Coordinate Standard Measurement Development

Federal Manufacturing & Technologies

R. A. Hanshaw

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Abstract

A Shelton Precision Interferometer Base, which is used for calibration of coordinate standards, was improved through hardware replacement, software geometry error correction, and reduction of vibration effects. Substantial increases in resolution and reliability, as well as reduction in sampling time, were achieved through hardware replacement; vibration effects were reduced substantially through modification of the machine component dampening and software routines; and the majority of the machine's geometry error was corrected through software geometry error correction. Because of these modifications, the uncertainty of coordinate standards calibrated on this device has been reduced dramatically.

Summary

This project was a result of concerns over the capability to calibrate coordinate standards on a Shelton Precision Interferometer Base (SPIB). The hardware on the SPIB was becoming marginal, and at the same time the uncertainty of the coordinate standards was becoming the major uncertainty contributor in the calibration of several new high-accuracy coordinate measuring machines (CMMs). There were three major concerns: aging laser interferometer and computer hardware, excessive error due to geometry and

vibration, and operator fatigue.

The laser interferometer hardware was becoming unreliable and did not have the necessary resolution. Replacement of the electronics increased the resolution from 6 microinches to 0.4 microinch, and it increased the sampling rate.

The original computer system consisted of a DEC PDP 11/84 mainframe system which ran at about 16 MHz and with 64K of system memory. The mainframe system was replaced with a dual Pentium PC, which has a system processor speed of 200 MHz and 128Mb of RAM memory. The replacement cleared up a Y2K problem, the additional memory made it possible to analyze larger measurement matrices, and the increased processor speed increased sampling speed. The increased sampling speed provided the capability for additional software routines to analyze vibration during measurement and to correct for geometry errors. In addition, the Fortran software on the PC was able to use the existing Fortran code for the measurement and analysis routines with very little modification. Modification and assembly of the existing Fortran code were also much simpler with the PC Fortran.

The error due to the vibration of the system was decreased by taking a greater number of samples for each measurement point and by incorporating a software routine to monitor the amount of vibration in each axis. The routine allows measurement points to be taken only if the vibration is below a user-selectable level. A software routine was also developed to compensate for the

majority of the geometry error. Fixturing was also developed in conjunction with this software to facilitate in the positioning of a portable laser for geometry error data. The geometry error affecting the calibration of coordinate standards has almost been reduced to the repeatability of the machine.

The concern over operator fatigue was due to manual positioning of the Z axis. This was most fatiguing when the measurements were at a distance from the operator. This also created additional error in Z-axis positioning as well as the thermal error due to the proximity of the operator to the piece being measured. Mounting a small stepper motor to the Z axis of the machine and interfacing the motor to a joystick alleviated the problem. This allows the operator to keep a greater distance from the device to be measured, thereby reducing thermal and operator fatigue error.

Incorporation of the hardware replacements and software routines has decreased calibration/repair time, the time required to revise software, and it has decreased the uncertainty by approximately 40%.

Discussion

Scope and Purpose

This project was initiated as an Advanced Design and Production Technologies (ADAPT) project. The specific objectives of the ADAPT program are (1) to maintain competence in key production processes; (2) to develop and demonstrate production capability for components, subassemblies, and assemblies acceptable for weapons use and which have application to enhance the safety, security, or reliability of the enduring stockpile; (3) to maintain viable design, development, and production interrelationships

within the Nuclear Weapons Complex (NWC); (4) improvement of current production processes; and (5) development of processes for future production and ensuring they are production capable, including supporting feasibility demonstration studies. The purpose of this project was to maintain and improve the capability to calibrate coordinate standards, which are used for the calibration of coordinate measuring machines (CMMs).

The scope of the project was limited to a Shelton Precision Interferometer Base (SPIB), shown in Figure 1, where 95% of the coordinate standards at Federal Manufacturing & Technologies (FM&T) are calibrated. The construction of the SPIB was considered adequate; therefore, the project was focused upon replacing components that were becoming inadequate due to age as well as improvements that could be made to lower the major sources of machine error.

Activity

Background

The Shelton Precision Interferometer Base is a fixed bridge type CMM. It uses precision granite surfaces to guide all motion. This design offers excellent repeatability with a minimum of maintenance. In the past, the geometry of the machine had been corrected by laboriously lapping the granite guideways to provide the required geometry in each axis. A number of measurements had to be made and analyzed before removal of any material in the guideway. A small amount of material was removed and the process was repeated until the desired geometry was achieved. This process required a great deal of expertise and time. A mistake in material removal from the guideway could result in a condition that could not be corrected.

The SPIB was fitted with stepper motors attached to the X and Y axes of the machine. Very precise movements along the X and Y axes were made using a joystick to control the stepper motors. The Z axis was positioned by rotating a knob, which was located on the Y axis carriage. Very fine movements could be made because the rotation was decreased through a gear reduction unit. Movement in this manner in the Z axis was tedious and became more difficult as the Y axis carriage was moved further from the operator as would be necessary in the calibration of ball plates.

Figure 1. Shelton Precision Interferometer Base

The laser interferometer electronics consisted of a 1074A Coupler, three 10760A Counters, a 10745A HP-IB Interface, and a model 63312F Multiple Output DC Power Supply. The electronics were becoming increasingly unreliable.

