Correcting Steady State Temperature influences on Coordinate Measuring Machines.

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Abstract

The use of CMMs outside a strictly controlled environment necessitates the management of the temperature dependent geometry of the machines. The paper presents a thermal error compensation based on physical relations between temperature and deformation, rather than on an empirical model linking inputs and outputs (e.g. regression model, neural network). Based on an extensive set of laser interferometer measurements a thermal compensation scheme is composed.

A Zerodur hole plate is used to verify the applicability of the model via real measurements. This thermal stable artefact allows to monitor the machine geometry under various thermal loads. Different parameters like lengths and angles are measured under various near steady-state environment conditions. The developed thermal correction uses only six thermometer inputs. For temperatures different from 20°C the model reduces the uncertainty of length measurements to the level of the stochastic errors at 20°C. Under spatial temperature gradients a significant reduction is also obtained.

keywords: Spatial temperature gradients, thermal behaviour, software correction

1 Introduction

Temperature has always affected the accuracy of machines. In the past these effects were limited as compared to other error sources. Several keynote papers indicate the increasing relative importance of thermal deformations on machine performance and the need to deal with these effects [2, 4, 5].

The always increasing demand for more accuracy has already — or better finally — forced the manufacturers of machine tools to deal with thermal deformations. With the current requirements for product tolerances, the control of temperature dependent machine behaviour is in many cases a must. Although the demands on coordinate measuring machines (CMM) are much stricter, CMM manufacturers have long escaped this trend. Different reasons can be found for the limited attention for the thermal behaviour of CMM structures. In general they have no strong internal heat sources like spindles, drives or gearboxes. The main temperature influence on the CMM accuracy comes from the environment. Often the machine expands in a similar way as the work pieces. In some cases the effects on the work piece and the measurement device could even out. Traditionally these machines are also located in temperature controlled rooms with relative strict environmental requirements. CMM manufacturers impose severe restrictions on the environment to allow their machines to achieve the promised accuracy specifications. The growing demand for quality control on the workshop floor forces the manufacturers to come with alternative solutions to deal with the environmental issues. Approaches vary from the use of encapsulation boxes with controlled environments, over stable machine designs, up to software correction of identified errors [1, 2, 5, 7].

This paper describes a parametric compensation technique for dealing with measurement errors on a small sized CMM caused by non-standard environment conditions. The focus lies on near steady state situations of uniform temperature distributions at temperature values within the range of 17 to 25°C.

The goal was to give an alternative for the empiric black-box models, like neural networks, fuzzy controllers, regression techniques, commonly used to deal with thermal problems. These models depend strongly on the quality — range — of the learning data, as they have generally poor extrapolation abilities [7, 1]. In theory such a black-box model does not require an extensive knowledge about thermal deformations from the user. However this is an illusion; the know-how is merely shifted forward in the modelling chain. The data collection phase requires more attention. In the presented approach the balance is tilted differently. The know-how is more focused on the deformation process. Finding the correct equations to describe these phenomenons is not always straightforward.

The presented model is based on physical, thermo-elastic equations. Such models are less obscure than the black box approaches, thus more easily adapted for a commercial implementation by industry. Extrapolation with this type of models is not a step in the dark. Special attention was given to the possibility of extending the developed techniques to other machines of the same type, with limited efforts. Verification of the developed compensation is done based on evaluation of the standard deviation on length measurements on a Zerodur artefact under varying temperature conditions.

2 Test subject

The subject of this research is a small sized, numerically controlled CMM. It has a L-shaped bridge configuration (see figure 4 and 6). The machine structure has a very homogeneous construction. The guides, the slides as well as the base structure are made out of aluminium. A granite worktable is placed in the base, but can easily be removed. The main machine properties can be summarized by:

- work volume: $500 * 400 * 300 \text{ mm}^3$,
- $u_3 = 3 + 3,5 * \frac{L}{1000} \text{ }\mu\text{m}$ at $20 \pm 1^\circ\text{C}$ with L in mm.

Although materials are selected for various requirements, the material choice plays an important role in the thermal behaviour of a machine. The high heat conductivity of aluminium minimizes the internal temperature gradients. The large thermal expansion coefficient results in relative large deformations.

The CMM controller is equipped with a geometrical compensation procedure. This compensation corrects the values read out by the scales for the geometrical imperfections in the CMM. The parameters for the geometrical correction are determined after assembly and installation of the machine. They are only valid within strict temperature conditions.

