Performance of CMMs: Testing, Calibration, and Uncertainty

Dr. James G. Salsbury

Introduction

Coordinate measuring machines (CMMs) are the most advanced dimensional measuring instruments on the market today. Their unlimited versatility allows them to be used for an infinite number of measurements. But the inherent flexibility of CMMs can also make them difficult to implement. If you are new to CMMs, you are probably wondering how to determine which of the many available machines will be accurate enough for your needs and also how to best compare two similar looking machines. Once a CMM is installed, the question of how to calibrate a machine with so many capabilities is often asked. And now, with many new quality initiatives being pushed onto manufacturing and calibration, the big question is how to estimate the uncertainty of measurements being made using CMMs.

We will try to answer all these questions here. We will first discuss performance testing of CMMs and how to best use these tests. Then we will discuss what it means to calibrate a CMM and what to look for when someone arrives to calibrate your machine. We will also discuss interim tests, which are simple tests that you can run between calibrations to ensure your CMM is still in tolerance. Finally, we will discuss measurement uncertainty and give direction on how you can use all the other stuff, i.e. the performance tests, calibration, and interim testing, to get a good handle on the uncertainty.

Performance Testing

CMMs have been around since the late 1950’s, but when standardized performance tests hit the market in the 1980’s, the quality of machines increased significantly. The primary purpose of performance tests is for improved commerce. If you are looking to buy a CMM, you can easily scan the specifications from the different CMM manufacturers and compare tolerances for the various performance tests. Since the standardized testing procedures are well documented, you can ensure that you are truly comparing “apples to apples”. For this reason, some CMM manufacturers either improved their quality or got out of the CMM business when the standards were released.

The performance test specifications are also part of the machine quote and become your guarantee that you are indeed getting the machine you paid for. However, since increased machine accuracy usually comes at a higher cost, it is important for you to understand what the tests mean. Do you check the size of the engine in your new car before driving it home? Sure you do, and it only takes a minute to ensure that the optional V-8 you just paid extra for is really under the hood. If you don’t check or don’t know what to look for, then there is no telling what you might actually be driving.

The same is true for CMM performance tests – learn the tests before you buy a machine and make sure your machine meets the specifications before you send in that final payment.

History of Performance Tests

We are primarily going to discuss two different performance tests: (1) the international standard, "ISO 10360", and (2) the U.S. standard, "ASME B89.4.1". We will also briefly review the German "VDI/VDE 2617" test, as it has been used a lot in the past. In addition, we will highlight some of the other test procedures that have been used over the years, but the ISO, ASME, and VDI/VDE tests are the important ones. All of these major CMM standards are still in use internationally for CMM commerce.

The reason there is more than one internationally accepted standard is mostly political, but we won't bore you with that here. In the end, there is more than one that you may come across. In the U.S. market, both the ISO and ASME standards see a lot of use, and some large companies prefer the use of one to the other. Most international CMM manufacturers will commonly provide specifications to all the major standards in their literature, but more and more are starting to just use the ISO standard. So, let's start by discussing this ISO standard.

ISO 10360

The ISO 10360 standard is really a series of standards. The most important part of the series is Part 2, which was first published in 1994. The official designation is ISO 10360-2:1994. As with all standards, the part number (2) and the date (1994) are both very important as the standard could, and will, change over time. The ISO standard is the youngest of all the CMM standards, but since it is the ISO standard, it is fast becoming the most popular, both in the U.S. and worldwide.

10360-2 has two separate tests. The first is the length measuring performance, designated as "E", and the second is the probing performance, designated as "R". The E test is a complete test of the CMM to measure length, an important fundamental characteristic of a machine. The test procedure calls for a series of measurements of either calibrated gage blocks or a step gage. If you haven't seen one before, a step gage is a unique gage with a series of linear steps. See Figures 1, 2, and 3. Step gages have long been popular for checking machine tools and measuring instruments, and they are particularly useful for testing CMMs.

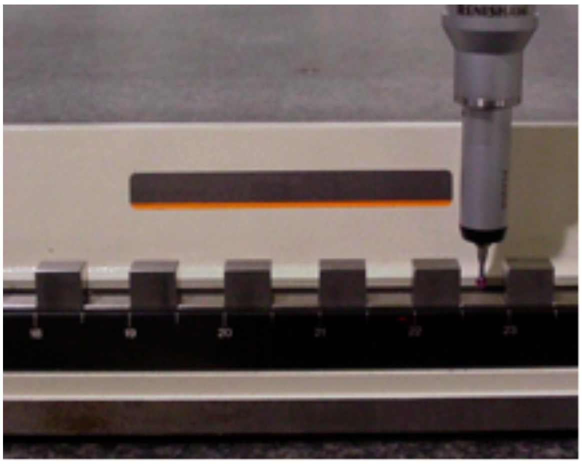

Figure 1. Step gage close-up.

