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Calculating Uncertainty of 1-D Measurements on a Coordinate Measuring Machine

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Calculating Uncertainty of 1-D Measurements On a CMM

Nick Zurcher
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This presentation is a quick review of the actions taken to calculate the uncertainty of measurements made along one axis of the M-60 Coordinate Measuring Machine (CMM). National Institute of Standards and Technology (NIST) Technical Note 1297 "Guidelines for Evaluating the Uncertainty of NIST Measurement Results," was used as a guide to define what actions would be taken. Very simply stated, TN 1297 says that the uncertainty of a measurement result consists of a combination of several components (sources of variation) in the measuring process. The basic approach is to represent each component of uncertainty by an estimated standard deviation. These standard deviations are then combined by the "root-sum-of-squares" technique to arrive at the estimated standard deviation of the measurement result.

Each component (source of variation) of the uncertainty of a measurement result is designated as either Category A or Category B on the basis of the method used to determine numerical estimates of the standard deviation of the component (source of variation).

Category A – determined by statistical methods.
Category B – determined by other means (i.e., manufacturers specifications, experience, measurement data, handbooks, etc.).

Obviously, for Category A components, statistical methods will be used to calculate the estimated standard deviation. TN 1297 provides guidance on how to calculate the estimated standard deviation for Category B components. This involves some decisions about whether to model the quantity in question as a normal distribution, a rectangular distribution, or a triangular distribution.

After understanding these basics of uncertainty calculation, it became apparent that the task at hand was to identify the sources of variation in making measurements along the X-axis of the M-60 CMM and to estimate the standard deviation of each source. The next part of this presentation will show this process, but first, a brief description of the M-60 is in order.

As shown in Figure 1, the M-60 CMM, built by Moore Tool Co., is a fixed-bridge, moving table design. The lengths of travel for each axis are: X = 55 in., Y = 48 in., and Z = 51 in. Other characteristics include:

- Double-V way with roller bearings for X and Y axes
- Air bearing for Z axis
- Laser positioning
- HP Tracker for laser wavelength compensation
- 3-D analog probe head by Movomatic
- Kinetically mounted super table
- Mapping of all 21 geometric error sources

As we began to identify the sources of variation in making 1-D measurements along the X-axis, we realized that some sources are length dependent and some are not. Thus, the sources of variation have been grouped into two categories—length-independent errors and length-dependent errors.

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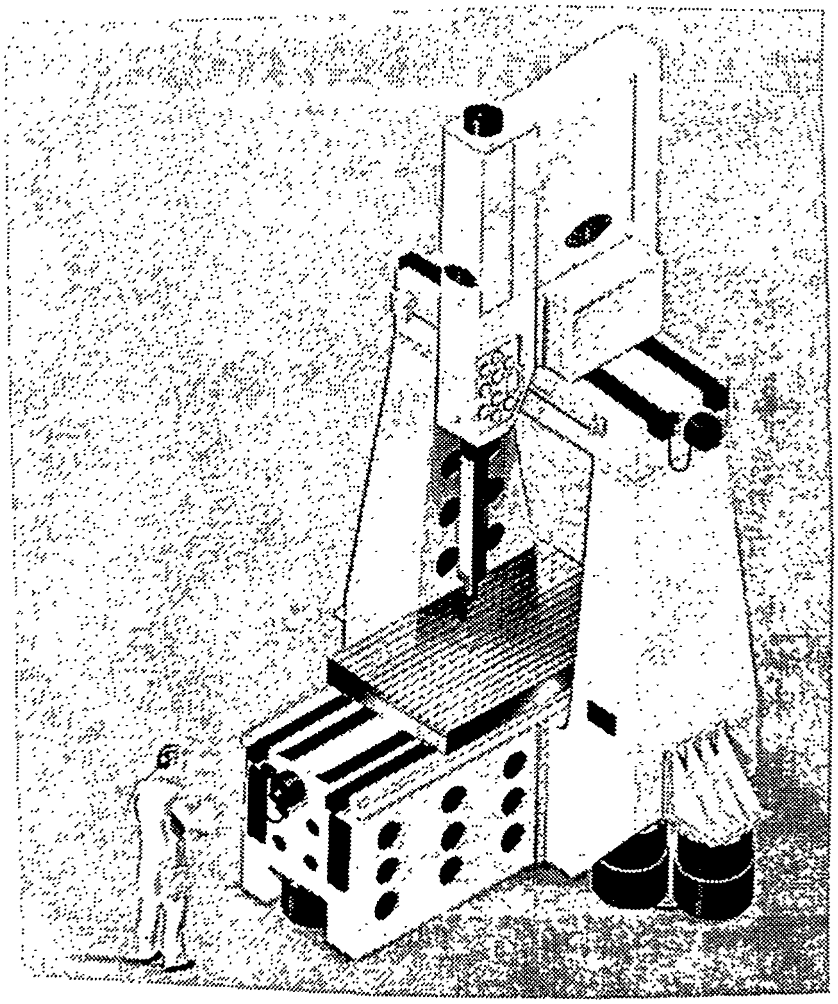

