The virtual CMM method for three-dimensional coordinate machines

B. van Dorp, H. Haitjema, P. Schellekens

Precision Engineering section, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

Abstract

In coordinate measurement metrology, assessment of the measurement uncertainty of a particular measurement is not a straight forward task. We have developed a Monte Carlo method that can be used for CMM’s that takes into account the most important error sources, including linearity errors, rotational errors, straightness errors, squareness errors and temperature uncertainty. Special measurement tools have been developed and applied to measure straightness and linearity errors. The short-wave as well as the long-wave behavior of these errors of two machines have been calibrated. A machine model that takes these effects into account is used to calculate the respective measurement uncertainties of several tasks on these machines. These calculations were compared to real measurements.

Uncertainty calculation

Assessing measurement uncertainty implies assessing the distribution of the possible measurement results. Methods involving Monte Carlo simulation consist of a model of the measurement process, and knowledge of the most important influence quantities. Knowledge of influence quantities can be determined analytically or by calibration, and in both cases it should consist of a probability distribution. Such a model is called a virtual machine. In case of a coordinate measurement machine, it is called a virtual CMM [1]. This virtual CMM is used to numerically estimate the distribution of the possible results, which is a measure of the uncertainty. For every simulation, a sample of every influence quantity is taken using a random generator. These samples are evaluated by the model resulting in a distribution of virtual results.

In general, a measurement result $M$ is a function of a number of measured values, the input quantities $m_i$. $M$ is calculated using a model function $f$:

$$M = f(m_1, m_2, \ldots, m_n)$$

This model function $f$ often is not a function, but an algorithm that is implemented in a computer. The measurement uncertainty of $M$ is defined as:

$$u_M^2 = \sum_i \left( \frac{\partial M}{\partial m_i} \right)^2 \cdot u(m_i)^2 + 2 \sum_{i \neq j} \frac{\partial^2 M}{\partial m_i \partial m_j} \cdot \langle u(m_i) \cdot u(m_j) \rangle$$

Here, $u(m_i)^2$ is the uncertainty of input quantity $m_i$ and $\langle u(m_i) \cdot u(m_j) \rangle$ is the covariance of $m_i$ and $m_j$. Consider a simple one dimensional length measurement, with only two measurement points, $x_1$ and $x_2$, and one result: $L = x_2 - x_1$. Using the above equation, we find the following expression for the uncertainty $u_L$ of the measurement:

$$u_L^2 = \left( \frac{\partial L}{\partial x_1} \right)^2 \cdot u_1^2 + \left( \frac{\partial L}{\partial x_2} \right)^2 \cdot u_2^2 + 2 \left( \frac{\partial L}{\partial x_1} \right) \left( \frac{\partial L}{\partial x_2} \right) \langle u(x_1) \cdot u(x_2) \rangle$$

In the above expression, $u_1 = u(x_1)$ and $u_2 = u(x_2)$ are the random errors on these measurements.
positions. The term \( \langle u(x_i) \cdot u(x_j) \rangle \) is the auto correlation of the error signal, with lag \( \Delta x = x_2 - x_1 \). This leads to the conclusion that a satisfactory machine model should take into account the auto correlation of the error signal.

A model that uses this approach using a virtual CMM, would require the errors of all simulated points within one simulation to be correlated with each other in the same way they are correlated in the actual machine. In the above example, this would imply that the points \( x_1 \) and \( x_2 \) are drawn from a signal that has the same auto correlation as the original error signal of the machine. A signal with this property is called a surrogate signal.

The machine model

The geometric errors of the machine are separated in linearity errors, straightness errors and squareness errors. Linearity errors are errors that occur in the direction the machine is moving. For example, when the machine moves in \( x \)-direction, there’s an error in \( x \) direction. This error is called the \( xT_x \) error. In a three dimensional measurement machine, there are three linearity errors, \( xT_x, yT_y \) and \( zT_z \). The linear terms of the respective straightness errors are ignored at this point. The linear term of these errors can be the result of an actual linearity error, but also of incorrect temperature measurement during calibration. In the model, all linear terms of the linearity errors are accounted for in the temperature uncertainty.

Straightness errors are the errors that occur perpendicular to the moving direction of the machine. For example, when the machine moves in \( x \)-direction and there’s an error in \( y \) direction, this error is called the \( xT_y \) error. In the three dimensional case there are six straightness errors. A straightness error does not have a linear term. A linear straightness error can be the result of either misalignment during calibration or of the squareness error.

The axes of the machine are not perfectly perpendicular to each other. The expected value of the deviation of the right angle is defined the squareness error. In the three dimensional machine, there are three squareness errors.

