

Good Things Come in Small Packages

A Table Top CMM With Sub-Micron Capability

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Abstract

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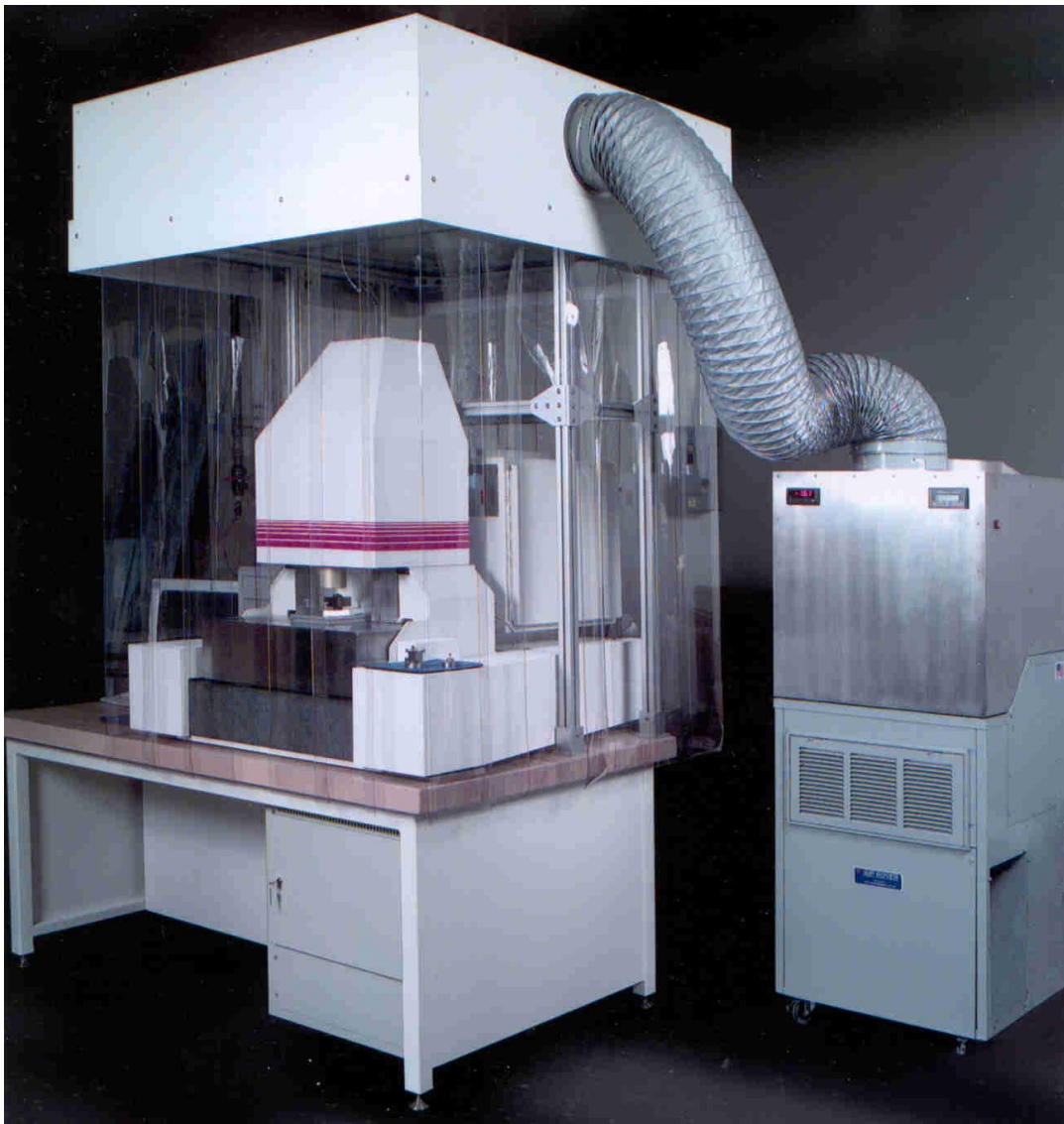
Background

It has long been stated, and it is generally agreed, that a large majority of the manufactured parts in the world are small enough to fit into a 50 mm cube. For some reason, however, most coordinate measuring machines (CMMs) have a capacity much greater than 50 mm. Capacities of 500, or even 2000 mm cubes are not all that uncommon. This is probably true because, if an organization commits the funds necessary to purchase a good CMM, there must be assurances that it will be capable of inspecting the largest part that anyone can ever imagine manufacturing. I submit that this is a poor approach to the issue. As good precision engineers, we know that size comes at a significant price in terms of accuracy and repeatability. Therefore, I submit that, to maximize the accuracy of the CMM, it should be as small as possible while still having the capacity to inspect a large percentage of the work at hand.

