.039650	0.048313	0.0033579
116	160	-0.041488	0.046752	8.0000e-06	-1.0000e-06	-0.041471	0.051091	-0.040591	0.047525	0.0033038
117	161	-0.042412	0.045915	8.0000e-06	-1.0000e-06	-0.042383	0.050262	-0.041516	0.046719	0.0032464
118	162	-0.043301	0.045077	-3.0000e-06	-1.1000e-05	-0.043284	0.049411	-0.042425	0.045895	0.0031883
119	163	-0.044242	0.044154	3.0000e-06	-6.0000e-06	-0.044220	0.048498	-0.043318	0.045053	0.0031313
120	164	-0.045098	0.043280	3.0000e-06	-6.0000e-06	-0.045085	0.047610	-0.044194	0.044194	0.0030696
121	165	-0.045951	0.042372	9.0000e-06	1.0000e-06	-0.045935	0.046706	-0.045053	0.043318	0.0030093
122	166	-0.046787	0.041448	1.0000e-05	2.0000e-06	-0.046767	0.045787	-0.045895	0.042425	0.0029492
123	167	-0.047604	0.040506	9.0000e-06	1.0000e-06	-0.047577	0.044850	-0.046719	0.041516	0.0028842
124	168	-0.048388	0.039568	9.0000e-06	1.0000e-06	-0.048370	0.043898	-0.047525	0.040591	0.0028199
125	169	-0.049167	0.038594	8.0000e-06	1.0000e-06	-0.049145	0.042930	-0.048313	0.039650	0.0027550
126	170	-0.049927	0.037607	8.0000e-06	1.0000e-06	-0.049899	0.041950	-0.049082	0.038693	0.0026898
127	171	-0.050653	0.036623	-1.0000e-06	-1.1000e-05	-0.050629	0.040958	-0.049833	0.037722	0.0026218
128	172	-0.051386	0.035586	8.0000e-06	1.0000e-06	-0.051362	0.039923	-0.050564	0.036737	0.0025531
129	173	-0.052087	0.034554	8.0000e-06	1.0000e-06	-0.052059	0.038896	-0.051275	0.035737	0.0024849
130	174	-0.052752	0.033529	0.0000	-1.1000e-05	-0.052728	0.037861	-0.051967	0.034723	0.0024130
131	175	-0.053410	0.032471	1.0000e-06	-1.1000e-05	-0.053381	0.036807	-0.052639	0.033696	0.0023405
132	176	-0.054047	0.031399	1.0000e-06	-1.1000e-05	-0.054017	0.035743	-0.053290	0.032656	0.0022719
133	177	-0.054651	0.030336	5.0000e-06	-5.0000e-06	-0.054627	0.034665	-0.053921	0.031604	0.0021975
134	178	-0.055245	0.029240	4.0000e-06	-6.0000e-06	-0.055217	0.033574	-0.054531	0.030539	0.0021230
135	179	-0.055817	0.028133	4.0000e-06	-4.0000e-06	-0.055782	0.032474	-0.055120	0.029462	0.0020460
136	180	-0.056356	0.027036	9.0000e-06	4.0000e-06	-0.056329	0.031366	-0.055688	0.028374	0.0019731
137	181	-0.056884	0.025906	8.0000e-06	4.0000e-06	-0.056855	0.030240	-0.056234	0.027276	0.0018968
138	182	-0.057409	0.024723	3.0000e-06	-1.0000e-05	-0.057381	0.029050	-0.056759	0.026166	0.0018155
139	183	-0.057890	0.023574	1.0000e-06	-1.1000e-05	-0.057856	0.027908	-0.057262	0.025047	0.0017353

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
140	184	-0.058349	0.022415	3.0000e-06	-1.1000e-05	-0.058309	0.026762	-0.057742	0.023918	0.0016572
141	185	-0.058776	0.021269	6.0000e-06	-5.0000e-06	-0.058744	0.025597	-0.058201	0.022779	0.0015786
142	186	-0.059188	0.020093	5.0000e-06	-4.0000e-06	-0.059157	0.024426	-0.058637	0.021632	0.0015014
143	187	-0.059578	0.018908	6.0000e-06	-4.0000e-06	-0.059540	0.023255	-0.059050	0.020477	0.0014203
144	188	-0.059942	0.017717	5.0000e-06	-4.0000e-06	-0.059904	0.022065	-0.059441	0.019314	0.0013385
145	189	-0.060278	0.016541	8.0000e-06	5.0000e-06	-0.060243	0.020874	-0.059809	0.018143	0.0012569
146	190	-0.060595	0.015336	8.0000e-06	6.0000e-06	-0.060556	0.019680	-0.060153	0.016965	0.0011736
147	191	-0.060889	0.014124	8.0000e-06	6.0000e-06	-0.060852	0.018455	-0.060475	0.015781	0.0010889