3 The measurement set up

A test set up is build up to efficiently monitor the thermal deformations [3]. Two main topics arise while looking at the thermo-elastic behaviour of a machine. *Temperatures* need to be recorded together with their influence on the machine, i.e. the resulting *deformations*.

3.1 Temperature measurements

The temperature distribution of the CMM is recorded with a set of temperature sensors. Traditionally sensor types like Pt100 or thermocouples are used for thermal deformations studies [1, 7]. In this research negative temperature coefficient (NTC) thermistors are selected for the job. These semiconductor thermometers have a very high output and signal-to-noise ratio, which makes them ideal for use in an industrial environment. Their application temperature range (-20 to 200°C) is wide enough. The very low price and sufficiently compact dimensions are additional benefits. For industrial application their long term stability is also a key factor. In combination with a multiplexor and a good-quality multimeter (with an integrating A/D convertor) with a serial output to a PC, these sensors allow very accurate automatic measurements. The problem of the non-linear behaviour of NTCs is solved by letting the software calculate the conversion from resistance value to temperature. The created set up proved to be very reliable and easy to use for a fraction of the costs of the more commercial solutions.

Thermistors can be mounted on (and in) the different machine elements. During the research multiple sensors in different locations were used to examine the CMM behaviour. Special attention has been given to the attachment of the sensors. By shielding the sensors for environment influences, the used procedure ensures that only the temperature of the CMM structure is measured.

3.2 Deformation measurements

The main issue in thermal deformation research is the way the machine structure responds to a thermal load. For machine tools the displacement of the cutting tip of the tool is the key item. For CMM, the probe position under various non-standard temperature conditions is needed. Practically the displacements of the machine head in which the probe is mounted — the end of the Z-axis — is examined.

A laser interferometer with temperature influence correction is used to measure the difference between the actual machine head position and the value read out by the machine. The interferometer optic is placed on the aluminium base of the CMM thereby eliminating the influence of the granite table for the data collection phase.

During the verification phase the machine performs actual measurements on an artefact. For these measurements the normal measurement probe supplied with the machine was used.

4 Data collection

The data collection tests cover the entire machine work area. Laser interferometer measurements are done along each axis at different locations — i.e. different measurement lines at which the axis' positioning accuracy is recorded — in the work area of the CMM. Different sets were recorded for each axis at three different temperature levels.

During the data collection phase with the interferometer the CMM's internal geometrical correction was disabled.

Figure 1 illustrates the recorded data for the X-axis. The abscis shows the X co-ordinate, the ordinate shows the difference between the values recorded by the interferometer and scale read out of the CMM. The figure depicts the results at one axis location at different

temperatures. Figure 1 proves that the environment influence on the measurement is not negligible.

Figure 1: *Measurements at various temperatures along a X-axis measurement line.*

Figure 2 introduces the manner in which the data are used in the compensation scheme. A linear approximation based on a least square line can be calculated for the measured curve. The difference between the measured curve and the least-square line can be determined. This can be done for each measurement line at the all temperature levels. The obtained difference curves for each individual location are identical on the micrometer for the temperature range under consideration. They can be considered temperature independent for this research.

Figure 2: *Least square approximation of a position deviation curve.*

5 Temperature dependent error compensation

The goal of the compensation efforts is to enable correction of the measured co-ordinates to obtain the displacements that would be recorded with a CMM at 20°C. This is done without reference to the temperature of the measured object. The CMM and the object are looked at independently. In this research the focus lies on the machine. The correction for the measured object's thermal behaviour is part of a different study.

The need for temperature dependent correction is sometimes questioned. One could argue that an aluminium object at the same temperature level as this CMM would be measured correctly at each temperature level hence eliminating the need for thermal correction. A variety of situations exist to justify the use of thermal compensation. Large difference can occur in expansion coefficients for one kind of material. Different types of aluminium are used in every day products and aluminium is far from the only material used for work pieces. Also when investigating a general approach, one has to consider that other machines are constructed with different materials.

5.1 Basic compensation scheme

This section explains step-by-step the way the model is build up. Figure 3 depicts the compensation approach for the X-axis, comprising five sections [A] to [E].

Figure 3: Build up of a thermal compensation model for the X-axis.