The rotational errors are not calibrated directly, but are incorporated in the machine model by measuring the straightness and linearity errors on different positions, making it possible to calculate the rotational errors from these errors.

Calibration of errors

In calibrating the errors we take several basic assumptions. First, we want all calibration data to be the result of actual probings of the calibration artefact by the machine. Second, we want to make sure we gather enough data to provide the model with enough information on the autocorrelation spectrum.

The model uses the autocorrelation information of the straightness and linearity errors. To calculate these autocorrelations, the calibration data have to provide both long wave information and short wave information. Therefore, it is necessary that the measurement setup allows us to measure a small step (for example 1 micrometer), and also extends to almost the maximum length of the machine axes, for example 300 mm. It is evident that it is not possible to measure the complete axis with the smallest step, as this would require 300,000 measurement points. For this reason, the measurement of the error was split up in three levels of magnification. For example, the first level consists of 41 points with a stepsize of micrometer, resulting in a total measurement length of 40 micrometer. The second level consists of 41
points with a stepsize of 40 micrometer, total length is 1.6 mm. The top level consists of 188 points of 1.6 mm, total length 299.2 mm. This scheme should provide us with sufficient data, only when we can assume that the short wave behavior of each axis on one position can assumed roughly the same as the short wave behavior of that axis on another position. Looking at the construction of a coordinate measurement machine with stacked axes, there is no reason to believe that this short wave behavior is much different on different positions. the investigated machines, a Zeiss Prismo and a Zeiss UMM 550, did not show that this assumption was not valid.

Straightness errors of a CMM can be determined by probing a straightness gauge. A calibrated straightness gauge with a length of 320 mm and a straightness error smaller than 0.1 micrometer was used to determine both straightness errors. The straightness gauge is placed on the machine and probed on different positions using the data collection scheme mentioned in the previous section.

Linearity errors are traditionally measured using a stepping gauge. This instrument has a fixed step, and this fixed step is usually not smaller than 10 mm. This makes the stepping gauge not suited for small wavelengths, certainly not if we want to measure the 1 micrometer step. Therefore, an instrument that can measure linearity errors using a variable step has been developed, a laser stepping gauge. A flat plane is mounted on the carriage of a computer controlled linear positioning stage. The position of the carriage can be accurately measured using a laser interferometer setup. The moving mirror is mounted on the carriage, the fixed mirror is mounted on the base of the instrument. The instrument is used as follows: the carriage is moved to the desired position, and stopped. It’s position is measured accurately using the laser interferometer. The CMM moves to the flat plane and determines it’s position by probing it. When this is done, the CMM moves back and waits for the carriage to move to the next position where the process repeats itself. The entire process is automated, which makes it possible to reliably collect large amounts of data. The positions given by the machine can now be compared to the positions given by the laser interferometer, which makes it possible to calculate the machine error.

Generation of signals
An simple and straightforward way of generating a signal with the same auto correlation as the measured signal is to take the original signal and perform a transformation on it that does not affect the auto correlation. There are four simple transformations that have this property: 1. don’t change the signal, 2. reverse the sign, 3 flip the signal from left to right, 4. a combination of 2 and 3.

This would allow four simulations to be done with one signal. Because the signal is measured in three levels with different stepsize, there are three signals on every axis. This gives a total of $4^3=64$ possible simulations for one axis.

Temperature and squareness
An error in temperature measurement of a real measurement would result in a systematic error of this measurement. To express the uncertainty of this error, it is simulated as if it were a random error. The temperature error or length dependent error is simulated as if every simulated measurement were performed with a different random error in the temperature measurement.

The squareness error of a CMM results in a systematic error that is the same in all measurements. Analogous to the length dependent error, to express the uncertainty of the squareness error, it is simulated as if it were a random error.
Evaluation of results

The machine model is implemented in a computer using Matlab. A calculation of the measurement uncertainty is now performed by generating a number of sets of virtual measurement points. These data sets are evaluated by the software of the measurement machine, resulting in a set of virtual results. The evaluation of these virtual results is demonstrated from an example. Let’s say we have a measurement with a nominal result of 5 mm. An example of a histogram of possible measurement results is shown in figure 1. The measurement uncertainty with a 95% confidence level is the half width of the interval that covers 95% of the area of the histogram. In figure 1, this is 2.6 micrometer. For the 68% confidence level, this width is 1.5 micrometer.

Conclusions

A fully operational virtual CMM, including a machine model, a calibration procedure, calibration setups, and an implementation of the model in a computer are realized. This entire system is tested on two different machines and preliminary results have shown the approach to be successful.

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