In mid 1998, I got a chance to prove my point. There developed a need within Kodak for a small CMM with exceptional accuracy, and as the resident precision engineers, it fell to Karl Falter and myself to design, build, and qualify such a machine. Other members of our team included Bob Smarcz, who oversaw our interface with the purchasing and manufacturing systems; Marty Wilk, our draftsman; and Joe Coffey, the technician responsible for actually building the machine. Many others from the Kodak organization contributed to the project and I wish to take this opportunity to thank everyone for their individual contributions to the project.

Machine overview

The Ultra Precision Coordinate Measuring Machine is a three-axis device with a work envelope of 50 mm (X) by 50 mm (Y) by 50 mm (Z). The gauge is carried on the Z axis while the work piece is located on the compound XY axis. Many different gauge heads can be accommodated. The gauge used initially with the machine is a three-axis analog LVDT-based design. All of the axes of the machine are supported on air hydrostatic bearings and are driven in translation by linear DC servomotors. The position feedback consists of four axes of laser plane mirror interferometry. In addition to the three linear axes (X, Y, and Z) the yaw motion of the XY compound axis is measured and used to correct the drive current to the two Y axis servomotors. The linear interferometers have a resolution of 0.31 nanometers and the angular interferometer has a resolution of 0.02 arc seconds



Y axis

The Y axis is an H shaped structure that is driven by two motors, one on each leg of the H. The crossbar of the H is the guide bearing for the compound main slide. Air bearings around three sides of each of the legs support and guide the assembly. There are shock absorbing stops at each end of the assembly's motion. A home switch is provided for initializing the position registers associated with the laser feedback sub-system. The bearing components of the Y axis are constructed of aluminum which has been hardcoated to provide wear resistance, and lapped to achieve superior geometry.

X axis

X axis motion is attained by the motion of the main slide along the guide way of the Y axis. The main slide is an aluminum block that is supported on air hydrostatic bearings. This block has a recess along its bottom surface that accepts the guide way of the Y axis. Three axes laser interferometry impinge upon a ULE glass square that is carried on the top surface of the main slide. These are the X and Y position feedback and the XY yaw feedback. The work stage is mounted directly above the glass square minimizing the Abbe offset of the stage.

Machine base

The XY compound stage is mounted on the machine base plate, which is a granite surface plate 700 mm wide, 700 mm long, and 150 mm thick. This plate is, in turn, supported by three pneumatic vibration isolation and leveling devices that are mounted on the supporting steel base assembly. The base assembly contains the electronic sub-systems and the air preparation equipment. At the rear of the base is the laser support bracket. This bracket serves to attach the rear vibration isolation mount to the base as well as supporting the laser head and the electronics termination panel.



Column support

The column support weldment mounts on the top of the machine base plate to the rear of the XY compound slide assembly. This steel fabrication supports the column and the Z axis.

Column

The column is also a steel fabrication. Three identical adjustable mounting assemblies kinematically mount it on the top surface of the column support.

Z axis

The Z axis is located on the front face of the column. Two 45 degree angle blocks and two L shaped preload blocks contain the air bearings that constrain the aluminum moving slide. At the front end of the moving slide is the gauge head mounting block. This block also carries the plane mirror that is the target for the Z axis interferometer, and the shutter for the Z axis home switch. The interferometer itself is mounted on a bridge that spans the moving slide and mounts atop the two preload blocks. The drive motor is located behind the interferometer bridge. At the rear end of the moving slide is the attachment point for the counterbalance band. The counterbalance band is made of stainless steel. It is .05 mm thick and 40 mm wide. The band passes up from the moving slide to the top of the column where it bends 180 degrees around a cylindrical air bearing and then down inside the column to the counterweight. Thus, when the slide moves, the band slides around the cylinder without friction, stick-slip, or bearing noise. The counterbalance weight may be bolted it to the interior wall of the column during transportation of the machine.