Data collection and analysis was performed on a DEC PDP 11/84 which used Fortran for the programming of the collection and analysis routines. With the advent of more popular programming languages and retirement of programmers, it was very difficult to revise the software and impossible to write any new software. The processor speed of the computer was also deemed inadequate for geometry error correction or vibration analysis routines.

Laser Interferometer Electronics Replacement

The replacement of the electronics involved replacement of the 1074A Coupler, three 10760A Counters, a 10745A HP-IB Interface, and a model 63312F Multiple Output DC Power Supply with an HP 5507A Laser Transducer Electronics. The new electronics provided increased resolution, the ability to interface to servo electronics, error messages, and the ability to upgrade or add on as necessary. The new system was also much more compact, which allowed all of the

electronics for the SPIB to be placed into a single rack. The complete laser system consists of an HP5507A Laser Transducer Electronics, an HP5501B Laser Transducer, two HP10700A 50% Beam Splitters, five 10707A Beam Benders, three 10704A Retroreflectors, three 10780C Receivers, and three 10702A Linear Interferometers.

Computer Replacement

There were five objectives for the replacement of the DEC computer system:

1. The computer must be accessible from each dimensional engineer's desk.
2. Network access should not significantly affect measurement speed.
3. The integrity of the data must be ensured.
4. The system memory must be sufficient for future software needs.
5. There should be sufficient disk space for historical data and all dimensional software.

One of the most useful features of the DEC computer system was the network, which connected each engineer to the computer system. The network was dedicated solely to the engineers in the department. This allowed the engineer access to the analysis software and data while the system was being used for data collection. This was also important since the analysis software could only be used on the DEC. This objective was met by using the existing Saturn network with a Windows NT operating system on a new PC.

There was some concern that a large amount of network access would slow data collection speed and thereby have a detrimental effect on the quality of the data. Sampling rate/system speed were considered to be extremely important, not only for reliable data but also for the ease of use of the data collection software. The objective to reduce the impact of network access and use was lessened by limiting network access to the system with the Windows NT security features and by using a dual processor PC.

The system memory and disk space objectives were easily met with a new PC. The system memory of 128 megabytes and disk space of eight gigabytes were determined to be adequate for future needs as well.

The integrity of both the data and the software is important. The software represents a huge investment in time and effort. Certain programs took years to develop. The calibration data is important for trend and uncertainty analyses. Three techniques were implemented to ensure the integrity of the data and software: a redundant array of independent disks (RAID) was installed, scheduling of unattended backups was implemented, and an uninterruptible power supply (UPS) was attached to the computer.

Four 4-gigabyte drives were installed in the computer, and a RAID technique of disk striping with parity was implemented. The method provides complete data redundancy by dividing all data and parity blocks between the drives in such a way that if any drive fails, data on the failed drive can be regenerated using the data and parity information of the remaining drives.¹

The ability to schedule unattended backups was necessary to ensure the integrity of the software and the historical data. This became especially important when it was determined to use the PC for a central distribution point for all of the calibration software. A 4-gigabyte tape drive was installed on the PC. Backups were scheduled using the 'AT' command in conjunction with the 'BACKUP' command at the command prompt. The 'AT' command schedules commands and programs to run on a computer at a specified time and date.

In order to minimize the amount of heat introduced into the lab, all of the computer equipment and hardware was moved outside of the lab. Two terminals were connected to the computer, one next to the

computer and the other next to the SPIB. This was accomplished by using a terminal extender. Both of the terminals are active. This allows the ability to troubleshoot while monitoring the hardware as well as normal data collection inside the lab without extra heat being introduced.

Software

The DEC computer system contained approximately 375 different Fortran programs. Many of these programs were no longer necessary; however, those that were necessary contained thousands of lines of Fortran code. The time and resources required to create software in another programming language were not available; therefore, it was decided to use Fortran on the PC.

The Fortran package installed on the PC was a considerable improvement over the Fortran on the DEC. Memory was no longer a problem, additional commands had been added to the language, help files were easily accessible, many of the functions could be executed by a mouse click, debugging was possible a line at a time, and user interfaces were easily added.

The Fortran code was transferred across by connecting the PC to the network attached to the DEC. The code was easily downloaded using the terminal accessory available in Windows NT. The latest version of the code for each Fortran program was downloaded, as well as all of the historical data. The Fortran code then had to be rebuilt using the Fortran programming language for the PC. A number of difficulties were encountered in rebuilding the executable code.

The major difficulty involved the portability of the Fortran code to the new environment. The difficulty concerned the use of Hollerith constants in the Fortran code. Hollerith constants are a string of ASCII characters preceded by a character count and the letter H. The constant is stored as byte strings, one character per byte. The difficulty arose when these constants were assigned to real and integer variables. The new Fortran language uses Hollerith constants, but the

manipulation of these constants within real and integer variables was handled differently than the DEC Fortran. All of the Fortran code was revised to change the way that ASCII characters are manipulated. Revision was made easier with the search capabilities present in the Fortran software.

Another portability problem arose over filename structure. The DEC system used a version number appended to the end of a filename. For example, if you save a file named 'plate.dat', the name would be saved as 'plate.dat;1' under the DEC filename convention. If the file was revised, the revision would be named 'plate.dat;2'. This had been a very useful feature of the DEC system; therefore, the revised Fortran programs were written to use this type of system. In order to implement this filename convention, a routine named "ASSIGN" was created. This routine also corrected a problem with the portability of the original code. The Fortran language on the DEC had an 'ASSIGN' command whereas the PC Fortran did not. The new software routine made it unnecessary to change any of the code that had an 'ASSIGN' command. The appendix contains the code for the 'ASSIGN' routine.