In the ISO E test, at least 105 length measurements are performed across seven different positions. The seven measurement positions can be chosen at the discretion of the customer, per the standard, but manufacturers will usually recommend three positions be parallel to each of the three machine axes (X,Y,Z) and the other four be the body diagonals. The body diagonals usually show the worst machine errors, and the runs parallel to the machine axes show how good each axis is independently. A step gage being used for these measurements is shown in Figures 2 and 3.

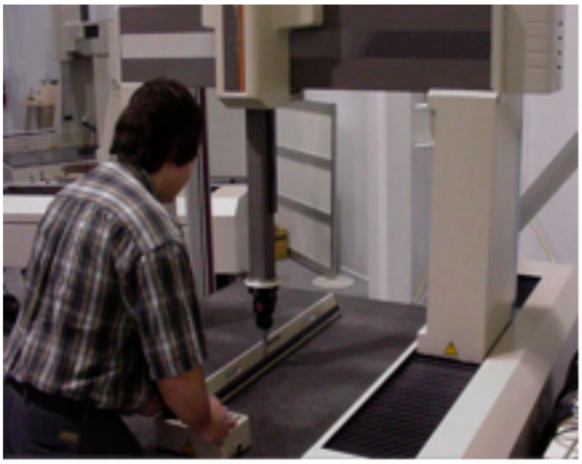

Figure 2. Checking Y-axis with step gage.

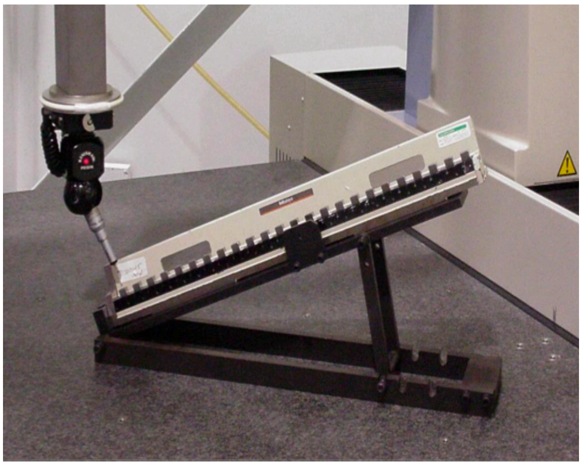

Figure 3. Body diagonal measurement.

The method of specifying the manufacturer's tolerance for E can often be confusing for those new to CMMs. The most common method is the use of an equation that looks something like

MPEE = A + L/K µm

where MPE is the maximum permissible error, a relatively new term being used in ISO standards today (note that just E, not MPE, is also used). In other words, MPE is the tolerance. The A and K terms are constants supplied by the manufacturer, and L is the measured length in millimeters (mm). For a typical machine, the specification might look like

MPEE = 2.5+3L/1000 µm.

If this equation is applied to a few different lengths, you might see results like those listed in Table 1. As shown, the specification is plus or minus the value calculated using the equation.

Table 1. Using MPEE=2.5+3L/1000 µm.

L in mm	100	500	1000	1500
MPE_E in µm	±2.8	±4.0	±5.5	±7.0

To verify a CMM meets its specification, a minimum of five length measurements are made three times at each of the seven positions (that's 105 total). The measured lengths are then compared to the calibrated values of the step gage and deviations must be less than the machine specification for all 105 measurements. An example of one of the seven runs is shown in Figure 4.

The E test is a thorough system test of the CMM and is sensitive to machine geometry and scale errors, repeatability, and some probing errors. As will be discussed later, E is a key test in establishing traceability for your CMM. Since E is also sensitive to thermal variation, it is always specified for a particular temperature range. Machines equipped with automatic temperature compensation usually allow that range to be extended.

E is not sensitive to all probing errors, and therefore the probing test R is also used. R is a simple and quick test that uses a calibrated precision sphere. Twenty-five points are taken across half the sphere, and the measured form is reported.