148	192	-0.061159	0.012908	8.0000e-06	7.0000e-06	-0.061119	0.017245	-0.060773	0.014590	0.0010053
149	193	-0.061404	0.011685	8.0000e-06	6.0000e-06	-0.061364	0.016034	-0.061048	0.013394	0.00092421
150	194	-0.061621	0.010482	8.0000e-06	4.0000e-06	-0.061583	0.014811	-0.061299	0.012193	0.00083902
151	195	-0.061818	0.0092510	8.0000e-06	4.0000e-06	-0.061779	0.013592	-0.061527	0.010987	0.00075652
152	196	-0.061990	0.0080160	7.0000e-06	4.0000e-06	-0.061949	0.012362	-0.061731	0.0097772	0.00067039
153	197	-0.062135	0.0068040	5.0000e-06	-1.0000e-05	-0.062095	0.011138	-0.061911	0.0085633	0.00058601
154	198	-0.062258	0.0055630	5.0000e-06	-9.0000e-06	-0.062218	0.0098960	-0.062067	0.0073461	0.00050009
155	199	-0.062357	0.0043210	6.0000e-06	-9.0000e-06	-0.062315	0.0086650	-0.062199	0.0061261	0.00041456
156	200	-0.062429	0.0030990	6.0000e-06	-4.0000e-06	-0.062388	0.0074340	-0.062307	0.0049037	0.00032935
157	201	-0.062481	0.0017830	7.0000e-06	7.0000e-06	-0.062439	0.0061200	-0.062392	0.0036794	0.00023821
158	202	-0.062504	0.00053600	6.0000e-06	8.0000e-06	-0.062463	0.0048770	-0.062452	0.0024537	0.00015310
159	203	-0.062503	-0.00068600	6.0000e-06	6.0000e-06	-0.062469	0.0036510	-0.062488	0.0012271	7.5599e-05
160	204	-0.062475	-0.0019320	5.0000e-06	6.0000e-06	-0.062469	0.0024130	-0.062500	7.6538e-18	1.5584e-05
161	205	-0.062427	-0.0031530	8.0000e-06	-9.0000e-06	-0.062469	0.0011840	-0.062488	-0.0012271	-1.9782e-05
162	206	-0.062352	-0.0043980	8.0000e-06	-8.0000e-06	-0.062468	-4.8000e-05	-0.062452	-0.0024537	-3.1982e-05
163	207	-0.062253	-0.0056160	6.0000e-06	-3.0000e-06	-0.062447	-0.0012740	-0.062392	-0.0036794	-4.0009e-05
164	208	-0.062129	-0.0068560	7.0000e-06	-2.0000e-06	-0.062347	-0.0025080	-0.062307	-0.0049037	-0.00010257
165	209	-0.061983	-0.0080700	5.0000e-06	9.0000e-06	-0.062348	-0.0037320	-0.062199	-0.0061261	-4.0405e-05
166	210	-0.061807	-0.0093280	7.0000e-06	-1.0000e-06	-0.062348	-0.0049990	-0.062067	-0.0073461	4.8087e-05
167	211	-0.061608	-0.010558	6.0000e-06	-2.0000e-06	-0.062348	-0.0062230	-0.061911	-0.0085633	0.00015779
168	212	-0.061385	-0.011785	6.0000e-06	-1.0000e-06	-0.062348	-0.0074450	-0.061731	-0.0097772	0.00029093
169	213	-0.061143	-0.012984	4.0000e-06	9.0000e-06	-0.062348	-0.0086500	-0.061527	-0.010987	0.00044518
170	214	-0.060872	-0.014200	4.0000e-06	9.0000e-06	-0.062348	-0.0098580	-0.061299	-0.012193	0.00062253
171	215	-0.060583	-0.015388	4.0000e-06	7.0000e-06	-0.062348	-0.011064	-0.061048	-0.013394	0.00082208
172	216	-0.060264	-0.016593	5.0000e-06	7.0000e-06	-0.062348	-0.012251	-0.060773	-0.014590	0.0010402
173	217	-0.059928	-0.017768	9.0000e-06	-7.0000e-06	-0.062348	-0.013442	-0.060475	-0.015781	0.0012806
174	218	-0.059562	-0.018959	9.0000e-06	-6.0000e-06	-0.062348	-0.014621	-0.060153	-0.016965	0.0015394

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
175	219	-0.059179	-0.020120	7.0000e-06	-2.0000e-06	-0.062348	-0.015792	-0.059809	-0.018143	0.0018169
176	220	-0.058758	-0.021319	9.0000e-06	-6.0000e-06	-0.062348	-0.016993	-0.059441	-0.019314	0.0021223
177	221	-0.058322	-0.022486	1.0000e-05	-6.0000e-06	-0.062348	-0.018148	-0.059050	-0.020477	0.0024355