Another software problem concerned the HP-IB hardware interface. The HP-IB hardware did not support the Fortran language under Windows NT. This made it necessary to write a software interface in order to use the HP-IB hardware. The help files shipped with the HP-IB hardware contained enough information in order to construct the software interface. Once the software interface was constructed, it was much easier to use and understand than the macro language that had been present on the DEC system for HP-IB communications.

Replacement of the laser transducer electronics also required a change in the programming. The new

electronics used a completely different set of commands. The changes were limited to a small number of routines contained within the data collection programs. The programming mnemonics executed by the HP5507A's HP-IB board were easy to understand, allowed more control of the electronics, and provided much better error information.

A concern over data collection speed prompted a change in the Fortran code. The data collection software used on the DEC spawned a separate program to continuously read the X, Y, and Z machine positions and update of the numeric displays. A bottleneck was created when the data collection program required position data from the laser electronics at the same time as the numeric display program. Data collection then became much too slow to allow the acquisition of larger volumes of data required for the vibration analysis, which was planned for the new system. The Fortran code was revised to create a separate thread of program execution that would share a common data area with the data collection program. In this way, the 'thread' would read position data from the laser electronics and store it in the common data area where the data collection program would retrieve it. The data area is refreshed at a rate of approximately ten readings per second, which is more than adequate for the speed at which the measurements are taken. The software is also constructed to make sure the memory area has been refreshed before taking an additional sample.

The revision of the software was simplified due to the way the original Fortran programs had been constructed. The software had been constructed using common subroutines, which were stored in software libraries. The routines in the libraries were then used in a number of different programs. Corrections made to one subroutine would then be applied across a number of different Fortran programs.

An additional Fortran program was written to monitor the laboratory temperature. The program reads the temperature and barometric pressure in the lab and records the time, temperature, and barometric pressure in a file, which includes the date in the name of the file. In this way, the engineers can monitor the temperature of the lab from their desk. It also makes it easier to analyze the lab's performance. The 'AT' command is used to activate the laboratory temperature-monitoring program. The program runs in the background and is invisible to the operator.

Geometry Error Correction

The most important objective of this project was to correct the geometry error of the machine within the data collection software. This would involve measuring the machine error and placing the measured errors in a file to be input into the data collection software. This process is called geometry error mapping. A time-consuming process of hand lapping had been used in the past to correct the geometry. Hand lapping required the measurement of the machine geometry that would be affected by the removal of material on the guideway. For example, to correct the X-axis horizontal straightness, measurement of the horizontal straightness was necessary as well as measurement of the X-axis yaw. Lapping might correct the straightness but worsen the yaw error. Elimination of too much material would result in a 'hole' in the guide-way, which would then require additional lapping of the rest of the guide-way. This process had been necessary in the past in order to achieve the required uncertainty for coordinate standards.

In order to determine the amount of 'mapping' to perform, it was necessary to analyze the types of errors present in the system and their effect on the measurements. A CMM contains 21 different sources of error that can be mapped: yaw in each axis (3), pitch in each axis (3), roll in each axis (3), linear scale

error in each axis (3), XY squareness (1), YZ squareness (1), XZ squareness (1), horizontal and vertical straightness along the X axis (2), horizontal and vertical straightness along the Y axis (2), and Z-axis straightness error in the X and Y direction (2). Mapping each individual error source is difficult and time-consuming. There is also an issue with the uncertainty of the items used to create the error map. For instance, in order to measure the angular errors (yaw, pitch, and roll) an autocollimator or laser with angular optics must be used. The uncertainty of these instruments can create errors larger than the machine errors. The primary objective was to use the most accurate instrument to measure the majority of the machine errors. A secondary objective was to make the process as simple and easy to understand as possible. In order to determine the best type of error correction to use for the SPIB, it was necessary to look at the types of measurements that were being taken.

The majority of the measurements taken on the SPIB are single-axis measurements taken along the X axis. A smaller number of two-dimensional measurements are taken on glass grid plates in the XY plane. The measurements taken along the X axis and in the XY plane require small movement along the Z axis of less than 0.002 inch. Therefore, the error map needed to be set up to eliminate as much of the error as possible in the XY plane. In order to do this without performing angular measurements; the majority of the error map was created using axial measurements with a laser. The straightness and squareness measurements were taken with a straightedge and square.

The X axis was the primary area of concern since most of the measurements are taken along that axis. In order to obtain the least amount of point-to-point error, the X axis was measured at four different locations along the length of the X axis in increments of one inch with a laser interferometer system. The measurements were located in each of the four corners of the machine volume that parallel the X axis (see Figure 2). The averaging effect of the air bearings made it unnecessary to take measurements any closer than one inch apart. The horizontal and vertical straightness along the X axis was also measured. The straightness error in the horizontal direction is very accurately determined through a reversal method to separate machine errors from straightedge errors. The straightedge error data can then be used when measuring the vertical straightness error of the machine. The errors were then placed in a table to serve as the X-axis error map (see Table 1).