Gauge head

The gauge head is mounted to the front of the z axis directly in front of and in line with the Z axis target mirror. It is a three-axis device. Each of the three axes is comprised of an identical pair of flexures that allows plus or minus 0.25 mm of travel. Each axis has an LVDT that provides a linear displacement signal. The excitation voltages to the three LVDTs are phase locked together to minimize cross talk between the axes. A variety of other gauge heads may be fitted to the machine.

Covers

There are five main covers on the machine. The largest cover is the column and Z axis cover that mounts on the top of the column riser and covers the front and sides of the machine upper structure. The rear of this cover is open to allow air to flow over the upper structure. The XY compound slide is covered with a sheet stainless steel cover that protects it from dust, dirt, and falling parts. Each of the two front vibration isolation supports has a cover to prevent items from becoming pinched between the machine and the table when the isolation system is turned off. Finally, there is a transparent cover that encompasses the work area. This cover has doors to allow access to the stage on the top of the XY compound slide. It protects the work area from air movement and dust. In addition to these, there is a small cover over the front of the column riser that serves to complete the work area containment.

Table

The entire machine is mounted on a rigid table 1525 mm (60") wide, 762 mm (30") high and 1067 mm (42") deep. Air filtering and monitoring components are also mounted on this table.

Control electronics

The electronic equipment that controls the machine is contained, for the most part, in cabinets located beneath the table that supports the machine. The electronic equipment includes a personal computer, the Zygo laser control system, several Delta Tau PMAC printed circuit boards that are mounted in a personal computer expansion chassis, the gauge head control electronics, and miscellaneous other electrical and electronic components. The personal computer, the video display and a keyboard are located on the table adjacent to the machine.

Temperature control system

The machine is surrounded by an enclosure containing an open loop air shower. Temperature controlled air flows from an overhead plenum down around the machine, exiting the enclosure several inches below the table top. The air cooling and tempering equipment is located in a free standing cabinet that can be located near the machine. Temperature control is achieved by mixing the cold air from the evaporator of the air conditioner with the hot air stream from the condenser. The mixing fans are driven by the output of a cascaded dual loop PID controller. This system has proven to be able to hold $\pm 0.01^\circ$ F for long periods of time.

Axis straightness and noise

Axis straightness and noise measurements were made by placing a glass straight edge on the XY compound slide and mounting an LVDT displacement probe on the Z axis. The appropriate axis was then moved and a recording was made of the probe signal. In the case of the Z axis, the straight edge was mounted on the stationary frame of the compound slide. The straight edge was known to be straight within about 50 nm over its 330 mm length. The following table summarizes the results of these measurements.

AXIS	DIRECTION	STRAIGHTNESS	NOISE	DATE
X	HORIZONTAL	53 nm	30 nm	11/17/00
X	VERTICAL	25 nm	20 nm	12/7/00
Y	HORIZONTAL	125 nm	50 nm	12/5/00
Y	VERTICAL	75 nm	40 nm	12/7/00
Z	L-R	250 nm	65 nm	12/6/00
Z	F-B	125 nm	25 nm	12/6/00

Straightness measurements refer to long wavelength features where the wavelength is longer than the length of travel of the axis. Noise measurements refer to features with a wavelength less than 5 mm. Note that the X and Y axes each have a travel of 50 mm, and the Z axis has a travel of 100 mm. Note, also, that there are no guide bearings to provide control the Y axis horizontal travel. These numbers are a result of servo system response only.

Squareness

The squareness of the X axis to the Y axis is completely dependent upon the squareness of the stage mirror. This mirror is square to about 0.1 arc seconds. We have no way to verify this number. The squareness of the Z axis to the X and Y axes is adjustable by use of the column mounts. At the time of the testing no precision square was available, so no attempt was made to square the Z axis travel to the X and Y axes.