Starting from an uncompensated set of co-ordinates (X_u, Y_u, Z_u) measured at a *uniform temperature* T_m , the correct value can be calculated axis per axis. The foundation for the correction are the recorded data values: see section [A].

1. For the X-axis, different sets of data $[X_1, X_2, X_3, X_4]$ corresponding to (Y, Z) positions near the work volume edges are available [A]. These sets are called cube-edges in figure 3. They form the bases for the second section [B].

- (a) For each cube-edge, data at different temperatures are available. In a first step, the least-square-best-fit-line through each curve is calculated (see [A]). The difference $\Delta X - (ic(T) \cdot X)$ between each measured curve and the least-square line can be determined. The obtained sets of difference values are identical on the micrometer level within the temperature range under consideration (see figure 2) and thus temperature independent. It is possible to describe these differences with a polynomial. A linear interpolation based on a discrete table proved to be sufficient for the practical solution.
 - (b) A relation exists between the inclination coefficient (ic) of each best-fit line and the corresponding temperature value. The relation can be modeled by a least-square linear equation between the various ic and T pairs of data [B]. This latter relation allows to determine ic at any temperature, for example T_m . Adding the differences values to the linear deviation yields the deviation $\Delta X(X)$ that prevails at T_m [C].
2. The previous steps can be repeated for the X-data curves at the other locations [C].
 3. Once the correction curves at each cube-edge are known, the values Y_u and Z_u are used in a geometrical linear interpolation between the four curves. This results in a correction curve for the X-axis through Y_u , Z_u at the temperature of the measurement T_m [D].
 4. The value X_u can now be used to determine the correction term ΔX [E]. The correct value X_c can be calculated.

The described procedure can be repeated for the Y-axis, as well as for the Z-axis. For these co-ordinate directions the geometrical interpolation from step [C] to [D] can be simplified. For the Y-axis only curve sets measured at two different Z-values are required. Interpolation is done between these two, based on the Z_u value. In case of the Z-axis, one data set including the different temperature levels along the axis is sufficient. The measurements are preferably done near the middle of the work table. No geometrical interpolation is needed.

5.2 Temperature inputs for the correction algorithm

The actual compensation algorithm is somewhat more complex than described above. The temperature T_m is never exactly uniform for the whole machine. Thus instead of a single temperature value T_m , different thermometers are mounted to monitor temperatures in the structure. Practically thermometers can be placed on each axis. For this research one sensor is placed at each axis end as shown in figure 4. The values recorded by these inputs can be processed in different ways:

- A basic correction approach uses the average temperature value over each axis. In the presented scheme of figure 3, $\bar{T}_{m,X-axis}$ will replace T_m for the X-axis scheme. $\bar{T}_{m,Y-axis}$ and $\bar{T}_{m,Z-axis}$ will be used for the Y and Z axes. A possible simplification is to place one sensor centrally within each axis, but this was impossible on the CMM used for this research.
- A more advanced approach uses the different temperature inputs individually. A linear temperature gradient is assumed over each scale. This assumption can be used to calculate the incremental expansion at each location of the scale (see figure 5), thus

Figure 4: *Temperature sensor placement on the CMM.*

increasing the model's accuracy under an environment load involving spatial gradients. If the thermal stable point of the element known, the displacement of a point on the scale relative to the previous element in the chain between work piece and probe tip can be calculated. In figure 5 the thermal stable point is near the right-hand side NTC.

Figure 5: *Temperature measurement on a guideway.*

In the remaining sections, the differences in performance between both approaches will be shown.

6 Verification of the thermal model for uniform temperature distributions

To verify the applicability of the model type described in section 5.1, measurements were done with a thermal stable artefact. For these tests a hole plate made out of Zerodur was

used. This material has a very low coefficient of expansion, $|\alpha| < 0,05 \mu\text{m}/\text{m}\cdot^\circ\text{C}$. For the temperature range in focus, the object dimensions can be considered constant. Figure 6 depicts the CMM together with the Zerodur artefact.

Figure 6: *CMM with the Zerodur artefact.*

In order to get a fair appreciation of the normal performance of the CMM, the standard geometrical compensation, which does not use thermometer values, is taken into consideration. The complete correction (geometrical correction complemented with the developed thermal compensation) is compared with the standard compensation. The complete correction is also referred to as the *full* correction.