Figure 2. X-Axis Laser Measurement Positions

Table 1. X-Axis Correction File (in microinches)

Y axis	Y axis	Y axis	Y axis	Horiz	Vert
0	0	36	36		
Z axis	Z axis	Z axis	Z axis	Str	Str
0	10	0	10		
0	0	0	0	0	0
11	3	-17	-21	-14	-22
30	15	-34	-42	-20	-33
43	25	-45	-57	-18	-35
54	32	-56	-66	-14	-34
56	35	-61	-71	-13	-32
63	39	-64	-77	-13	-33
67	45	-72	-79	-19	-29
74	49	-72	-84	-16	-26
68	51	-74	-81	-10	-19
73	57	-76	-80	-7	-18
71	54	-75	-78	-7	-20

69	54	-75	-79	-7	-18
66	52	-75	-81	-7	-25
66	48	-72	-79	-3	-28
65	46	-71	-84	-3	-33
67	44	-72	-87	-2	-30
68	45	-74	-89	-5	-35
68	47	-78	-91	-9	-34
72	52	-79	-92	-11	-30
72	55	-79	-91	-8	-26
77	54	-84	-93	-2	-24
79	55	-85	-100	-2	-27
78	52	-87	-103	2	-28
76	53	-85	-103	3	-30
74	48	-83	-99	4	-29
71	45	-81	-99	5	-28
70	46	-82	-95	7	-30
68	49	-82	-96	7	-28
67	54	-81	-90	7	-25
67	55	-81	-91	12	-21
67	55	-82	-92	13	-17
67	57	-82	-91	15	-17
70	58	-85	-95	16	-15
72	61	-90	-101	19	-12
74	59	-89	-106	15	-9
71	53	-88	-106	17	-7
64	48	-80	-102	6	-20
59	43	-76	-97	-3	-16
53	40	-72	-92	-14	-20
53	38	-72	-97	-24	-19
52	34	-75	-100	-28	-8
58	36	-78	-102	-19	-11
64	43	-87	-110	-12	-7
63	40	-87	-113	-2	-3
64	34	-87	-117	6	-3
56	34	-85	-110	10	-3
51	28	-77	-110	6	0
47	24	-72	-102	0	0
47	24	-72	-102	0	0

In order to make the process of data collection easier and more reliable, a fixture was developed that

attaches to one end of the machine at the required measurement locations. The center section of a laser tripod is inserted into the fixture and clamped in place. This allows movement of the laser parallel to the Z axis. The tripod center section is used for the fine rotations and translations needed to align the laser with the machine travel (see Figure 3).

Figure 3. X-Axis Laser Setup

Only two sets of Y-axis laser measurements were needed in conjunction with the horizontal and vertical straightness measurements. The number of laser measurements is reduced because this is a fixed bridge type CMM. With this type of CMM, the Y axis abbe’ error in the X direction remains constant regardless of the positioning of the X axis. This is not the case with the X axis measurements where changes in the Y-axis position could increase or decrease the abbe’ error. Laser measurements could then be reduced to a set of measurements with the quill of the machine fully extended and another set with the quill fully retracted. In the case of the SPIB, it was not necessary to measure the errors with the quill fully retracted because the CMM is used for very specific types of measurements, none of which occurs more than 10 inches above the table surface. An example Y axis error correction file is shown in Table 2. This reduced Z-axis height allowed for a more stable setup of the reference laser. It should also be noted that although the upper set of measurements is taken at 10 inches, the full 12 inches could be corrected through data extrapolation. Again, the data was taken in one-inch increments.

Table 2. Y-Axis Correction File (in microinches)

X axis	X axis	Horiz	Vert
5.5	5.5		

Z axis	Z axis	Str	Str
0	0	0	0
-4	0	-7	-2
-4	0	-14	0
0	0	-22	5
11	1	-8	-4
16	10	-19	-2
19	9	-8	-11
10	6	-23	-6
-5	-1	-11	-12
-13	-6	-7	-6
-14	-7	-19	0
-16	-9	-3	4
-18	-10	-16	6
-14	-6	-20	0
-15	-8	-18	-11
-18	-7	-15	-5
-14	-7	-16	-6
-14	-4	0	-8
-14	-7	-14	4
-8	-3	-13	-6
-10	-3	-12	-6
-12	-5	-14	4
-10	-5	-23	7
-11	-3	-12	8
-7	-2	-1	-9
-2	2	-22	-2
-5	1	-10	-15
-8	0	-13	-20
-22	-4	1	-16
-28	-7	-4	-13
-29	-6	7	-21
-27	-5	-4	-16
-25	-4	0	-20
-23	-5	5	-17
-22	-8	-9	-7
-21	-8	2	2
-27	-12	0	0
-27	-12	0	0

The Z-axis laser measurements were further reduced to one set of measurements, since the abbe' error does not change with a change in position of either the X or Y axis. Straightness measurements were made in the X-axis direction and in the Y-axis direction. An example of the Z axis error correction file can be seen in Table 3.

Table 3. Z-Axis Correction File (in microinches)

X axis	X axis	Y Axis
0		
Y axis	Str	Str
0		
0	0	0
1	18	-8
2	8	-21
5	3	-25
11	-2	-38
12	0	-41
5	7	-54
17	10	-53
12	8	-45
0	9	-33
9	8	-30
3	1	-21
-16	0	0
-16	0	0

In order to determine the error correction at any specific point within the CMM volume, the data must be interpolated a number of times. The X-axis linear correction requires seven interpolations.

