Coordinate Measuring Machines and Accreditation

Paper Author and Presenter:
Dr. Henrik S. Nielsen
HN Metrology Consulting, Inc
10219 Coral Reef Way, Indianapolis, IN 46256
Phone: (317) 849 9577, Fax: (317) 849 9578
E-mail: hsnielsen@HN-Metrology.com

Abstract

CMMs are very flexible and versatile machines. This makes them especially challenging in the context of accreditation, since the uncertainty of the actual measurements has to be estimated and stated in calibration certificates and test reports.

The paper looks at some of the difficulties caused by the lack of national or international standards for calibration of CMMs.

It also explores some of the practical approaches, based on performance evaluation standards and a combination of calibrations, interim testing and determination of measurement-specific contributors, that can be applied in a simplified, practical concept for estimating the uncertainty of CMM measurements.

Introduction

There are two separate situations, which have to be considered in the context of CMMs and accreditation:

- The calibration of CMMs.
- Measurements using CMMs.

Calibration of CMMs is by far the easiest to handle, if you take the approach, which is common in the US, that it is up to the user of the CMM to decide what is necessary in his or her situation to establish traceability for the measurements he or she performs on the CMM.

Measurements using CMMs is harder to handle, because it is necessary to determine what must be known about the CMM, and therefore what must be calibrated, in order to perform traceable measurements on the CMM.

Calibration, Traceability and Uncertainty

Before we start discussing the CMMs, it will be useful to consider the definitions of the terms *calibration*, *traceability* and *uncertainty*.

Calibration is defined in VIM[1] as a *set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring system ... and the corresponding values realized by standards.* Consequently, calibration is concerned with specific metrological characteristics of a measuring instrument, such as a CMM and the simplistic notion of a measuring instrument either being calibrated or not has to be discarded and replaced by an analysis of which attributes of an instrument has been calibrated.

In the context of CMMs it is easy to perform this comparison for specific characteristics or performance metrics of the CMM.

VIM[1] defines traceability as a *property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.* This is where the problem comes in for measurements using CMMs, because it is difficult to establish that a comparison to a standard during the calibration of a CMM is relevant for the measurement, where the CMM may be used in a significantly different way.

Finally, VIM[1] defines uncertainty as a *parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.* While it is fairly easy for the calibration laboratory to estimate the uncertainty of the calibration of the CMM, it is generally quite complex for the measuring laboratory to figure out what it needs to know about its CMM in order to make this estimate for general measurements using the CMM.

Standards for CMMs

There is a number of standards available for CMMs. Within ISO there is the ISO 10360[2] series. In the US ANSI/ASME has published B89.4.1[3] and in Germany the VDI/VDE 2617[4] series of guidelines is available. These are by far the most commonly used standards for describing the performance of CMMs.

All of these standards are performance standards. They give manufacturers of CMMs a standardized way to quantify the performance of their CMMs and they give the buyers of CMMs a standardized way to specify their requirements to a CMM and standardized procedures to verify that a purchased CMM lives up to the manufacturer’s claims.

The standards are not calibration standards. The procedures contained in the standards are not intended for calibration and do not ensure traceability or facilitate the estimation of uncertainty of subsequent measurements on the CMM.

Calibration of the CMM

In the US, the general approach to accreditation of calibration laboratories has been that the laboratory can be accredited for any procedure they choose and it is up to the calibration laboratory's customer to decide, whether the calibrations offered by the accredited laboratory fit his or her need.

From an accreditaton point of view this make calibration of CMMs fairly easy to handle. The calibration laboratory has to describe its calibration procedures and demonstrate that it is able to perform calibrations in accordance with those procedures.

In the case of procedures that are developed by the laboratory (i.e. procedures that are not part of any standard), the laboratory is required to validate the procedure, which encompasses defining what the procedure is designed to do and show that the procedure is indeed able to do this.

Most CMM calibration laboratories base their procedures on parts of the standards mentioned above, in which case they are not required to validate their procedures.

The advantage of this approach is that it offer maximum flexibility to the calibration laboratories and their customers. The laboratories are free to offer the calibrations they think their customers want and the CMM user is not forced to buy a calibration package, which contains elements that he or she does not need.

This approach put a fairly heavy burden of responsibility on the user of the CMM, since he or she has to analyze the measurements performed on the CMM and from that derive what attributes of the CMM shall be calibrated. However, the user is the only person, who has the information necessary to understand exactly what the calibration requirements are.

Measurements using the CMM

The problems with CMM measurements in the context of accreditation starts with the definition of measurement uncertainty. Uncertainty is an attribute of a measured value and in principle each measured value has its own uncertainty. The uncertainty of the center coordinates of a hole is different from the uncertainty of the diameter or form error of the hole, even though they are all derived from the same measured points measured on the same CMM.

There are several ways of tackling this issue. The various approaches are generally either very specific and precise or more general and either less precise or increasingly elaborate.