178	222	-0.057871	-0.023623	6.0000e-06	1.0000e-06	-0.062348	-0.019293	-0.058637	-0.021632	0.0027648
179	223	-0.057398	-0.024751	3.0000e-06	9.0000e-06	-0.062010	-0.020425	-0.058201	-0.022779	0.0027872
180	224	-0.056893	-0.025890	2.0000e-06	9.0000e-06	-0.061515	-0.021560	-0.057742	-0.023918	0.0026838
181	225	-0.056364	-0.027019	2.0000e-06	9.0000e-06	-0.060994	-0.022685	-0.057262	-0.025047	0.0025759
182	226	-0.055826	-0.028116	4.0000e-06	8.0000e-06	-0.060453	-0.023787	-0.056759	-0.026166	0.0024645
183	227	-0.055254	-0.029224	3.0000e-06	8.0000e-06	-0.059888	-0.024889	-0.056234	-0.027276	0.0023539
184	228	-0.054672	-0.030298	1.0000e-05	-5.0000e-06	-0.059299	-0.025979	-0.055688	-0.028374	0.0022401
185	229	-0.054033	-0.031424	2.0000e-06	9.0000e-06	-0.058669	-0.027088	-0.055120	-0.029462	0.0021205
186	230	-0.053408	-0.032475	3.0000e-06	8.0000e-06	-0.058034	-0.028153	-0.054531	-0.030539	0.0020022
187	231	-0.052750	-0.033534	3.0000e-06	8.0000e-06	-0.057386	-0.029200	-0.053921	-0.031604	0.0018878
188	232	-0.052084	-0.034558	1.0000e-05	-4.0000e-06	-0.056716	-0.030236	-0.053290	-0.032656	0.0017722
189	233	-0.051384	-0.035590	1.1000e-05	-4.0000e-06	-0.056022	-0.031258	-0.052639	-0.033696	0.0016524
190	234	-0.050679	-0.036589	6.0000e-06	1.0000e-06	-0.055308	-0.032266	-0.051967	-0.034723	0.0015318
191	235	-0.049939	-0.037592	6.0000e-06	1.0000e-06	-0.054577	-0.033261	-0.051275	-0.035737	0.0014136
192	236	-0.049194	-0.038562	0.0000	1.0000e-05	-0.053825	-0.034236	-0.050564	-0.036737	0.0012905
193	237	-0.048415	-0.039535	0.0000	9.0000e-06	-0.053049	-0.035205	-0.049833	-0.037722	0.0011678
194	238	-0.047633	-0.040474	2.0000e-06	8.0000e-06	-0.052259	-0.036153	-0.049082	-0.038693	0.0010456
195	239	-0.046801	-0.041434	0.0000	9.0000e-06	-0.051431	-0.037107	-0.048313	-0.039650	0.00091985
196	240	-0.045966	-0.042359	-1.0000e-06	9.0000e-06	-0.050599	-0.038028	-0.047525	-0.040591	0.00079603
197	241	-0.045128	-0.043249	1.0000e-06	8.0000e-06	-0.049750	-0.038929	-0.046719	-0.041516	0.00067064
198	242	-0.044274	-0.044123	1.0000e-06	8.0000e-06	-0.048891	-0.039808	-0.045895	-0.042425	0.00054766
199	243	-0.043384	-0.044998	1.1000e-05	-2.0000e-06	-0.048006	-0.040674	-0.045053	-0.043318	0.00042019
200	244	-0.042479	-0.045854	1.1000e-05	-1.0000e-06	-0.047113	-0.041521	-0.044194	-0.044194	0.00029832
201	245	-0.041574	-0.046676	6.0000e-06	2.0000e-06	-0.046196	-0.042354	-0.043318	-0.045053	0.00017321
202	246	-0.040635	-0.047495	5.0000e-06	3.0000e-06	-0.045264	-0.043165	-0.042425	-0.045895	4.6356e-05
203	247	-0.039699	-0.048281	-2.0000e-06	1.0000e-05	-0.044319	-0.043957	-0.041516	-0.046719	-7.8920e-05
204	248	-0.038690	-0.049093	1.1000e-05	-1.0000e-06	-0.043311	-0.044767	-0.040591	-0.047525	-0.00021094
205	249	-0.037723	-0.049840	6.0000e-06	3.0000e-06	-0.042338	-0.045517	-0.039650	-0.048313	-0.00033648
206	250	-0.036721	-0.050583	6.0000e-06	4.0000e-06	-0.041341	-0.046250	-0.038693	-0.049082	-0.00046662
207	251	-0.035706	-0.051304	5.0000e-06	4.0000e-06	-0.040333	-0.046965	-0.037722	-0.049833	-0.00059312
208	252	-0.034695	-0.051993	-3.0000e-06	9.0000e-06	-0.039321	-0.047657	-0.036737	-0.050564	-0.00071545