Figure 1. MOORE M-60 CNC Universal Coordinate Measuring Machine

Length-Independent Errors

1. Machine Positioning Errors—Geometry

The M-60 geometry positioning errors are mapped at 1-inch intervals. (During this mapping, alignment error in the metrology laser will be "mapped into" the machine. This length-dependent error is accounted for as item 3 under the Length-Dependent Error section below.) When tested along one measuring line at these same 1-inch intervals, the average error is 1 microinch or less; however, when tested along the same measuring line at a different interval, the average error has been seen to increase to 4 microinches. Small scale errors or map software errors, etc., could be causing this problem. This, coupled with the desire to have the uncertainty statement cover more than one measuring line, has led to the identification of a machine positioning error. The position test was performed with the machine laser and metrology laser "locked" on the same compensation number to eliminate the errors caused by laser compensation. These are accounted for as length-dependent errors. The difference between the maximum and minimum deviation of a position test represents the worst case position error for making a length measurement. It is guesstimated this represents 95% of the error actually present.

Two position tests along the X-axis have been run at each of two locations (Y=15 and Y=24) and the differences between the maximum and minimum deviations (range) has been calculated. The four range values are 6, 7, 7, and 8 microinches. For the uncertainty calculation, the range of 8 microinches will be used as the Machine Positioning Error—Geometry.

This component of uncertainty was determined to be in Category B. It was decided that the data could be modeled by a normal distribution. By using the guidance in TN 1297, it was estimated that the standard deviation for this component is 2 microinches.

2. **Length Measuring Nonrepeatability**

This item represents the overall inspection process's inability to report the same value for the same measuring actions. This includes the probe head nonrepeatability, as well as, the machine positioning nonrepeatability. The test was performed at several locations along a measuring line on a short gage block to eliminate artifact temperature and laser compensation errors which are accounted for as length-dependent errors. An experimentally calculated two sigma repeatability will be used in the overall uncertainty calculation.

The length of a 1-inch gage block was measured six times at each of four locations along the X-axis (X=1, 23, 31, 52). This was done twice for a total of eight groups of six measurements each. The average single standard deviation of the eight groups was 3.5 microinches. For the uncertainty calculation a single standard deviation value of 4 microinches will be used as a the Length Measuring Nonrepeatability. Since this is already a statistically derived standard deviation (Category A), no further computation is necessary.