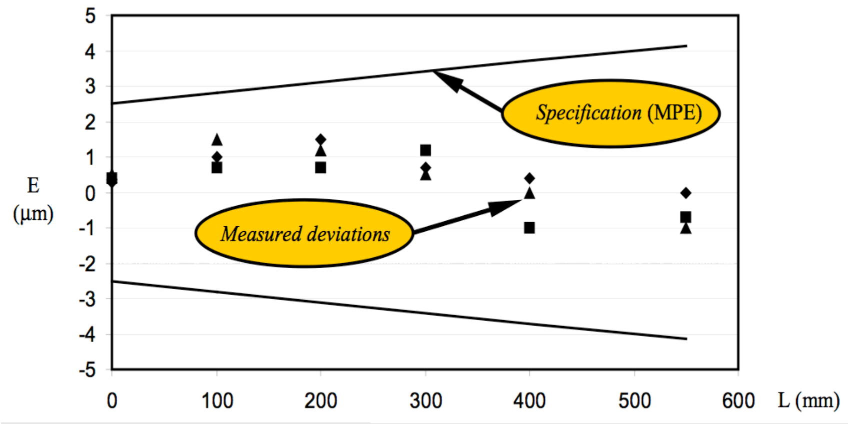

Figure 4. Example E results for one of the seven positions.

The setup for performing the R test is shown graphically in Figure 5. This test is sensitive to any directional measuring problems with the probing system. Though this test does not isolate probe problems, it is very good at finding any random or systematic errors with the probe, including the well known Ӿlobing errorŦ that occurs with some touch trigger probes.

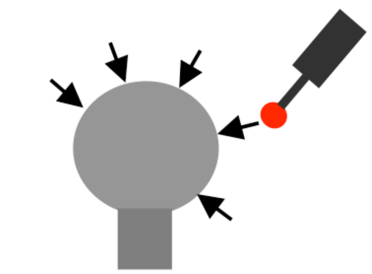

Figure 5. The R test in ISO 10360-2.A total of 25 points
are taken across half the sphere.

E and R are currently the only tests for which you will generally find specifications when using ISO standards. Recently, additional parts have been published. These parts include:

ISO 10360-1:2000, Vocabulary
ISO 10360-3:2000, Rotary Table
ISO 10360-4:2000, Scanning
ISO 10360-5:2000, Multiple-stylus

These parts are still too new to expect all manufacturers to have specifications available in their literature. They also apply to only particular machines and not to all situations. However, if they apply to your machine, you should study these tests as well.

Of all the new ISO tests, the one that is receiving the most interest in the CMM community is Part 4, the scanning test. As high-speed contact scanning is becoming more and more popular on CMMs, this new test should be very useful. The scanning test is similar to the R test in Part 2, but involves scanning the sphere instead of taking only single points. A graphic of this test is shown in Figure 6, where the paths A, B, C, and D define the scan measurement path. In addition, the scanning test is a timed test. Since scanning performance is directly related to the measurement speed, it is important that the time for this test is also included in machine specifications.

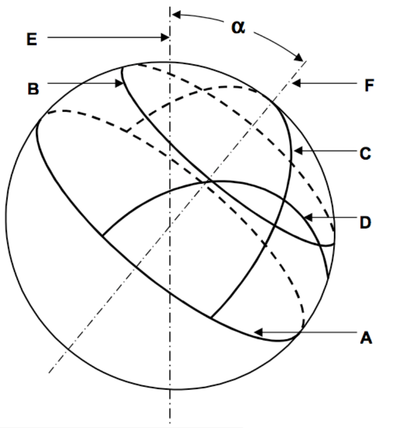

Figure 6. The new ISO 10360-4 scanning test.

There are also plans for a new release of Part 2 sometime in late 2001. The only expected difference between the current 10360-2:1994 version and the new version will be the handling of measurement uncertainty. In current ISO thinking, uncertainty must be accounted for when proving conformance. This may sound like a minor difference, but it could have a major impact on the E test. For now, a word of warning ⋛ be certain you know the date of the standard being referenced in specifications and quotes, as the values may be different between the two versions. Under the new version, E specifications may increase.

ASME B89.4.1 (revised B89.1.12)

The U.S. standard for testing CMMs is analogous to the current use of the inch system over metric in the U.S. It works just fine, but it is very different than the standards used outside the U.S. Originally published as ASME/ANSI B89.1.12 in 1985, this standard changed its name with the 1997 publication, but the heart of the test procedures have not changed over time.