209	253	-0.033651	-0.052675	-3.0000e-06	9.0000e-06	-0.038281	-0.048333	-0.035737	-0.051275	-0.00084358

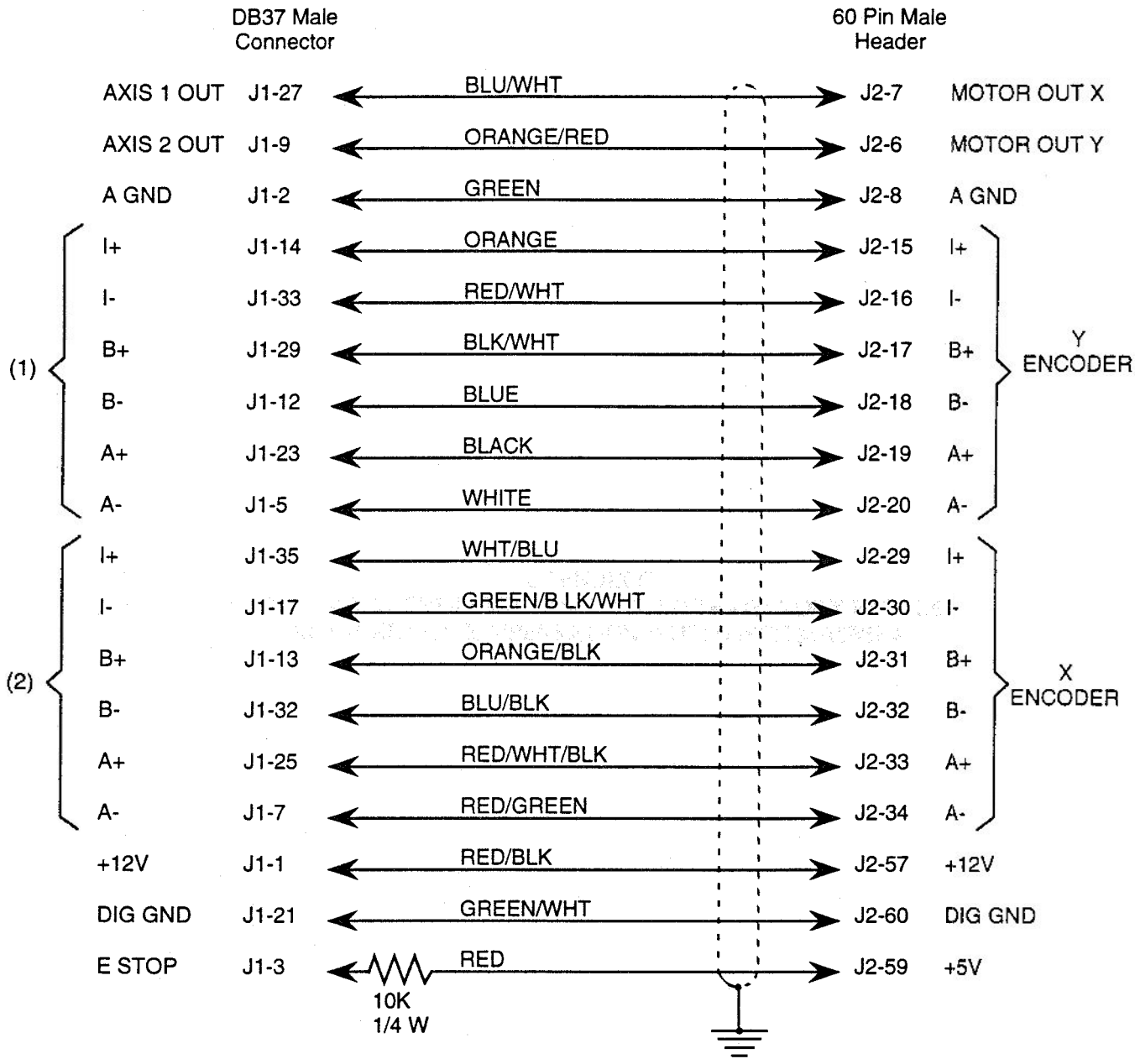
	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
210	254	-0.032614	-0.053323	-1.0000e-06	8.0000e-06	-0.037230	-0.048989	-0.034723	-0.051967	-0.00096956
211	255	-0.031566	-0.053950	-2.0000e-06	8.0000e-06	-0.036174	-0.049619	-0.033696	-0.052639	-0.0010948
212	256	-0.030484	-0.054569	1.1000e-05	1.0000e-06	-0.035100	-0.050235	-0.032656	-0.053290	-0.0012173
213	257	-0.029411	-0.055155	1.1000e-05	1.0000e-06	-0.034019	-0.050822	-0.031604	-0.053921	-0.0013431
214	258	-0.028284	-0.055741	1.1000e-05	1.0000e-06	-0.032893	-0.051405	-0.030539	-0.054531	-0.0014719
215	259	-0.027167	-0.056294	1.1000e-05	1.0000e-06	-0.031784	-0.051954	-0.029462	-0.055120	-0.0015948
216	260	-0.026039	-0.056824	1.2000e-05	2.0000e-06	-0.030666	-0.052479	-0.028374	-0.055688	-0.0017180
217	261	-0.024923	-0.057323	4.0000e-06	5.0000e-06	-0.029542	-0.052981	-0.027276	-0.056234	-0.0018393
218	262	-0.023797	-0.057799	-4.0000e-06	9.0000e-06	-0.028406	-0.053458	-0.026166	-0.056759	-0.0019636
219	263	-0.022639	-0.058263	-5.0000e-06	9.0000e-06	-0.027254	-0.053916	-0.025047	-0.057262	-0.0020871
220	264	-0.021473	-0.058703	-5.0000e-06	8.0000e-06	-0.026095	-0.054353	-0.023918	-0.057742	-0.0022074
221	265	-0.020321	-0.059111	-3.0000e-06	8.0000e-06	-0.024939	-0.054763	-0.022779	-0.058201	-0.0023258
222	266	-0.019138	-0.059504	-3.0000e-06	8.0000e-06	-0.023764	-0.055154	-0.021632	-0.058637	-0.0024443
223	267	-0.017925	-0.059881	-5.0000e-06	8.0000e-06	-0.022533	-0.055534	-0.020477	-0.059050	-0.0025687
224	268	-0.016750	-0.060220	-6.0000e-06	8.0000e-06	-0.021354	-0.055873	-0.019314	-0.059441	-0.0026854
225	269	-0.015546	-0.060543	-3.0000e-06	7.0000e-06	-0.020154	-0.056192	-0.018143	-0.059809	-0.0028031
226	270	-0.014336	-0.060840	-3.0000e-06	7.0000e-06	-0.018959	-0.056484	-0.016965	-0.060153	-0.0029191
227	271	-0.013144	-0.061109	1.0000e-05	4.0000e-06	-0.017754	-0.056754	-0.015781	-0.060475	-0.0030339
228	272	-0.011923	-0.061359	1.1000e-05	4.0000e-06	-0.016542	-0.057001	-0.014590	-0.060773	-0.0031472
229	273	-0.010721	-0.061580	3.0000e-06	6.0000e-06	-0.015326	-0.057223	-0.013394	-0.061048	-0.0032602
230	274	-0.0094900	-0.061782	4.0000e-06	6.0000e-06	-0.014110	-0.057422	-0.012193	-0.061299	-0.0033698
231	275	-0.0082800	-0.061955	-7.0000e-06	7.0000e-06	-0.012894	-0.057597	-0.010987	-0.061527	-0.0034774
232	276	-0.0069950	-0.062114	1.0000e-05	5.0000e-06	-0.011605	-0.057754	-0.0097772	-0.061731	-0.0035916
233	277	-0.0057550	-0.062241	1.0000e-05	5.0000e-06	-0.010372	-0.057877	-0.0085633	-0.061911	-0.0037010
234	278	-0.0045380	-0.062341	3.0000e-06	6.0000e-06	-0.0091490	-0.057975	-0.0073461	-0.062067	-0.0038075
235	279	-0.0032930	-0.062419	2.0000e-06	6.0000e-06	-0.0079120	-0.058047	-0.0061261	-0.062199	-0.0039163
236	280	-0.0020710	-0.062472	-8.0000e-06	6.0000e-06	-0.0066770	-0.058097	-0.0049037	-0.062307	-0.0040206
237	281	-0.00084900	-0.062501	-5.0000e-06	6.0000e-06	-0.0054500	-0.058126	-0.0036794	-0.062392	-0.0041191
238	282	0.00039700	-0.062505	-6.0000e-06	6.0000e-06	-0.0042130	-0.058133	-0.0024537	-0.062452	-0.0042145