X-Y error map

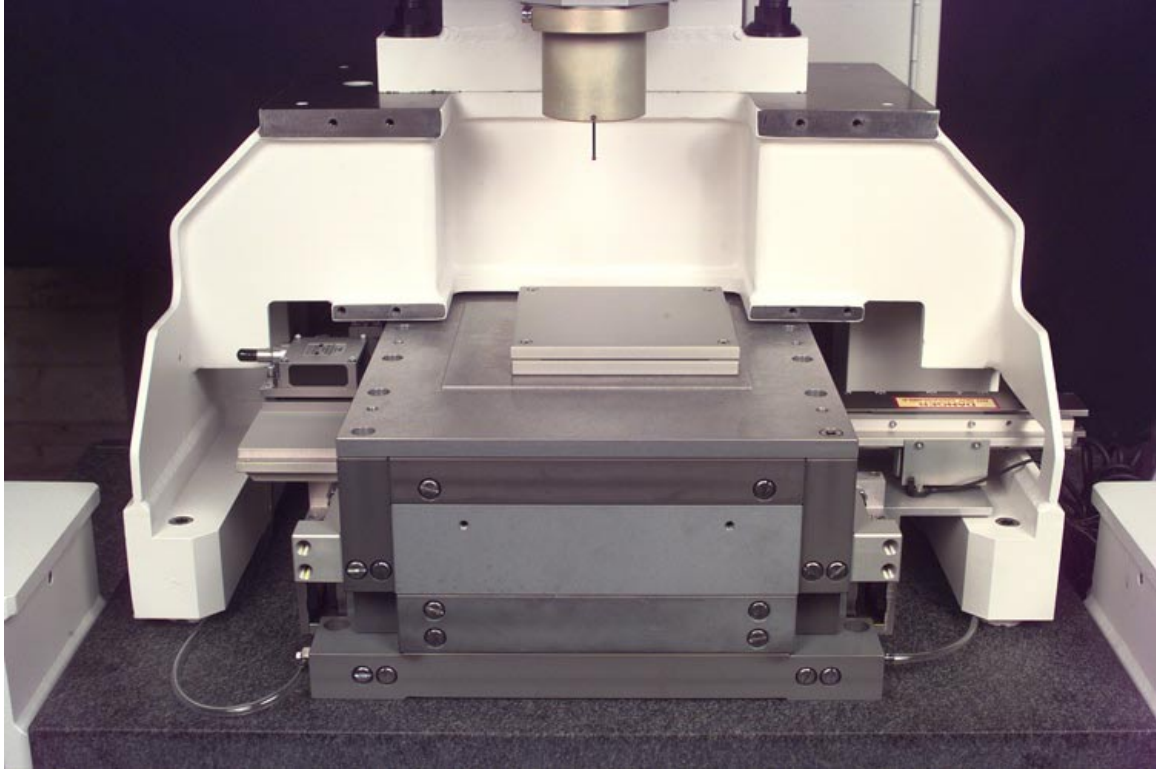
The motion of the XY compound slide should be such that the distance from the gauge mounting surface to the surface of the work platen does not change as the X and Y axes move. The actual change in this distance was measured on a grid with a spacing of 12 mm. A best fit plane was calculated and subtracted from the measured data.

The raw, uncorrected data showed a range of 214 nm peak to valley. The best fit plane had a peak to valley range of 196.4 nm. The corrected data displayed a total error, or deviation from a plane, of +21.2 nm, -21.4 nm. This indicates that careful lapping of the platen feet can bring the uncorrected X-Y plane of the machine to within 25 nm of perfection, leaving only the remaining few nanometers to be removed by error mapping. It was elected to leave the implementation of the error map for a future project.

Repeatability

The repeatability of the Ultra Precision Coordinate Measuring Machine was tested in accordance with paragraph 5.3 of ASME B89.4.1-1997. The results are presented below. The spreadsheet lists the minimum and maximum values for the X, Y, and Z coordinates of the center of the test sphere along with the calculated value of its radius. There are 10 sets of readings reported. Each set of readings required about 41 seconds of machine time. The temperature in the work enclosure is also reported, but the value reported is raw analog to digital converter output. The reported value for temperature must be divided by -327, and then an offset value of 141.2 must be subtracted from the result to arrive at degrees Celsius.

The test ball used for this test was not a precision ball, therefore we are slightly limited in our ability to calculate its radius because the ball is not truly spherical. Nevertheless, the repeatability of the X and Y axes is on the order of 25 nanometers, and the Z axis repeatability is about 35 nanometers. The temperature did not drift more than about 0.003° C during the 7 minutes of the test.