The biggest difference between the ASME and ISO standard is the total number of tests. Where ISO has one machine system test, E, there are five tests in the ASME standard, each one being sensitive to different machine errors. These tests include:

1. Repeatability
2. Linear Displacement Accuracy
3. Volumetric Performance
4. Offset Probe Performance
5. Bidirectional Length

The advantage of having multiple tests is that you get potentially more useful information, as certain measurements you make will be influenced by some of the errors but not others.

The disadvantage of the ASME standard is that you need to know all the tests, and the manufacturer needs to specify them all. This is actually a big problem with the ASME standard. Most commerce using this test standard is unfortunately based solely on the Volumetric Performance test, often called the “ball bar” test. See Figure 7.

The Volumetric Performance test involves measuring the length of the ball bar as the distance between its two end spheres. This measurement is repeated in many positions throughout the machine volume. Any change in the measured length reflects machine geometry errors. Though this is a good test, repeatability errors are averaged out and since the ball bar is not calibrated, this test does not provide any traceability. The ASME standard does provide tests to handle these other issues (the Repeatability and Linear Displacement Accuracy tests), but these tests must be used. In addition, any influence of probe tip calibration on size measurement must be tested for separately using the ASME Bidirectional Length test, as none of the other tests are sensitive to this error.

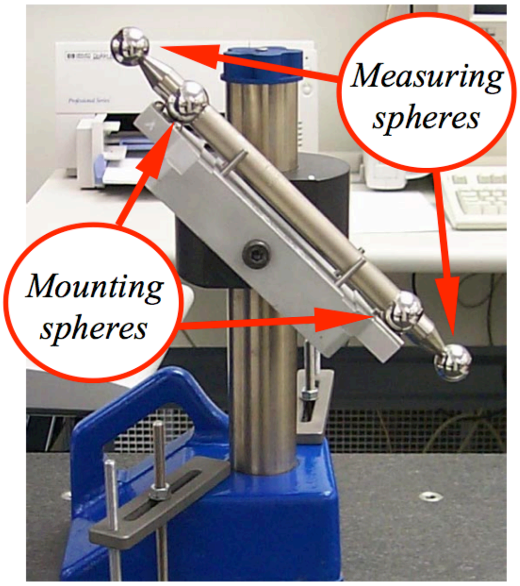

Figure 7. A better ball bar. The dual balls on each end provide a superior mounting method.

If just a single number is listed in CMM literature under ASME, then the manufacturer is probably providing a specification for the ball bar test. Be sure to ask for specifications for all the other tests as well. Since you will need to know more about these tests, here is a short summary of the test procedures:

1. Repeatability: The center coordinates of a sphere are measured ten times quickly. Only four probing points per sphere are allowed. The range of the coordinates is reported.

2. Linear Displacement Accuracy: This test is similar to the ISO E test, but measurements are only made parallel to the machine axes. This is the key test for traceability, and either a step gage or laser interferometer is used.

3. Volumetric Performance: This is the ball bar test described above. The nominal length of the ball bar must be included with specifications. For ӿapples to applesŦ comparison, always reference the same length ball bar.

4. Offset Probe Performance: This test also uses the ball bar, but the test is done in such a manner that the angular error motion of the ram axis influences the results.

5. Bidirectional Length: A small gage block is measured in multiple positions to detect any size measurement error due to probe tip calibration.

In addition to the five general tests, the ASME standard also includes two probing tests. There is the Point-to-Point Probing Performance test, which is the same as the ISO R test, with the only difference being that 49 points are used instead of 25. There is also a Multiple Tip Probing Performance test, one of the new tests added in the 1997 release. This test is similar to the new ISO 10360-5, though some of the details are different in the two standards at this time. This test is designed to be sensitive to the additional error that occurs when multiple tips are used, whether via a probe cluster, probehead articulation, as shown in Figure 8, or a probe or stylus changer. There is always residual error in the offset vectors between various probe stylus tips after calibration. To test for this error, the ASME standard requires that five different tips be used to measure the same sphere. As shown in Figure 8, the center of a measured sphere may vary from tip to tip.

In addition to the five machine system tests and the two probe tests, the ASME standard also includes a number of other special tests. These include a specific test for large volume machines, an advantage that is not found in the other standards. There is also a rotary table test, which is similar to the test in ISO 10360-3. In addition, there is a machine load effects test and a duplex mode test for some more unusual cases.