239	283	0.0016190	-0.062484	9.0000e-06	6.0000e-06	-0.0029830	-0.058135	-0.0012271	-0.062488	-0.0042885
240	284	0.0028410	-0.062441	9.0000e-06	6.0000e-06	-0.0017570	-0.058135	-1.1481e-17	-0.062500	-0.0043385
241	285	0.0040850	-0.062373	1.0000e-06	6.0000e-06	-0.00052300	-0.058135	0.0012271	-0.062488	-0.0043626
242	286	0.0053520	-0.062276	9.0000e-06	6.0000e-06	0.00074400	-0.058134	0.0024537	-0.062452	-0.0043612
243	287	0.0065690	-0.062160	8.0000e-06	8.0000e-06	0.0019680	-0.058130	0.0036794	-0.062392	-0.0043367
244	288	0.0078080	-0.062016	2.0000e-06	7.0000e-06	0.0031830	-0.058129	0.0049037	-0.062307	-0.0042839

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
245	289	0.0090180	-0.061852	-8.0000e-06	4.0000e-06	0.0044080	-0.058129	0.0061261	-0.062199	-0.0042041
246	290	0.010250	-0.061659	-8.0000e-06	4.0000e-06	0.0056290	-0.058129	0.0073461	-0.062067	-0.0040991
247	291	0.011478	-0.061443	-9.0000e-06	4.0000e-06	0.0068570	-0.058129	0.0085633	-0.061911	-0.0039680
248	292	0.012701	-0.061202	-9.0000e-06	4.0000e-06	0.0080790	-0.058129	0.0097772	-0.061731	-0.0038123
249	293	0.013895	-0.060942	-6.0000e-06	4.0000e-06	0.0092880	-0.058129	0.010987	-0.061527	-0.0036336
250	294	0.015084	-0.060659	8.0000e-06	8.0000e-06	0.010478	-0.058129	0.012193	-0.061299	-0.0034342
251	295	0.016338	-0.060333	-9.0000e-06	4.0000e-06	0.011730	-0.058129	0.013394	-0.061048	-0.0031993
252	296	0.017514	-0.060002	-6.0000e-06	4.0000e-06	0.012912	-0.058129	0.014590	-0.060773	-0.0029542
253	297	0.018707	-0.059641	-7.0000e-06	4.0000e-06	0.014093	-0.058130	0.015781	-0.060475	-0.0026860
254	298	0.019869	-0.059263	6.0000e-06	9.0000e-06	0.015263	-0.058129	0.016965	-0.060153	-0.0024006
255	299	0.021025	-0.058863	1.0000e-06	7.0000e-06	0.016426	-0.058129	0.018143	-0.059809	-0.0020947
256	300	0.022194	-0.058433	1.0000e-06	6.0000e-06	0.017582	-0.058130	0.019314	-0.059441	-0.0017693
257	301	0.023333	-0.057987	-9.0000e-06	3.0000e-06	0.018714	-0.058076	0.020477	-0.059050	-0.0014833
258	302	0.024484	-0.057510	-8.0000e-06	3.0000e-06	0.019860	-0.057611	0.021632	-0.058637	-0.0015619
259	303	0.025605	-0.057021	-7.0000e-06	3.0000e-06	0.020986	-0.057113	0.022779	-0.058201	-0.0016534
260	304	0.026715	-0.056509	6.0000e-06	9.0000e-06	0.022101	-0.056593	0.023918	-0.057742	-0.0017446
261	305	0.027901	-0.055933	-1.0000e-06	7.0000e-06	0.023292	-0.056005	0.025047	-0.057262	-0.0018446
262	306	0.029011	-0.055365	-1.0000e-06	7.0000e-06	0.024394	-0.055438	0.026166	-0.056759	-0.0019324
263	307	0.030088	-0.054788	-1.0000e-05	2.0000e-06	0.025471	-0.054856	0.027276	-0.056234	-0.0020190
264	308	0.031154	-0.054188	-8.0000e-06	3.0000e-06	0.026551	-0.054251	0.028374	-0.055688	-0.0021003
265	309	0.032228	-0.053556	-8.0000e-06	3.0000e-06	0.027610	-0.053621	0.029462	-0.055120	-0.0021881
266	310	0.033269	-0.052916	5.0000e-06	9.0000e-06	0.028656	-0.052978	0.030539	-0.054531	-0.0022685
267	311	0.034418	-0.052176	-8.0000e-06	2.0000e-06	0.029809	-0.052235	0.031604	-0.053921	-0.0023579
268	312	0.035431	-0.051493	-9.0000e-06	2.0000e-06	0.030828	-0.051547	0.032656	-0.053290	-0.0024379
269	313	0.036451	-0.050776	4.0000e-06	9.0000e-06	0.031834	-0.050836	0.033696	-0.052639	-0.0025191