Number of Sphere Readings: 10

Calibration File: C:\WINDOWS\Desktop\probe_cal\calibration_file_feb15_lo_defl.txt

Date this file was generated: 2/16/2001 7:59:45

Min/Max Values:

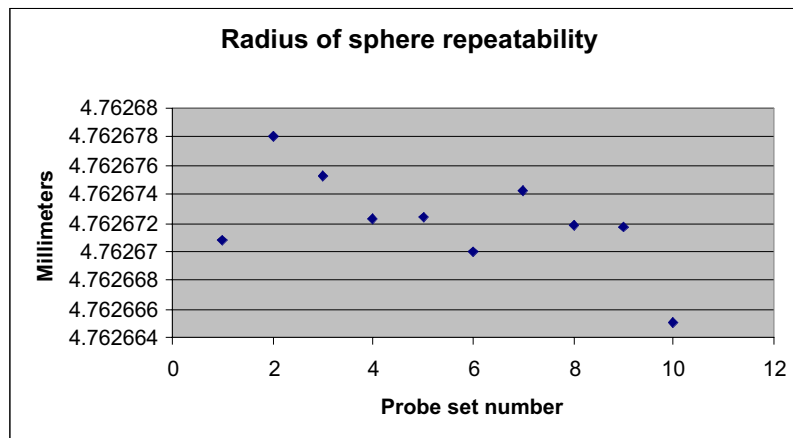
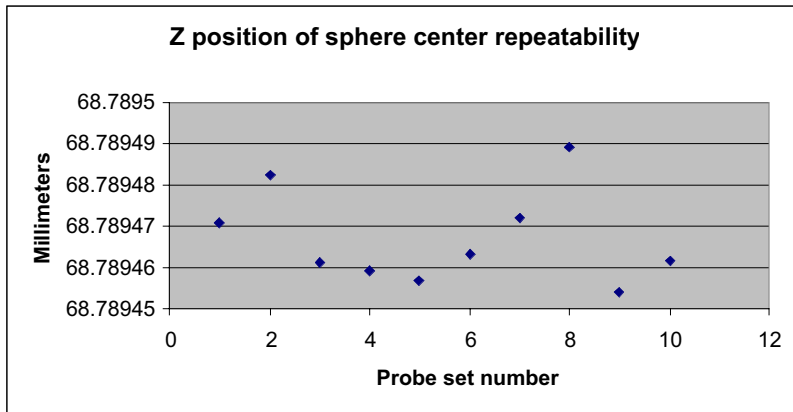
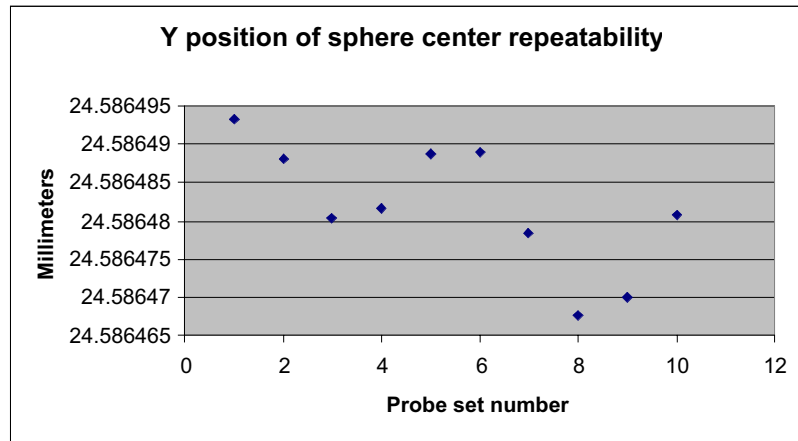
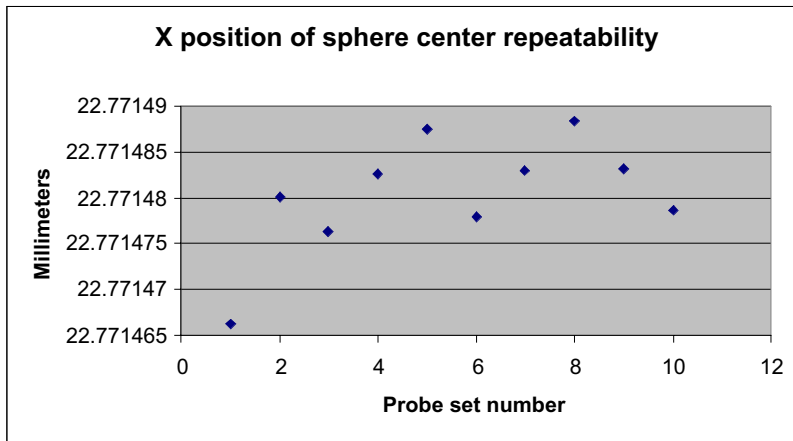
min/max x center	min/max y center	min/max z center	min/max radius	min/max time	min/max temp	min/max_err
22.77146	24.58646	68.78945	4.762665	66.71875	39519.25	3.55E-15
22.77148	24.58649	68.78948	4.762678	480.5937	39520.25	2.75E-14