- One interpolation for each of the four sets of linear error data to tie down the correction in the X-axis direction.
- An interpolation between the results of the lower two sets of X-axis interpolations (Z=0) and an interpolation between the results of the upper two sets of X axis interpolation (Z=10) to tie down the correction in the Y-axis direction.
- One additional interpolation is required to find the X axis linear correction for an exact point (X, Y, Z) in the volume.

The Y-axis linear correction then requires three interpolations to reach the specific correction.

- One interpolation is required for each of the two sets of linear error data.
- Then an interpolation is required between the results of these two interpolations.

The Z-axis requires one interpolation to reach the required correction.

Each of the straightness errors also requires an interpolation.

The software routine used to perform the interpolation is contained in the appendix.

The validity of this approach was verified by measuring the error with a reference laser at the same locations as the errors were previously measured and at a point parallel to and midway between the previously measured locations (see Figure 4). The laser was set up and aligned at each location, and the readings from the reference laser were compared to the readings from the SPIB using the error correction software and data files. The largest deviation at the corner locations was 0.000012 inch while the largest deviation at the center was 0.000018 inch at 48 inches.

Figure 4. X-Axis Verification Measurement Positions

The squareness was measured in three locations in each plane. The average error in each plane was then placed in a file for software correction.

The selective error correction resulted in reduction of the error due to X-axis yaw, pitch, and straightness; the Y-axis pitch and straightness; Z-axis straightness; squareness; and linear errors. The decrease in X, Y, and Z-axis linear errors was very close to the repeatability of the machine. The need to hand lap the granite ways was eliminated while reducing the uncertainty by almost a third.

Vibration Reduction

The SPIB is located in a metrology laboratory in the basement of the building at a large distance from any type of equipment (such as punch presses) that might lead to unsuitable vibration. However, there is a small amount of forklift traffic in an aisle near the machine. The vibration occurred sporadically and when it did it created unacceptable measurement error. At such times the operator could see the vibration on the indicator amplifier. In order to identify bad measurements caused by vibration, the software on the SPIB was set up to output the standard deviation of the samples that make up a data point (ten samples per data point at that time). The operator could then reject a measurement and take it over again if the standard deviation exceeded a certain level (40 microinches for X-axis measurements, 15 for the Y and Z axes). This level of data variability still caused excessive error.

Vibration measurements showed low frequency horizontal vibration in approximately the X-axis direction. The amplitude of the vibration was significantly less than expected when considering the X-axis measurement error. Investigation centered on a steel upright that held the X-axis retroreflector. The upright was acting as a cantilever beam and magnifying the vibration, which was coming through a poorly installed vibration pad. The installation of the upright was corrected by adjusting the position of the vibration pad and using a greater amount of torque to hold the upright against the pad (see Figure 5). Vibration was reduced by almost half.

Figure 5. X-Axis Retroreflector Mounting

A software routine was developed to reduce the effect of vibration further. Since the vibration was sporadic, the software was designed to monitor the effect of the vibration on each measurement point. The number of samples required for each measurement point was increased from 10 to 30. This was made possible by the huge increases in processing speed of a PC versus the DEC that was replaced. The software measures the standard deviation for 30 samples; if the standard deviation is over a certain level (15 microinches), the routine would successively replace measurement samples until the standard deviation fell below the required level. The measurement speed with the vibration routine and the geometry correction routine was still at least twice as fast as the older system had been.

Z-Axis Motor Installation

A number of requests had been made to eliminate the need for the operator to reach across the table of the machine when taking measurements on ball plates. This practice also required the operator to be in close proximity to the ball plate when making the fine Z-axis adjustments, which resulted in excessive heat transfer to the ball plate. The SPIB was equipped with a rough adjustment knob that worked under the influence of air pressure. However, the rough adjustment knob could only be used to get the indicator near the measurement location. The fine adjustment knob was located close to the machine's quill on the Y-axis carriage. The knob was connected to a gear reducer, which drove a rod (see Figure 6). When the rough adjustment mechanism was locked, a transmission block gripped the drive rod. Since only a small amount of torque is required to turn the fine adjustment mechanism, a very small motor could be used.

Figure 6. Z-Axis Fine Adjustment Mechanism

There appeared to be an area a little over an inch in diameter and about two inches long beneath the gear reduction housing where a motor could fit without interfering with measurements. A size 14 hybrid stepper motor was located that measured slightly over one inch square and approximately 1.5 inches long. A two-piece fixture was designed to mount directly to the gearbox housing. The housing was slotted to allow access to a flexible delron coupling which connected the drive rod to the motor. A double shaft on the stepper motor made it possible to retain the fine adjustment knob. The same controller then drives each axis.

Mounting of the motor took approximately an hour. The machine was operating with the Z-axis motor on the same day. The operator is now able to stay at a greater distance from the item being measured and there is no longer the need to stretch across the machine in an uncomfortable position. All fine adjustments are made with a joystick controlling the motors for each axis.