270	314	0.037457	-0.050039	-1.0000e-05	0.0000	0.032853	-0.050094	0.034723	-0.051967	-0.0025940
271	315	0.038446	-0.049283	4.0000e-06	1.0000e-05	0.033830	-0.049345	0.035737	-0.051275	-0.0026719
272	316	0.039403	-0.048521	-3.0000e-06	6.0000e-06	0.034796	-0.048572	0.036737	-0.050564	-0.0027505
273	317	0.040345	-0.047741	-9.0000e-06	0.0000	0.035739	-0.047799	0.037722	-0.049833	-0.0028173
274	318	0.041289	-0.046927	-1.0000e-05	-1.0000e-06	0.036676	-0.046986	0.038693	-0.049082	-0.0028945
275	319	0.042199	-0.046111	-8.0000e-06	1.0000e-06	0.037592	-0.046155	0.039650	-0.048313	-0.0029732
276	320	0.043093	-0.045277	3.0000e-06	1.1000e-05	0.038487	-0.045316	0.040591	-0.047525	-0.0030459
277	321	0.043986	-0.044408	3.0000e-06	1.0000e-05	0.039374	-0.044455	0.041516	-0.046719	-0.0031152
278	322	0.044847	-0.043539	-3.0000e-06	6.0000e-06	0.040237	-0.043575	0.042425	-0.045895	-0.0031890
279	323	0.045690	-0.042654	-1.0000e-05	-1.0000e-06	0.041085	-0.042684	0.043318	-0.045053	-0.0032556

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
280	324	0.046579	-0.041681	-8.0000e-06	0.0000	0.041966	-0.041719	0.044194	-0.044194	-0.0033255
281	325	0.047386	-0.040762	1.0000e-06	1.0000e-05	0.042776	-0.040790	0.045053	-0.043318	-0.0033932
282	326	0.048174	-0.039828	-4.0000e-06	6.0000e-06	0.043568	-0.039858	0.045895	-0.042425	-0.0034506
283	327	0.048958	-0.038859	-3.0000e-06	6.0000e-06	0.044345	-0.038893	0.046719	-0.041516	-0.0035157
284	328	0.049709	-0.037893	-9.0000e-06	-3.0000e-06	0.045097	-0.037921	0.047525	-0.040591	-0.0035785
285	329	0.050454	-0.036895	-1.0000e-05	-3.0000e-06	0.045835	-0.036935	0.048313	-0.039650	-0.0036354
286	330	0.051167	-0.035901	-8.0000e-06	-1.0000e-06	0.046550	-0.035931	0.049082	-0.038693	-0.0036958
287	331	0.051859	-0.034894	0.0000	1.1000e-05	0.047248	-0.034918	0.049833	-0.037722	-0.0037493
288	332	0.052544	-0.033853	-1.0000e-06	1.1000e-05	0.047924	-0.033885	0.050564	-0.036737	-0.0038067
289	333	0.053234	-0.032757	-9.0000e-06	-4.0000e-06	0.048623	-0.032773	0.051275	-0.035737	-0.0038633
290	334	0.053877	-0.031689	-9.0000e-06	-3.0000e-06	0.049261	-0.031716	0.051967	-0.034723	-0.0039120
291	335	0.054486	-0.030629	-8.0000e-06	-3.0000e-06	0.049873	-0.030644	0.052639	-0.033696	-0.0039648
292	336	0.055075	-0.029558	-1.0000e-06	1.1000e-05	0.050460	-0.029573	0.053290	-0.032656	-0.0040126
293	337	0.055654	-0.028454	-2.0000e-06	1.0000e-05	0.051036	-0.028475	0.053921	-0.031604	-0.0040577
294	338	0.056199	-0.027361	-5.0000e-06	6.0000e-06	0.051585	-0.027383	0.054531	-0.030539	-0.0040976
295	339	0.056724	-0.026256	-9.0000e-06	-4.0000e-06	0.052112	-0.026265	0.055120	-0.029462	-0.0041432
296	340	0.057236	-0.025119	-9.0000e-06	-5.0000e-06	0.052616	-0.025148	0.055688	-0.028374	-0.0041831
297	341	0.057716	-0.023995	-7.0000e-06	-3.0000e-06	0.053097	-0.024016	0.056234	-0.027276	-0.0042243
298	342	0.058174	-0.022862	-3.0000e-06	1.1000e-05	0.053561	-0.022872	0.056759	-0.026166	-0.0042599
299	343	0.058644	-0.021630	-6.0000e-06	4.0000e-06	0.054024	-0.021653	0.057262	-0.025047	-0.0042982
300	344	0.059056	-0.020478	-8.0000e-06	-6.0000e-06	0.054440	-0.020486	0.057742	-0.023918	-0.0043331
301	345	0.059452	-0.019297	-8.0000e-06	-5.0000e-06	0.054831	-0.019318	0.058201	-0.022779	-0.0043655