(Max - Min) Ranges:

range_x	range_y	range_z	range_r	elapsed time	range_temp	range_err
2.21E-05	2.56E-05	3.49E-05	1.30E-05	413.875	1	2.40E-14

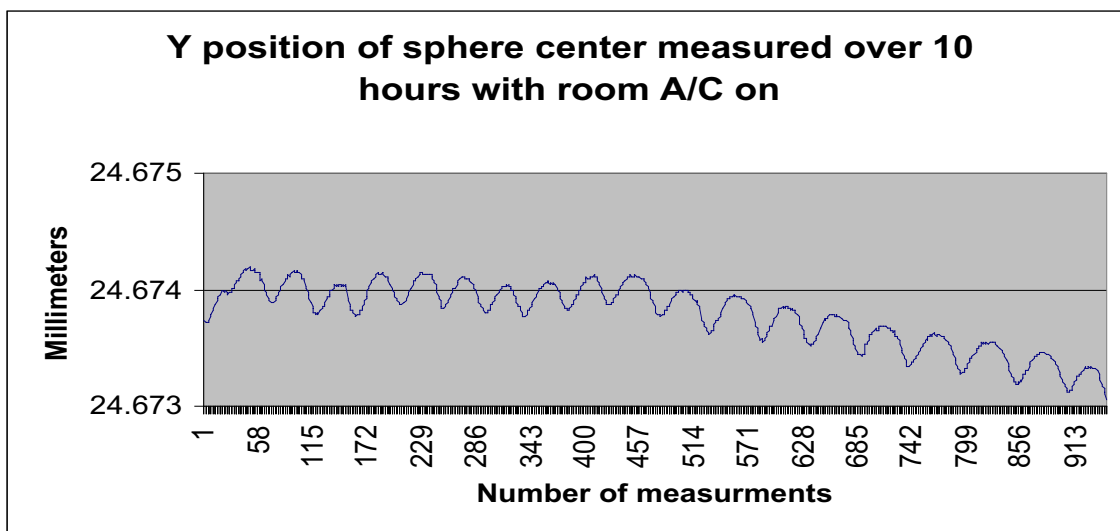
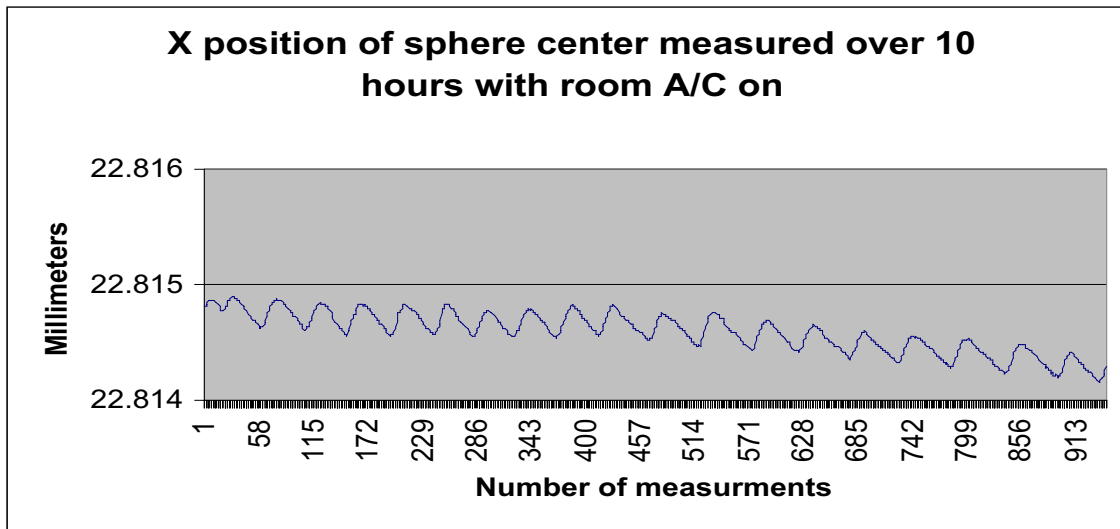
List of Spheres:

center_x	center_y	center_z	radius	time	temp	max_radius_error
22.77146	24.58649	68.78947	4.762670	66.71875	39520.25	2.31E-14
22.77148	24.58648	68.78948	4.762678	104.3437	39519.5	4.44E-15
22.77147	24.58648	68.78946	4.762675	141.9687	39519.25	9.77E-15
22.77148	24.58648	68.78945	4.762672	179.5937	39520.25	5.33E-15
22.77148	24.58648	68.78945	4.762672	217.2187	39520.25	3.55E-15
22.77147	24.58648	68.78946	4.762670	254.8437	39519.75	2.75E-14
22.77148	24.58647	68.78947	4.762674	367.7187	39519.5	9.77E-15
22.77148	24.58646	68.78948	4.762671	405.3437	39519.75	1.33E-14
22.77148	24.58646	68.78945	4.762671	443	39519.75	3.55E-15
22.77147	24.58648	68.78946	4.762665	480.5937	39519.5	1.07E-14

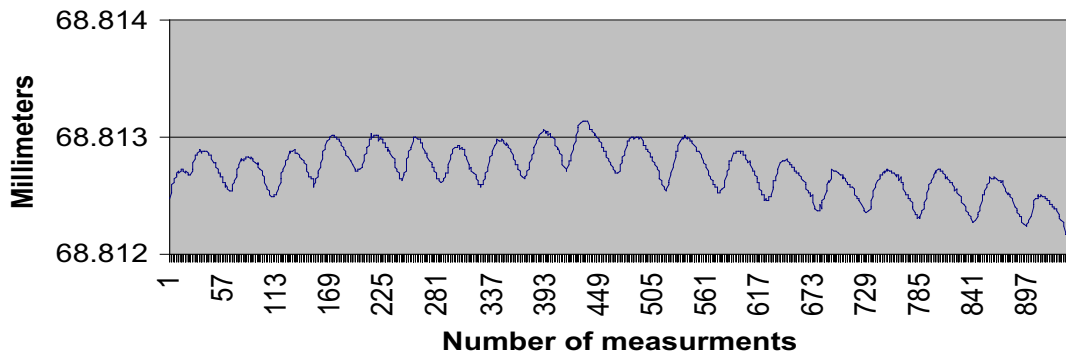


Temperature variation error

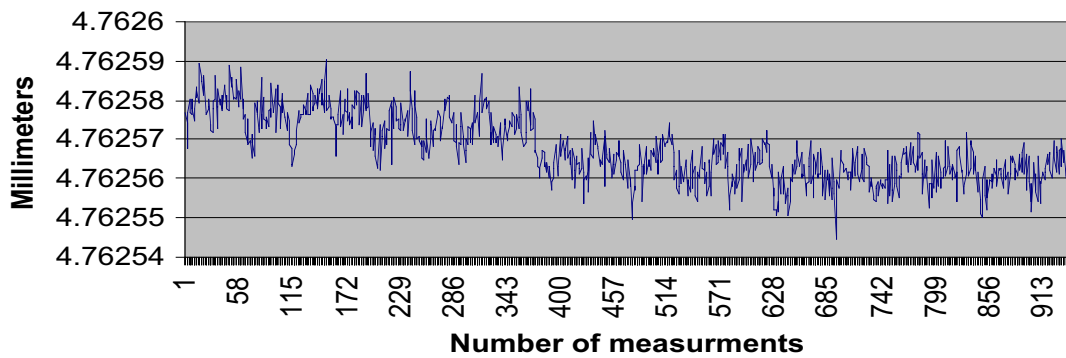
The temperature variation error (TVE) test was performed using a 3/8" (9.525 mm) diameter ball mounted near the center of the machine's working volume. This ball was probed at the pole, and at 3 points near its equator. From this information, the location of the center of the ball, and the radius of the ball were calculated. Each set of four measurements took 41.81 seconds to complete. Two long tests were run during which about 945 measurement sets were made. An additional short run was also made which had 110 measurement sets. The long runs took about ten and one-half hours to complete, and the short run was one hour and a quarter long. The first long run was made with the local room air conditioner running normally, which for this room produced a temperature swing of about two and one-half degrees Celsius. Results are shown for the X, Y, and Z directions, as well as for the ball radius and the temperature within the machine measurement enclosure.