The artefact was measured under different uniform, near steady-state environmental conditions. The temperature levels varied from $17,5^\circ\text{C}$ to 25°C . A total of nine holes were measured continuously during the tests. The co-ordinates of the middle point of each measured hole were projected in the top plane of the plate and registered to a file.

Based on these measurements different relative distances — or lengths — and angles can be defined. The evaluation of the model(s) is done based on these items. The results discussed in the following part of section 6, are equally valid for both the basic and the advanced approach mentioned in section 5.2.

6.1 Correction while measuring lengths

Of course the model is first tested for the situations it was developed for: measurements under uniform, near-steady state temperature conditions, in which the temperature is different from 20°C .

Tabel 1 summarizes the test results for length measurements. Different lengths can be defined between the measured 9 points. The first column of table 1 identifies the different lengths by their end points (see figure 7), for example (4-6) indicates the length defined by

Figure 7: *Identification of measured points on the holeplate.*

point 4 and 6. For the evaluation, the standard deviation (Std) on the measured lengths is compared. The values measured at different temperature levels are treated as one set. A high Std implies a large uncertainty interval on the length measured within the temperature interval. Because the standard geometrical correction does not use the temperature information the values recorded at the various conditions will be different. This leads to a large Std value.

Table 1: Results in uniform non-standard temperature conditions.

Lines	Standard correction		Full correction	
	Average value [mm]	Std [μm]	Average value [mm]	Std [μm]
(1-3)	319.498	14	319.509	1.0
(4-6)	319.325	14	319.337	1.3
(7-9)	319.594	14	319.606	1.5
(1-7)	319.468	15	319.489	1.5
(2-8)	319.347	15	319.358	1.1
(3-9)	319.607	15	319.618	1.1
(1-9)	451.874	21	451.892	1.1
(3-7)	451.926	20	451.940	1.5
Global		16		1.3
// axes		14		1.3
>< axes		20		1.3

Table 1 indicates that without the knowledge of the temperature — thus without temperature control or thermal compensation — the uncertainty of a measured length is relatively large.

The Std is smaller for lengths measured parallel (//) with the machine axes than for diagonal measurements (><). The first is a one-dimensional error (u_1), the second is a two-dimensional value (u_2).

With thermal compensation the uncertainty interval — which depends on the Std value —

reduces by more than 80%. The temperature dependent measurement error is eliminated, and the uncertainty for the temperature range in focus is reduced to the stochastic errors at 20°C that is about 1.3 μm . The thermal errors can be regarded as a correctable, systematic errors when temperatures can be recorded and used by the software, but they are random errors if the correction system cannot use thermometer data.

6.2 Correction while measuring angles

Apart from the distances, the angles between lines defined by the measured points on the holeplate can be examined. Table 2 lists the recorded angles by giving the line combination that defines them (see also figure 7). The average values differ from 90°C because of imperfections in the location of the elements in the hole plate. The holes are not positioned on a perfect grid, nor should they be. The important feature for this research is the plate’s stability. Any *variation* in the recorded angles during a test is a result of a variation in the angles between the CMM axes.

In near steady-state situations the interaction between the different axes does not change with the temperature level. The measured angle values do not change. Table 2 indicates that the thermal correction has no significant influence on the values.

Table 2: Angle measurements under uniform, near steady-state conditions.

Angles	Standard correction		Full correction	
	Average value [°]	Std ["]	Average value [°]	Std ["]
(2-8)×(4-6)	89.983	0.1	89.983	0.4
(1-9)×(3-7)	90.001	0.6	90.002	0.2

7 A more advanced thermal compensation for spatial temperature gradients

The more advanced variant of the thermal correction (see section 5.2) can compensate thermal errors under conditions beyond the restrictions that were originally set. The influence of limited — realistic — spatial gradients can be reduced as well.

7.1 Correction while measuring lengths

To illustrate the power of the advanced model, a second set of measurements are done with loads which involve spatial gradients. The temperature of the room was set at 20°C. Halogen and conventional filament lamps were used as heat sources to create spatial gradients. Different heat source locations were used during the tests. The values recorded at different near steady-state spatial gradients were combined and treated as one set. All measurements were processed with both the geometrical correction and the thermal correction. Table 3 lists the test results.

The fact that the Std values with the standard correction are much lower then in table 1 is due to the overall room temperature of 20°C during the tests. The values indicate that the

Table 3: Results under spatial gradients (near steady-state conditions).