302	346	0.059818	-0.018130	-8.0000e-06	-4.0000e-06	0.055196	-0.018143	0.058637	-0.021632	-0.0043987
303	347	0.060161	-0.016958	-4.0000e-06	1.1000e-05	0.055542	-0.016963	0.059050	-0.020477	-0.0044254
304	348	0.060481	-0.015778	-4.0000e-06	1.0000e-05	0.055865	-0.015770	0.059441	-0.019314	-0.0044518
305	349	0.060784	-0.014569	-6.0000e-06	5.0000e-06	0.056164	-0.014581	0.059809	-0.018143	-0.0044741
306	350	0.061057	-0.013376	-8.0000e-06	-6.0000e-06	0.056439	-0.013376	0.060153	-0.016965	-0.0044976
307	351	0.061307	-0.012181	-7.0000e-06	-4.0000e-06	0.056691	-0.012175	0.060475	-0.015781	-0.0045164
308	352	0.061555	-0.010861	-8.0000e-06	-5.0000e-06	0.056935	-0.010867	0.060773	-0.014590	-0.0045372
309	353	0.061756	-0.0096560	-4.0000e-06	1.0000e-05	0.057137	-0.0096570	0.061048	-0.013394	-0.0045527
310	354	0.061933	-0.0084460	-6.0000e-06	3.0000e-06	0.057315	-0.0084330	0.061299	-0.012193	-0.0045679
311	355	0.062088	-0.0072090	-6.0000e-06	4.0000e-06	0.057467	-0.0072180	0.061527	-0.010987	-0.0045815
312	356	0.062218	-0.0059930	-7.0000e-06	-8.0000e-06	0.057595	-0.0059960	0.061731	-0.0097772	-0.0045937
313	357	0.062323	-0.0047750	-6.0000e-06	-5.0000e-06	0.057701	-0.0047630	0.061911	-0.0085633	-0.0046028
314	358	0.062407	-0.0035070	-7.0000e-06	-8.0000e-06	0.057783	-0.0035060	0.062067	-0.0073461	-0.0046107

	i	x encoder	y encoder	x fol err	y fol err	x LASER	y LASER	x ideal	y ideal	Radius Error
315	359	0.062464	-0.0022860	-6.0000e-06	-5.0000e-06	0.057838	-0.0022900	0.062199	-0.0061261	-0.0046167
316	360	0.062497	-0.0010160	-6.0000e-06	-8.0000e-06	0.057872	-0.0010190	0.062307	-0.0049037	-0.0046190
317	361	0.062506	0.00015500	-6.0000e-06	-0.00015600	0.057883	0.00013800	0.062392	-0.0036794	-0.0046168
318	362	0.062502	0.00012100	-2.0000e-06	-0.00012100	0.057885	0.00020500	0.062452	-0.0024537	-0.0046146
319	363	0.062501	3.3000e-05	-1.0000e-06	-3.3000e-05	0.057886	0.00020500	0.062488	-0.0012271	-0.0046136
320	364	0.062500	9.0000e-06	0.0000	-9.0000e-06	0.057887	0.00020500	0.062500	0.0000	-0.0046126
321	365	0.062500	2.0000e-06	0.0000	-2.0000e-06	0.057887	0.00020500	0.062500	0.0000	-0.0046126
322	366	0.062500	1.0000e-06	0.0000	-1.0000e-06	0.057887	0.00020400	0.062500	0.0000	-0.0046126
323	367	0.062500	0.0000	0.0000	0.0000	0.057887	0.00020400	0.062500	0.0000	-0.0046126
324	368	0.062500	0.0000	0.0000	0.0000	0.057888	0.00020500	0.062500	0.0000	-0.0046116
325	369	0.062500	0.0000	0.0000	0.0000	0.057888	0.00020400	0.062500	0.0000	-0.0046116

APPENDIX B
DRAWING OF INTERFACE CABLE TO ADAPT DSPCG MATRIX4 FOR PIN-COMPATIBILITY WITH GALIL 621 MACHINE CONTROLLER



INTERFACE CABLE TO ADAPT DSPCG MATRIX4
FOR PIN-COMPATIBILITY WITH
GALIL 621 MACHINE CONTROLLER

APPENDIX C
PROGRAM TO GENERATE COMPENSATED TRAJECTORY PROFILE FOR BACKLASH COMPENSATION WITH DSPCG MATRIX4

```
/*  cirgencx.c
 *
 *  Program to generate a circle trajectory profile for DSPCG CRADA.
 *  Results are writtten to a binary file given as the argument when
 *  the program is run.
 *
 *  To execute, use 'CIRGENCX <filename>', where filename is the file in
 *  which the binary data points will be stored.
 *
 *  Written by: Wes Wysor, June 1994.