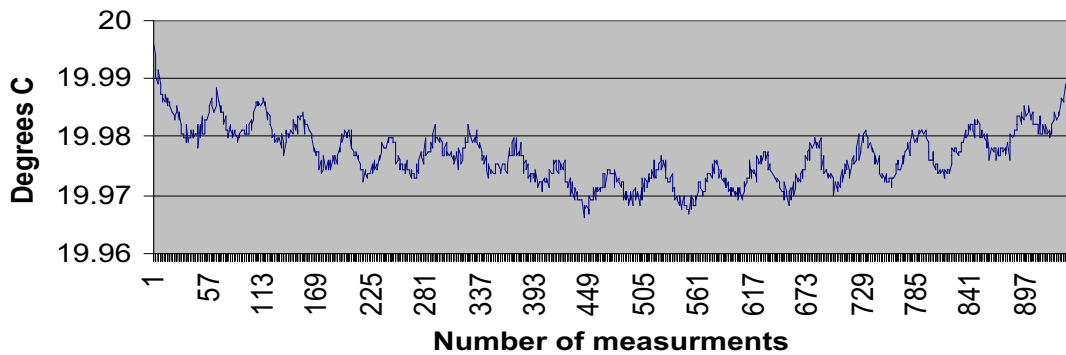
Z position of sphere center measured over 10 hours with room A/C on



Radius of sphere measured over 10 hours with room A/C on



Temperature in measurement box over 10 hours with room A/C on



Note that the temperature within the machine measurement box faithfully followed the room temperature with an amplitude of about 0.01° C. This may be due to radiative heat transfer through the vinyl curtains.

The following night the room air conditioner was shut down and the test was repeated. The results from this second test are shown below. During this test the room temperature increased by at least 10 degrees F. This gross temperature change overpowered the temperature control system on the machine and the temperature rose during the test by about 0.3 degrees C compared to the previous night when there was a 0.025 maximum temperature swing.

TVE Results	X Axis	Y Axis	Z Axis
RUN 1 (A/C On)	0.702 m	1.08 m	0.905 m
RUN 2 (A/C Off)	2.201 m	5.10 m	4.304 m

The results stated above are peak-to-valley readings for the two 10 hour tests. I estimate that, in a properly temperature controlled environment, the results would be about 50% of those shown for run 1. This is because the short term variations caused by room temperature variations would, for the most part, be gone.

Volumetric performance

Volumetric performance of the machine was evaluated using an artifact which is a cube with 9.55 mm balls, numbered 1 through 4, mounted on the top four corners. The four balls were measured, and the six distances between their centers were calculated. This gave us the four sides of a box and the two diagonals. This procedure was done twice and then the artifact was rotated about 90° (By eye) and the process was repeated. The results obtained are reported below.

	Distance 1-2	Distance 1-3	Distance 1-4	Distance 2-3	Distance 2-4	Distance 3-4
Run 1	28.12652	39.80367	28.19226	28.13287	39.79336	28.11556
Run 2	28.12575	39.80366	28.19211	28.13249	39.79217	28.11517
Run 3	28.12400	39.80310	28.19475	28.13388	39.79224	28.11217
Run 4	28.12356	39.80285	28.19395	28.13414	39.79226	28.11282
Deviation	0.00296	0.00082	0.00264	0.00165	0.00119	0.00339

Gauge head issues

The gauge head approach velocity used for all testing was 0.25 mm/sec. The gauge spring constant is about .004 Newton/Micron in each direction. The gauging force used for these tests was .01 Newton's (1 Gram force). The stylus was 30 mm long and had a 0.75 mm diameter ruby ball on the end of the shaft.

Error sources

The following items have been identified as potential sources of errors in our characterization of the small CMM:

1. The variation of the temperature of the room where the machine is located. The temperature change in this room is extreme for our purposes. Steps have been taken to correct the situation, but as the machine has been moved to a new location the results are unknown.
2. The squareness of the Z axis to the X-Y plane. This is readily adjustable but we do not have a good squareness standard to use for the adjustment.
3. Velocity of light calculation for the laser. We may, at some time, want to consider adjusting the laser scale factor as a function of barometric pressure. Temperature is not a big concern as we control it quite well. Relative humidity is a factor, but not a large one. Each machine axis should be independently adjustable because the Z axis of the machine uses a slightly different wavelength of light than the X and Y axes. This is because of the way the differently polarized laser beams are steered around the machine.
4. Tooling balls. None of the balls used for our testing had any degree of precision. This probably did not affect the results for repeatability and TVE but it did affect the volumetric data where the balls are probed at different places during different parts of the testing.

Conclusions

The small coordinate measuring machine meets the criteria for which it was designed. While there is no doubt that further significant improvements could still be made in the performance of the machine, this effort must be viewed as an academic exercise.