Lines	Standard correction		Full correction	
	Average value [mm]	Std [μm]	Average value [mm]	Std [μm]
(1-3)	319.494	4.6	319.508	1.0
(4-6)	319.322	5.0	319.336	1.3
(7-9)	319.590	5.1	319.606	1.5
(1-7)	319.464	6.6	319.479	0.8
(2-8)	319.342	6.7	319.358	1.0
(3-9)	319.602	7.0	319.618	1.1
(1-9)	451.867	9.2	451.889	3.6
(3-7)	451.922	7.8	451.942	3.3
Global		6.5		1.7
// axes		5.8		1.1
>< axes		8.5		3.5

thermal compensation can reduce the Std of the measured lengths. The correction is better for parallel then for diagonal orientations, because the spatial gradients have an influence on the interaction between the axes. Although the model can deal with temperature differences between two sensors on an axis, changes in axis orientation remain uncompensated for. Thus measurements of 2D-distances (><) are only partially corrected.

Again the thermal compensation algorithm can reduce the uncertainty interval on the length measurements. As a verification of the consistency of the correction a comparison can be made between the values for the full correction in table 1 and table 3.

7.2 Correction while measuring angles

The influence of spatial temperature gradients on the machine structure can be investigated through angular measurements on a stable artefact. Table 4 proves that spatial gradients, although in near steady-state, influence the measurement of angles. The Std values are higher than in table 2.

Table 4: Angle measurements under spatial gradients (near steady-state conditions).

Angles	Standard correction		Full correction	
	Average value [$^{\circ}$]	Std [$''$]	Average value [$^{\circ}$]	Std [$''$]
(2-8) $\times$ (4-6)	89.984	4.0	89.983	4.0
(1-9) $\times$ (3-7)	89.997	3.4	89.997	3.4

Table 4 also indicates that again the developed model has no influence on the measurement of angles. This is logical, because the system has not been designed for this, but the fact that it does not influence the values for the worse is important.

When comparing the average values in table 2 with those of table 4 the influence of the

local heat sources becomes clear. The spatial gradients influence the orientation of the axes. This results in errors while determining angles on a work piece. Because of the combination of the — almost at random — selected heat source locations the average value for the first combination of lines $(2-8) \times (4-6)$ does not differ from those in table 2. For the second set of lines the variations do not average out. The Std values however proves that through the various heat source locations the orientation of the machine axes varies strongly.

This section indicates the limitations of the developed correction technique. There is room for improvement based on the experience gained.

8 Implementation possibilities

The large number of measurements — at different locations and at 3 different temperature levels — can place a severe mortgage on the implementation of the presented approach. Several reductions are possible depending on the goals. For a new machine type, the number of temperature levels can be dropped to 2. A further reduction would be to only measure along one line for each axis, in the center of the work area. If the ic versus T_m relation is known through previous tests on similar machines, only one — arbitrary — temperature level is required. This is normally already done during the error-mapping of the machine. In order to achieve good results under spatial thermal gradients a minimum of six sensors is needed (see section 7).

As previously mentioned also the number of temperature sensors can be limited. Three sensors are principally sufficient to allow the model of section 6 to work.

9 Conclusions

A basic parametric compensation scheme is presented. Depending on the details of processing the temperature inputs the possibilities of the system vary. When using only one temperature input (one sensor or an average value of different sensors) for each axis the system is sufficient for the original goals. If temperature gradients form the basis for the calculations, thermal compensation under mild spatial gradients becomes possible. Both approaches use the same hardware but the complexity of the model is much higher for the second approach.

The compensation system eliminates most of the temperature dependent errors on length measurements. The uncertainty for the temperature range and conditions in focus is reduced to the level of the stochastic errors under standard conditions by means of only 6 thermometers. Based on the temperature readings the otherwise unknown environment influence is identified and the resulting errors become systematic and therefore manageable.

The procedure provides an alternative approach to the more common non-parametric models (e.g. neural network or regression models). This approach allows — and requires — more direct input for the creation of the model. The developer can — and should — input his know-how about the machine behaviour into the model. This results in more acceptable extrapolation abilities and a compensation that covers the entire machine working volume.

Further research in the field of thermal deformations at the K.U.Leuven has already shown promising developments towards non steady-state situations with thermal gradients. Severe dynamic thermal loads require a somewhat different approach but the experience gained on this research is a necessary step on the way to quality control on non-temperature conditioned shop floors.

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Biography

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