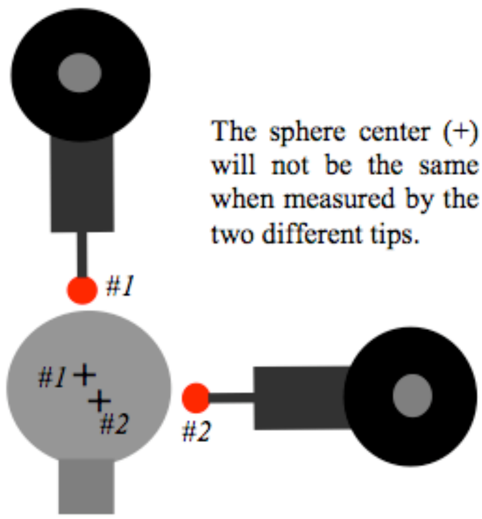

Figure 8. Using multiple tips is another error source that must be tested. Probe tip calibration does not eliminate this error.

VDI/VDE 2617 This standard is actually a German engineering guideline. It has been around since the mid-1980ls and has received the most international use prior to the release of the ISO standard. The ISO and VDI/VDE tests are very similar. In fact, you will probably notice that when machines are specified using both ISO and VDI/VDE that some values will be identical, though the nomenclature may be different. Instead of a single length measuring test like E in the ISO standard, there are three separate tests in VDI/VDE.

These tests are called U1, U2, and U3, which represent the one, two, and three dimensional length measurement tests respectively. All of the tests are done using step gages or gage blocks, just like the ISO E test. The only difference is that U1 is strictly parallel to the machine axes, U2 is only in machine planes, and U3 is only volumetric. Because it involves all three axes of motion, the specification for U3 is the largest, and its value is usually the same as that found for the ISO E test specification.

VDI/VDE also has three probing tests, and again they are broken down as one, two, and three dimensional tests. The 3-D probing test is V3, and this test is similar to both the ISO R test and the ASME Point-to-Point Probing test; however, VDI/VDE uses 50 points, ISO uses 25, and ASME uses 49. But, the key difference is that the specification for V3 is for the worst single deviation, not the range. The specification should therefore be read as plus or minus the V3 value.

The 2-D probing test is V2, and this test uses a precision ring gage versus the sphere. 50 points are taken in a circular pattern. The 1-D probing test, V1, is performed by measuring the length of a gage block 50 times. The worst case deviation from the average is reported.

Having six specifications (U1, U2, U3, V1, V2, V3) using VDI/VDE can be useful, but in general the worst errors will occur for U3 and V3, and therefore these are the specifications that are often included in machine literature. In addition, with the growing acceptance of the ISO tests, the use of VDI/VDE is beginning to disappear.

Other Test Standards

You may occasionally come across other CMM performance test standards. An old European standard is the CMMA, which is very similar to the VDI/VDE and ISO standards. For these reasons, it is not used anymore.

The Japanese CMM standard, JIS B 7440 has been around since 1987. The first version was similar to VDI/VDE. The new version, JIS B 7440-2:1997 is basically an adoption of the ISO standard, a trend that many countries are beginning to follow.

Interim Testing

After your CMM is installed and the manufacturer has completed all the performance tests to verify the machine meets its specification, you might be wondering what to do next? As soon as the machine is up and running, many users have found that some type of interim testing is very valuable to follow what the machine does over time. Interim testing is simply a test procedure of your own creation that you run at some interval to see if anything is changing. Interim testing is not a calibration but is done between calibrations to catch if anything happens to go wrong with your CMM.

The best interim testing strategy depends on how your machine is being used. If your CMM is in a laboratory environment, and you purchased the right tools and gages, you may want to run some of the performance tests yourself. However, getting time to measure artifacts can be difficult and costly on CMMs supporting production. In that case, a useful interim test artifact may be a Ӽgolden partŦ instead of a special artifact. A golden part is simply one of your own production parts that you set aside and measure each week, each month, or maybe at the beginning of each shift. Since the golden part uses the same setup and programs, its measurement is usually simple and fast.

There are also a number of useful interim test artifacts on the market today. One of the more popular ones is the Renishaw Machine Checking Gage, shown in Figure 9. This artifact can be measured in minutes in a single setup and does a fairly thorough volumetric test of the CMM.Another popularr interim test is the measurement of either a ball bar or a gage block in the body diagonal positions of the CMM.

Figure 9. The Machine Checking Gage from Renishaw
is a popular CMM interim test artifact.