An example of the first approach is the substitution method, where known, calibrated objects similar to the parts in question are being measured on the CMM in the vicinity of where the parts are to be measured. For example a calibrated ring gage may be measured on the CMM to evaluate how well it can measure a hole.

This method obviously negates the great advantage of the CMM - its flexibility.

At the opposite end of the spectrum is the virtual CMM, where a careful mapping of the CMM, its probing system and, if applicable, probe changing mechanism is done to provide input to a computer program which can predict the errors that may be introduced in the measurements.

The problem with this approach is that it requires a very elaborate mapping of the errors of the CMM. Furthermore, the necessary software is not widely available.

Accreditation of general CMM measurements - a practical approach

Realizing limitations of the very rigorous approaches listed above, there is a need for a practical approach, which allows a reasonably realistic estimation of the measurement uncertainty without requiring an excessively exhaustive set of calibration operations.

An analysis of the inaccuracies of CMMs, which contribute to the uncertainty of measurements performed on the CMM show that there is generally three items, which must be accounted for:

- The inaccuracies in the scales
- The inaccuracies in the machine geometry
- The inaccuracies in the probing system

In addition, there are uncertainty contributors from temperature effects, the measurement strategy used and how the measured value is calculated from the measured points.

Based on this analysis, a laboratory seeking accreditation for measurements using CMMs must be able to account for these effects in uncertainty budgets for the kinds of measurements it wishes to perform.

It should be noted that of the three machine related contributors, only the inaccuracies of the scales require traceability to an external standard. The other two contributors can be quantified using self-calibrating techniques.

Calibration based on the ISO 10360[2] or VDI/VDE 2617[4] standards

Both of these standards use step gages or stacks of gage blocks to quantify the inaccuracies of the scales and the machine geometry, either in a combined procedure or in two separate steps.

In the VDI/VDE 2617[4] standard a gage block, a ring and/or a sphere is used to quantify the inaccuracies in the probing system in 1, 2 or 3 dimensions.

In the ISO 10360[2] standard a sphere is used to quantify the inaccuracies in the probing system.

If the artifact is calibrated it can give additional information about the abilities of the probing system, but strictly speaking an un-calibrated artifact can be used, if it is acceptable that the process over-estimates the inaccuracies of the probing system, as inaccuracies in the artifact tend to add to the reported inaccuracies of the probing system.

Calibration based on the ANSI/ASME B89.4.1[3] standard

This standard allows a broad range of methods to be used for quantifying the inaccuracies of the scales, including lasers, gage blocks and step gages.

The inaccuracies of the geometry of the machine is quantified by measuring the length of a ball bar in several orientations within the machine's measuring volume. The range of measured lengths is a measure of the inaccuracies of the machine's geometry.

A sphere is used to quantify the inaccuracies in the probing system.

Evaluation of measurement uncertainty

Once the information about the machine attributes are available, either from calibration by external laboratories, or from tests run by the user, the next problem is to find a method to combine the effects of the inaccuracies of the machine on individual measurements.

One approach is to estimate how far the measured coordinates of an individual point may be from the true coordinates of the point. This estimate is then propagated through the equations used for calculating the attributes of features on parts, e.g. center coordinates for holes, diameters and form deviations.

It is clear that CMMs are better suited for measuring center coordinates and diameters than form deviations, since the center coordinates and diameters are calculated from an "average" of a number of points, where the form deviation primarily is calculated from individual points.

From this approach it will also be clear that there are certain attributes that do not lend themselves well to being measured on a CMM. Classic examples are radius and center coordinates of partial arcs, where only a small part of the arc is available and the coordinates of the apex of a slender cone. In both cases a small error in the individual measuring point is magnified by the equations used to calculate the measurands.

Other influences

All of these calculations are only meaningful, if the CMM programmer is knowledgeable about the strengths and weaknesses of his or her machine. The measuring strategy and the number of points used has to be adequate to realize the CMMs potential.

If it is not, then the relationship between the measured values and the true values of the measured parts - and thus the measurement uncertainty - is entirely unpredictable.

Conclusion

It is possible to make a reasonable estimate of the uncertainty of the coordinates of an individual point measured on a CMM based on the information that can be derived from the standardized performance tests.

It is further possible to propagate this estimate through the number of points and equations used to calculate the attributes of features on parts measured on the CMM.

This analysis will show that the CMM is very suitable for measuring some attributes, namely those that are based on an "average" of a number of points.

The analysis will also show that the CMM is less suitable for measuring other attributes, namely those that are based on a single point.

Finally the analysis will show that the CMM is unsuitable for measuring those attributes where the equations for calculating the attributes are poorly conditioned, i.e. magnifies the error in the individual measured point.

As always in metrology, it is a requirement that the person designing the measurement, in this case the programmer, has a thorough understanding of what the important considerations are, that has to be made for the measurement to be accurate.

References

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