3. **Probe Tip Diameter Calibration Error**

The "diameter" of the probe tip is calibrated by measuring the length of a 1-inch gage block aligned along the axis of measurement, and by software adjusting the diameter until the measured length equals the known length. The four sources of uncertainty for this operation are shown below:

a) Length uncertainty of the gage block. The NIST reported uncertainty of the 1-inch gage block is 1 microinch. This is assumed to be ± 2 standard deviations so that one standard deviation is 0.5 microinches.

b) To ease the task of calibration for the operator, an operational tolerance of ± 2 microinches will be allowed when adjusting the tip diameter to measure the correct block length. This Category B component is modeled by a rectangular distribution and per TN 1297 the standard deviation computes to be 1.155 microinches.

c) Length Measuring Nonrepeatability (*see 2 above*) will affect the uncertainty of the gage block length measurement. The average of six length measurements will be compared to the actual gage block length. For the uncertainty calculation, a single standard deviation value of 1.633 ($4/\sqrt{6}$) will be used.

d) Machine Positioning Errors (*see 1 above*) are also present during tip diameter calibration; however, the location of the 1-inch block will be controlled so that the value of this error is reduced for this length measurement. Using data gathered during the Machine Positioning Errors—Geometry tests, a location along the X-axis has been chosen where the value for this item is 2 microinches. Using the technique in item 1 above, the standard deviation for this component is estimated to be 0.5 microinches.

4. **Artifact Flatness/Parallelism**

The quality of the gauging surface on the end standard will contribute to the overall length measurement uncertainty. At this time no good method for estimating this component of uncertainty has been developed. For now, a value of 3 microinches has been assigned as the standard deviation for a "normal quality" gauging surface. If, during the course of a measurement, it appears that the surface quality is "abnormal" further evaluation will be done for that artifact.

Length-Dependent Errors

1. **Machine Positioning Errors - Scale (i.e., Laser)**

The M-60 uses a laser for machine positioning. Since the laser paths are not in vacuum, the effects of the environment on the laser beam must be compensated for producing an error which depends on the length of the measurement being made. (*Geometry errors in the machine that cause the probe head to not be where the laser thinks it is, are addressed as a length-independent error.*) The error sources for the laser are shown below:

a) Laser Vacuum Wavelength—Wavelength uncertainty in vacuum for the laser head is estimated to be 0.1 ppm. It is assumed that this Category B uncertainty is at the 95% confidence level and has a normal distribution. The resulting standard deviation then becomes 0.05 ppm.

b) Laser Environmental Errors—The Weather Station is used to calculate the refractivity of air which is then used to compensate the laser on the M-60. The Weather Station measures the temperature, pressure and humidity of the air at the front of the machine and, using the original Edlen equation, calculates the refractivity of the ambient air. (*This compensation number is then manually input to the HP Tracker as shown in item 3 below.*) Each of the three atmospheric parameters measured and the Edlen equation are sources of errors for determining the Laser Environmental Error.

1) Temperature Uncertainty of 0.02°C (0.015 calibration + 0.005 gradients) = 0.02 ppm

2) Barometric Pressure Uncertainty of 0.3 mm = 0.1 ppm

3) Relative Humidity Uncertainty of 5% = 0.05 ppm

4) Edlen Equation Uncertainty of 0.08 ppm

Using the technique from 1.a. above, the estimated standard deviations for these sources of uncertainty became 0.01, 0.05, 0.025 and 0.04 ppm respectively.

c) An HP Tracker is used to track the change in the laser compensation number and automatically send the change to the machine controller. The Tracker must be initialized with a compensation number from some external source and then it will track from that point on. The Tracker was tested against the Weather Station and the uncertainty published by Hewlett Packard of 0.1 ppm for the good temperature environment in which it is used is believed to be valid. Again using the technique from 1.a. above, the estimated standard deviation becomes 0.05 ppm.

d) Machine Controller Laser Compensation Resolution—A current M-60 machine design deficiency is that the controller will not respond to laser compensation information from the Tracker at a resolution that is smaller than 0.2 ppm different than the number currently in the machine controller. Using the rectangular distribution calculation approach, the estimated standard deviation becomes 0.1155 ppm.