Optical Coordinate Measurement Capability

The measurement of single-axis glass scales has recently taken large advances with automation, frame grabber boards, and software. This success with single-axis glass scales led to the plans to develop the same capabilities in the measurement of the larger two-dimensional glass grids. There are numerous large two-dimensional glass grids measured on the SPIB. These grids are used for calibration of video measuring machines at FM&T. The measurement of these glass grids requires the use of a camera and optics at high magnification. Although there has been some progress in this area, the measurement uncertainty is still unacceptably high. The measurements are taken by manually positioning the grid (with a joystick driving the motors) until an intersection is centered in a set of dual crosshairs. This operation

is dependent upon the operator's ability to position the machine and the operator's ability to resolve the edges of the lines. It is very common to see the lines change width from one location to another. To further aggravate the situation, the glass is seldom completely flat, resulting in changes in focus.

At this point, a frame grabber board has been installed in the PC on the SPIB. Software developed at FM&T for single-axis glass scales has been copied over to the PC for modification and further development for large two-dimensional grids. The camera, optics, and hardware were tested and found to function. The software has been modified up to the point where it can view the piece. Further work is necessary to develop it to the point where edge detection measurements with geometry correction can be taken. The development of the edge detection system should result in approximately a 50% reduction in measurement time and a decrease in the uncertainty of approximately 30%.

Accomplishments

The measurement uncertainty of coordinate standards calibrated on the Shelton Precision Interferometer Base has been reduced by approximately one third by software error correction, vibration reduction, and analysis, and by reduction in the amount of heat transfer from the operator to the standard.

The ability to keep the SPIB operational has been greatly increased through replacement of the laser interferometer electronics, computer operating system, and software. The replacements have increased the capability of the machine so that further improvements can be more easily accomplished. Year 2000 compliance problems have also been eliminated due to the computer replacement.

The addition of a motor on the Z axis of the SPIB has greatly reduced operator fatigue as well as providing for increased capability to automate the system in the future.

Future Work

Although the sampling speed has been greatly increased, additional speed can be easily achieved through simultaneous sampling of the axis boards on the HP5507A Laser Interferometer Electronics. A data input/output card has already been purchased and installed but is not operational at this point. Connecting an analog or digital output line to the hardware on the HP5507A will enable simultaneous sampling and further increase the reliability of the data.

The input/output card can also be used to integrate the indicator amplifier into the SPIB system. This integration would allow some amount of automation in the collection of the data. Once the amplifier output is input to the software, the motors can be used to automatically position over a small distance to automatically null the indicator reading. This technique would not only increase the speed of data collection but it would also improve the accuracy of the data through an unvarying repetitiveness of the tasks. An automated measurement, when correctly coded into the software, can perform a task more consistently than an operator can because the measurements are taken with equivalent forces in the same direction for each measurement. Rough positioning would still have to be done by the operator. A much greater modification would need to be made to fully automate the system.

The retroreflector bracket needs to be redesigned to reduce the effect of vibration. A modification of the vibration pad may also be necessary.

Development is needed in the area of two-dimensional glass grid plates. A frame grabber board has been installed in the system and is operational. However, the software needed to integrate the board into the system needs to be finished in order to reduce the major source of uncertainty for these glass plates.

Further work is also needed to increase the number of data points per sphere. Each sphere on a coordinate standard is measured using one measurement point along each axis to determine the X, Y, and Z position of the sphere. Although this technique is adequate for matched spheres of very low form error, it is inadequate for coordinate standards with unknown sphere sizes and forms. Either a three-dimensional probing system or an air-bearing spindle needs to be developed for integration into the SPIB. A compact air-bearing spindle has been purchased but requires fixturing to attach it to the machine, and the addition of a slip ring is needed in order to attach an indicator.

Reference

1MYLEX™, "Functional Description," *PCI RAID Controller Installation Guide*, Chapter 2, ©1996.

Appendix

Software Routines

A.1 Geometry Error Correction Routine

```
SUBROUTINE MAP(IER)
```

```
USE MSFLIB
```

```
C
```

```
C This routine is used to correct the X,Y,and Z coordinates
```

```
C for the point to point and straightness.
```

```
C
```

```
1 FORMAT(' MAP V.990330.',/)
```

```
C
```

```
C
```

```
CHARACTER EMSG*25,DEB*1,ANS1*1,ANS2*1,STR*50,ACOR*12,
```

```

+XINIT*6,YINIT*6,ZINIT*6

REAL*8 COR,VD,XYSQR,XZSQR,YZSQR

REAL*8 DATAX,DATAY,DATAZ,XINITCOR,YINITCOR,ZINITCOR

REAL*8 XZER,YZER,ZZER,A,B,C,D,V,H,XNUM,YNUM,ZNUM

REAL*8 XACOR,XBCOR,XCCOR,XDCOR,YACOR,YBCOR,FCOR,
+XHCOR,XVCOR,YHCOR,YVCOR,ZSXCOR,ZSYCOR

INTEGER NDX,NDY,NDZ

INTEGER(2) NAVE,NCY,LDPT,IER

INTEGER*2 LTE,DSP,CNTR,PSW,SW,ITHER,ITHFL,IERT

DIMENSION DSP(3),SW(2),DATAX(100),DATAY(100),
+DATAZ(100),A(2),B(2),C(2),D(2),H(2),V(2),FCOR(3),ACOR(3)

COMMON COR,ANS1,ANS2,NAVE,NCY,VD(400),DATAX,DATAY,DATAZ,
+LDPT,DEB

COMMON /DEV/CNTR,PSW,SW,LTE,DSP,EMSG,ITHER,ITHFL,
+XZER,YZER,ZZER,FCOR

COMMON /CCOR/ACOR,XINIT,YINIT,ZINIT,XINITCOR,YINITCOR,ZINITCOR

C

C Error Flag. Initial setting -1.

IER=-1

C Device setting - console

KU=5

C Error location initially at zero.

IERT=0

C Testing purposes only. Commented out now.

C WRITE(KU,1)

```


C _ZER is the position where the machine zero occurred. Must be added to the data to determine

C the actual location from the 'home' position.