It is also useful to test the CMM probing system on a regular basis. Probe stylus tips can wear, stylus shafts can get loose, and the probes themselves have a finite lifetime and their performance will degrade over time, potentially quickly after a bad crash. If your interim test is not sensitive to probe problems, you should do a separate test for probing, such as the ISO R test. Regardless of the interim test chosen, you should start immediately after installation or calibration. Chart the data in a manner similar to statistical process control techniques and watch for changes. Even though interim tests cost time and money, the cost associated with not checking the machine may be much higher if something does go wrong and you do not catch it. For additional information on interim testing, check out the ASME B89.4.1 standard, as it includes a very good discussion on this topic.

Calibration

The calibration of a measuring instrument as advanced as a CMM is not as easy as you might hope or expect. Unlike gage blocks or micrometers, which are defined by only a few simple metrological characteristics, what to calibrate on a CMM is often a subject of debate among experts. We will try to stay away from controversial topics here, and stick with what most users are successfully doing today.

The various CMM performance standards were not written as calibration procedures. As discussed before, these tests were written for improving commerce during the specifying and testing of new machines. However, all the various performance tests are very good testing procedures, and thus they have become de facto procedures for CMM calibration purposes in industry. When you ask your CMM manufacturer to calibrate your machine, the final calibration certificate will most likely be a series of performance tests following one of the standards. The manufacturers service engineers will likely have made some adjustments to your machine, such as correcting a squareness error, but the official calibration certificate will show final results against one of the performance test standards. A common practice is to make sure your machine still meets its original manufacturers specifications.

So is this the best method of calibrating your CMM? In general, yes, this is the most practical industrial method for CMM calibration. This method shifts the burden of calibration completely to the manufacturer and ensures there is no difference in machine performance over the years. However, although it is relatively unimportant which standard is used, it is critical that the standard be used correctly and completely. This can be a big problem when using the ASME standard for calibration. As discussed before, the ASME standard is often misinterpreted as just being the ball bar test. The Volumetric Performance test is a good test, but it doesnt do enough to calibrate a CMM. At a minimum, the Linear Displacement Accuracy test is also needed, as that is the key ASME test for the purposes of provided traceability.

Depending on your situation, probe specific tests, like the ISO R test, might be optional for purposes of calibration. Some users run this test regularly themselves using their most common probe setups. This is very good practice, particularly if you are using a variety of probe stylus setups. In these cases, a probe test during calibration does not tell you much additional information. Finally, be wary of anyone who is calibrating your CMM. All CMMs today are software corrected at some level, which means the wrong person could really mess up your machine. Recent quality standards have started requiring calibration services to be accredited in many industries. Accreditation is your way of knowing that the work being done on your machine has been validated by external experts. Whether you hire a third-party for your CMM calibration or use the original machine manufacturer, make sure they are accredited for the calibration work they are doing.

Measurement Uncertainty

A relatively obscure term only a few years ago, understanding measurement uncertainty has become important today with increased attention coming from various new quality standards. The uncertainty of measurements made on complex instruments like CMMs is not a trivial task. Though we can not cover all the details about uncertainty here, we hope to get you thinking in the right direction.

The key to measurement uncertainty is to know the measurement process well enough that you can determine which factors influence your measurements and then be able to estimate their impact. This is true for all measurements, not just with CMMs. For CMMs, the first step is to understand the performance tests. Hopefully all the sections above have been helpful. The performance tests were designed to be sensitive to a wide variety of error sources, with particular tests sensitive to particular errors. Once you understand the tests and how your own CMM responds to them, you will begin to understand how the test results apply to your individual measurements. With that information in your hands, you will be able to best use your CMM.

You will begin thinking ⋛ form measurement? Ok, what is R for this machine and probe stylus? Got a big part to measure? Well, which of my CMMs has the smallest E value over the length? Small bore diameter? Hmm, what does the Bidirectional Length test tell me about my capability?

CMM measurement uncertainty has been the topic of much research over the years, and various software packages will likely be available soon for estimating the uncertainty of specific measurements made on CMMs. But you still have to know what information goes into the software. Good knowledge of your CMM]s performance will always be useful. Whether you need to compare machines, improve a measuring process, or estimate uncertainty, knowing the various CMM performance tests is your first, and most important, step.

10th Floor Common Goal Tower, Finance St. cor. Industry St. Madrigal Business Park, Muntinlupa City 1702 Philippines
Tel# +632.8501505 Telefax# +632.850.1211
info@satech8.com