2. **Artifact Temperature Uncertainty**

Uncertainty of the artifact temperature produces a length error proportional to the length of the artifact and the Coefficient of Thermal Expansion (CTE). Error sources involving the temperature of the artifact are shown below:

a) Calibration of Temperature System — 0.015 C = 0.18 ppm
(*A CTE of 12 ppm was used for this calculation*)

b) Temperature Distribution in the Artifact — 0.05 ppm
If the difference in temperature readings between any adjacent thermistors does not exceed 0.01°C, and the average temperature does not change by more than 0.005°C between the beginning and end of a length measurement, then assume the value of the temperature distribution uncertainty is as shown.

c) Uncertainty of the CTE — 0.06 ppm
Assume an uncertainty of 1 ppm for the CTE and an average temperature departure from 20°C of 0.06°C.

All three of these sources of variation are treated as in 1.a. above, resulting in estimated standard deviations of 0.09, 0.025 and 0.03 ppm respectively.

3. **Laser Alignment**

Error in the metrology laser alignment is "mapped into" the machine. This uncertainty is estimated to be 0.08 ppm. Once again this is treated as in 1.a. above and the estimated standard deviation becomes 0.04 ppm.

Now we arrive at the situation much like the professor in the college math class when the bell was about to ring who then said "just plug the numbers in the equation and turn the crank to get the answer." Since we are short of time, just turn the crank using the above numbers and the estimated two sigma uncertainty for the X-axis becomes:

$\pm(12 + 0.4\ L)$ microinches where L=artifact length in inches.

or

$\pm(0.3 + 0.4\ L)$ micrometers where L=artifact length in meters.

The first value is the result of the Length-Independent sources of variation and the second value is the result of the Length-Dependent sources of variation.

Notice this is an estimated two sigma uncertainty. The raw RSS calculation yields a single standard deviation which requires multiplication by an appropriate factor (called a K factor) to achieve a desired level of confidence. NIST normally uses K=2 which approximates a 95% level of confidence. At this point, it should be noted that Mr. Mike Sherrill, the statistician in the Oak Ridge Metrology Center, is the individual who did all the digesting of TN 1297 and applied it to the numbers we generated which resulted in the final uncertainty calculation.

Having determined an uncertainty statement, it was now time to get down to the nitty-gritty and actually measure some known end standards. Up to this point, the only measurements made were of a 1-inch gage block. The hope was that the M-60 measurements would be well within our uncertainty estimate without taking into account the uncertainty of the "known" values. A variety of gage block and end standards were used. The results are shown in Figure 2. Needless to say, we were pleased with the results, but, we recognized that this test was a very, very short-term test.

Since this test was performed, some of the artifacts have been used as check standards and have more than fifty runs spread over ten months time. Three sigma control limits have been calculated for process control information. These limits are ±0.21 micrometers for a 1000-mm gage block, indicating that our initial estimated uncertainty calculation was indeed conservative. The control limits are smaller than just the Length-Independent uncertainty by itself. Once enough data is gathered over a long period of time, these control limits will contain most all of the sources of variation and may justify reducing the uncertainty statement.

Meanwhile the M-60 is being used by NIST to provide U.S. industry with NIST calibration of long end standards and step gages to an estimated two sigma uncertainty of

$$\pm(0.3 + 0.4\ L) \text{ micrometers where L is the artifact length in meters.}$$

Figure 2. M-60 Down-to-the-Nitty-Gritty-Test

Standard	Nominal	Day 1	Day 2	Day 3	Day 4	U
1"	0.999999	0	–1	–1	–1	12
2"	1.999998	–6	–4	–4	–4	12
10"	10.000020	–2	–1	0	0	16
20" (1536)	20.000032	+5	+4	+4	+4	20
24" Zerodur	24.027576	–11	–8	–14	–8	21
800 mm	31.496076	–8	–9	–12	–7	24
1000 mm	39.370086	–10	–13	–13	–12	27

U=Uncertainty calculated using ±(12 + 0.4 L) microinches.
All deviations are in microinches.

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