 *
 */

#include <process.h>
#include <stdio.h>
#include <math.h>
FILE *fptr;

double PI = 3.141592654;

void main( int argc, char *argv[] )
    {
    long i, npoints, amp;
    long p1, p2, oldp1, oldp2;
    long slop1 = 7485;
    long slop2 = 7165;
    long xswtchup, xswtchdn, yswtchup, yswtchdn, nsteps;
    int xup, yup;

    struct FDAT
       {
       long p1;
       long v1;
       long p2;
       long v2;
       } frec;

    size_t recsize = sizeof( frec );

    printf("\n Enter Period (number of points) > ");
    scanf("%ld", &npoints );
    printf("\n Enter Amplitude (circle radius, 1in = 1,6000,000) > ");
    scanf("%ld", &amp );
    printf("\n Enter Number of Transition Steps (counts) > ");
    scanf("%ld", &nsteps );
    printf("\n Period = %ld   Amplitude = %ld   # Steps = %ld \n",
            npoints, amp, nsteps );

    if(( fptr = fopen( argv[1], "wb" )) == NULL )
       {
       printf("\n ERROR Opening Contour Data File! ");
```

```
        printf("\n Run program using - CIRGEN <filename> \n\n");
        exit( 0 );
        }

/*  The following fills the buffer in the DSPCG board with 1024 zero points
 *  due to the fact that there seems to be an initialization problem
 */

    for (i = 0; i < 1024; i++)
        {
        frec.p1 = (long)(amp*cos((2.0*PI*(double)0.0)/((double)npoints)));
        frec.v1 = (long)(-2*PI*amp*sin((2.0*PI*(double)0.0)/((double)npoints))
                  /(double)npoints);
        frec.p2 = (long)(amp*sin((2.0*PI*(double)0.0)/((double)npoints)));
        frec.v2 = (long)(2*PI*amp*cos((2.0*PI*(double)0.0)/((double)npoints))
                  /(double)npoints);

        fwrite( &frec  recsize, 1, fptr );
        }

    oldp1 = frec.p1;
    oldp2 = frec.p2;

/*  Compute actual data points
 */

    xswtchup = 0;
    xswtchdn = -2*nsteps;
    yswtchup = -2*nsteps;
    yswtchdn = 0;
    xup = -1;
    yup = 1;

    for (i = 0; i <= 3*npoints; i++)
        {
        p1 = (long)(amp*cos((2.0*PI*(double)i)/((double)npoints)));
        frec.v1 = (long)(-2.0*PI*amp*sin((2.0*PI*(double)i)/((double)npoints))
                  /(double)npoints);
        p2 = (long)(amp*sin((2.0*PI*(double)i)/((double)npoints)));
        frec.v2 = (long)(2.0*PI*amp*cos((2.0*PI*(double)i)/((double)npoints))
                  /(double)npoints);

        if( (p1   oldp1) > 0 )        /* Increasing x                    */
            {
            xup = 1;
            if( xswtchup == 0 )       /* Did we just start increasing?   */
                {
                xswtchup = i;         /* Starting point for increase     */
                xswtchdn = 0;         /* Reset to detect next decrease   */
                }
            if( i <= ( xswtchup + nsteps ))       /* Still transitioning? */
```

```
        {
        frec.p1 = p1 + slop1*(i-xswtchup)/nsteps;
        frec.v1 = frec.v1 + slop1/nsteps;
        }
    else
        {
        frec.p1 = p1 + slop1;
        }
    }
else if( (p1 - oldp1) < 0 )  /* decreasing x                    */
    {
    xup = -1;
    if( xswtchdn == 0 )       /* Did we just start decreasing?   */
        {
        xswtchdn = i;         /* Starting point for decrease     */
        xswtchup = 0;         /* Reset to detect next increase   */
        }
    if( i <= ( xswtchdn + nsteps ))       /* Still transitioning? */
        {
        frec.p1 = p1 + slop1*(1-((float)(i-xswtchdn)/(float)nsteps));
        frec.v1 = frec.v1 - slop1/nsteps;
        }
    else
        {
        frec.p1 = p1;
        }
    }
else if( (p1 - oldp1) == 0 )              /* constant x          */
    if( xup > 0 )
        {
        if( i <= ( xswtchup + nsteps ))   /* Still transitioning? */
            {
            frec.p1 = p1 + slop1*(i-xswtchup)/nsteps;
            frec.v1 = frec.v1 + slop1/nsteps;
            }
        else
            {
            frec.p1 = p1 + slop1;
            }
        }
    else
        {
        if( i <= ( xswtchdn + nsteps ))   /* Still transitioning? */
            {
            frec.p1 = p1 + slop1*(1-((float)(i-xswtchdn)/(float)nsteps));
            frec.v1 = frec.v1 - slop1/nsteps;
            }
        else
            {
            frec.p1 = p1;
            }
```

```
      }

   if( (p2 - oldp2) > 0 )        /* Increasing y                          */
      {
      yup = 1;
      if( yswtchup == 0 )        /* Did we just start increasing?         */
         {
         yswtchup = i;           /* Starting point for increase           */
         yswtchdn = 0;           /* Reset to detect next decrease         */
         }
      if( i <= (yswtchup + nsteps ))        /* Still transitioning? */
         {
         frec.p2 = p2 - slop2 * (1-((float)(i-yswtchup)/(float)nsteps) );
         frec.v2 = frec.v2 + slop2/nsteps;
         }
      else
         {
         frec.p2 = p2;
         }
      }
   else if( (p2 - oldp2) < 0 )  /* Decreasing y                           */
      {
      yup = -1;
      if( yswtchdn == 0 )
         {
         yswtchdn = i;           /* Starting point for decrease           */
         yswtchup = 0;           /* Reset to detect next increase         */
         }
      if( i <= ( yswtchdn + nsteps ))       /* Still transitioning? */
         {
         frec.p2 = p2 - slop2*(i-yswtchdn)/nsteps;
         frec.v2 = frec.v2 - slop2/nsteps;
         }
      else
         {
         frec.p2 = p2 - slop2;
         }
      }
   else if( (p2 - oldp2) == 0 )             /* constant y            */
      if( yup > 0 )
         {
         if( i <= (yswtchup + nsteps ))     /* Still transitioning? */
            {
            frec.p2 = p2 - slop2*(1-((float)(i-yswtchup)/(float)nsteps));
            frec.v2 = frec.v2 + slop2/nsteps;
            }
         else
            {
            frec.p2 = p2;
            }
         }
```

```
    else
       {
       if( i <= ( yswtchdn + nsteps ))     /* Still transitioning? */
          {
          frec.p2 = p2 - slop2*(i-yswtchdn)/nsteps;
          frec.v2 = frec.v2 - slop2/nsteps;
          }
        else
          {
          frec.p2 = p2 - slop2;
          }
       }

fwrite( &frec, recsize, 1, fptr );

oldp1 = p1;
oldp2 = p2;

}

fclose( fptr );
```