XNUM=XZER+DATA(XLDPT)*1E-6

YNUM=YZER+DATA(YLDPT)*1E-6

ZNUM=ZZER+DATA(ZLDPT)*1E-6

C Open the X axis Correction File.

OPEN (1, FILE = 'F:\Shelton\Shelxcorr.map;1',ACCESS = 'SEQUENTIAL',STATUS = 'OLD')

C First five strings for operator info. only

READ (1, '(A28)')STR

C Testing purposes only. Commented Out.

C WRITE(KU, '(1X,A28)')STR

DO I=1,5

READ (1, '(A45)')STR

END DO

C Truncate the position data.

NDX=AIN(XNUM)

NDY=AIN(YNUM)

NDZ=AIN(ZNUM)

2 FORMAT(6(1X,F6.1))

C Read in the correction data

DO I=1,NDX

READ (1,2)A(1),B(1),C(1),D(1),H(1),V(1)

ENDDO

READ (1,2)A(1),B(1),C(1),D(1),H(1),V(1)

READ (1,2)A(2),B(2),C(2),D(2),H(2),V(2)

C Perform the first four interpolations for the X axis

$XACOR = A(1) + (A(2) - A(1)) * (XNUM - NDX)$

$XBCOR = B(1) + (B(2) - B(1)) * (XNUM - NDX)$

$XCCOR = C(1) + (C(2) - C(1)) * (XNUM - NDX)$

$XDCOR = D(1) + (D(2) - D(1)) * (XNUM - NDX)$

C Perform the second set of interpolations for the X axis

$YACOR = XACOR + ((XCCOR - XACOR) / 36) * YNUM$

$YBCOR = XBCOR + ((XDCOR - XBCOR) / 36) * YNUM$

C Perform the final interpolation for the X axis

$FCOR(1) = YACOR + ((YBCOR - YACOR) / 10) * ZNUM$

C Perform the X axis straightness interpolations

$XHCOR = H(1) + (H(2) - H(1)) * (XNUM - NDX)$

$XVCOR = V(1) + (V(2) - V(1)) * (XNUM - NDX)$

CLOSE(1)

C Open the Y Axis Correction File

OPEN (1, FILE = 'F:\Shelton\Shelycorr.map;1',

+ACCESS = 'SEQUENTIAL', STATUS = 'OLD')

READ (1, '(A28)') STR

C Used for testing purposes

C WRITE(KU, '(1X, A28)') STR

C First five lines operator info. only

DO I=1,5

READ (1, '(A45)') STR

END DO

3 FORMAT(4(1X, F6.1))

```

C Read in data corrections

DO I=1,NDY

READ (1,3)A(1),B(1),H(1),V(1)

ENDDO

READ (1,3)A(1),B(1),H(1),V(1)

READ (1,3)A(2),B(2),H(2),V(2)

C Perform first set of Y axis interpolations

YACOR=A(1)+(A(2)-A(1))*(YNUM-NDY)

YBCOR=B(1)+(B(2)-B(1))*(YNUM-NDY)

C Perform final interpolation for Y axis

FCOR(2)=YACOR+((YBCOR-YACOR)/10)*ZNUM

C Perform Y axis straightness interpolations

YHCOR=H(1)+(H(2)-H(1))*(YNUM-NDY)

YVCOR=V(1)+(V(2)-V(1))*(YNUM-NDY)

CLOSE(1)

C Open the Z axis correction file

OPEN (1, FILE = 'F:\Shelton\Shelzcorr.map;1',
+ACCESS = 'SEQUENTIAL',STATUS = 'OLD')

READ (1,'(A28)')STR

C For testing purposes only. Commented out.

C WRITE(KU,'(1X, A28)')STR

C First five lines for operator info. only

DO I=1,5

READ (1,'(A45)')STR

END DO

```

```

4 FORMAT(3(1X,F6.1))

C Read in data corrections for Z axis

DO I=1,NDZ

READ (1,4)A(1),H(1),V(1)

ENDDO

READ (1,4)A(1),H(1),V(1)

READ (1,4)A(2),H(2),V(2)

C Perform Z axis interpolation

FCOR(3)=A(1)+(A(2)-A(1))*(ZNUM-NDZ)

C Perform Z axis straightness interpolations

ZSXCOR=H(1)+(H(2)-H(1))*(ZNUM-NDZ)

ZSYCOR=V(1)+(V(2)-V(1))*(ZNUM-NDZ)

CLOSE(1)

C Open squareness correction file

OPEN (1, FILE = 'F:\Shelton\Shelsqr.map;1',
+ACCESS = 'SEQUENTIAL',STATUS = 'OLD')

READ (1,'(A28)')STR

C For testing purposes only. Commented Out.

C WRITE(KU,'(1X,A28)')STR

C First string for operator info. only

READ (1,'(A45)')STR

C Read in Squareness corrections.

READ (1,4)XYSQR,XZSQR,YZSQR

CLOSE(1)

C Apply corrections

```

```
FCOR(1)=FCOR(1)+YHCOR+ZSXCOR+XYSQR*YNUM+XZSQR*ZNUM
```

```
FCOR(2)=FCOR(2)+XHCOR+ZSYCOR+YZSQR*ZNUM
```

```
FCOR(3)=FCOR(3)+XVCOR+YVCOR
```

```
C
```

```
C Convert the data to characters.
```

```
WRITE(ACOR(1),'(F12.7)' )(-FCOR(1)*1E-6)
```

```
WRITE(ACOR(2),'(F12.7)' )(-FCOR(2)*1E-6)
```

```
WRITE(ACOR(3),'(F12.7)' )(-FCOR(3)*1E-6)
```

```
RETURN
```

```
END SUBROUTINE
```

A.2 File Extension Routine for DEC Compatibility

Note: Used to maintain the DEC type file extension of ";version".

```
SUBROUTINE ASSIGN(UNT,FNAME,LN,STTS,ACS)
```

```
USE MSFLIB
```

```
C !SUB USED TO SET UP A FILE SYSTEM LIKE THE OLD FORTRAN ON THE
```

```
C !DEC ;#.
```

```
C !Revised 07/02/97 for compatibility with Fortran on an IBM PC.
```

```
CHARACTER*30 FNAME,TNAME
```

```
CHARACTER*30 FLS
```

```
CHARACTER*3 FLNMB
```

```
CHARACTER*1 IAN
```

```
CHARACTER*(*) STTS
```

CHARACTER*(*) ACS

INTEGER UNT,MX,LN,LNA

LOGICAL EXISTS

C Determine if the ";" exists in the name

J=INDEX(FNAME,';')

C If the file exists and the status is "OLD" then go directly to the open statement.

IF (J.GT.0.AND.STTS.EQ.'OLD') THEN

TNAME=FNAME

GOTO 3

ENDIF

C If no filename was given, create a scratch file which will be deleted when closed.

IF (FNAME.EQ.' ') THEN

OPEN (UNIT=UNT,STATUS=STTS,ACCESS=ACS,ERR=23)

GOTO 25

ENDIF

C

MX=0

LNA=LN+1

TNAME=FNAME(1:LN) // ';'

C SET UP LOOP OF 250 CHECKS

C Software is setup to handle 250 versions.

DO 1 I=1,250

C !INQUIRE ABOUT FILE'S EXISTENCE

WRITE (FLNMB, 200) I

200 FORMAT (I3.1)

C Trim off leading or trailing blanks.

FLS=TNAME(1:LNA)//TRIM(ADJUSTL(FLNMB))

INQUIRE (FILE=FLS, EXIST=EXISTS)

IF (.NOT. EXISTS .AND. MX.EQ.0) THEN

IF (STTS.EQ.'NEW'.OR.STTS.EQ.'new') THEN

MX=I

ENDIF

IF (STTS.EQ.'OLD'.OR.STTS.EQ.'old') THEN

MX=I-1

ENDIF

ELSEIF (EXISTS)THEN

MX=0

ENDIF

1 CONTINUE

IF (MX.EQ.0) THEN

MX=1

ENDIF

WRITE (FLNMB,200)MX

TNAME=TNAME(1:LNA)//TRIM(ADJUSTL(FLNMB))

3 OPEN (UNIT=UNT,FILE=TNAME,STATUS=STTS,ACCESS=ACS,ERR=23)

FNAME=TNAME

RETURN

23 DO 22 I=1,10

WRITE(0,24)

24 FORMAT(/,'ERROR IN OPEN')

22 CONTINUE

25 RETURN

END SUBROUTINE

A.3 Vibration Analysis Code

Note: Checks the standard deviation of the data samples in order to determine validity. This is a small section of code taken from the data collection routine.

C Calculate the standard deviation of the samples. NX is the number of axes to check.

DO 310 M=1,NX

C start with standard deviation = 0

310 SD(M)=0.

C Bail out if the standard deviation limit is less than 0 (error). Or if the number of samples (NAVE)

C is less than two.

IF(SDL.LE.0.) GO TO 5

IF(NAVE.LT.2) GO TO 5

XNM=NAVE-1

DO 4 M=1,NX

S=0.

C The samples are stored in VALAVE(M), where M is the index number.

AV=VALAVE(M)

C Perform calculations of the samples where NAVE is the # of samples.

DO 3 I=1,NAVE

$D = AV - V(I, M)$

3 $S = S + D * D$

$S = S / XNM$

$SD(M) = \text{SQRT}(S)$

4 CONTINUE

C If the standard deviation in any axis is greater than the limit then...

C Move the second data point to the position of the first data point, decrement

C the count and take another sample. This will continue until the standard deviations

C of the samples is less than the limit.

IF(SD(1).GT.SDL.OR.SD(2).GT.SDL.OR.SD(3).GT.SDL)THEN

DO 21 M=1,NX

DO 21 I=1,NAVE-1

21 $V(I, M) = V(I + 1, M)$

NCY=NCY-1

GOTO 333

END IF