Temperature Compensation

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Introduction

This article describes the reasons for having the environment of a coordinate measuring machine at the standard reference temperature of 20˚C and the effects of using a CMM at a non-standard temperature. This article also looks at common methods used to compensate for temperature and the types of materials used in the construction of CMM's that have an impact on how the machine will perform when temperature changes.

Temperature variation in a lab environment, when using a coordinate measuring machine, can be a large source of measurement error. Partial solutions to temperature related problems exist but do not address all problems and may even introduce collateral problems in the process.

Most typical coordinate measuring machines are designed to operate in an environment between 18 and 22˚C with additional limits of max change of 1˚C/hr and 2˚C/24hr with a spacial gradient of no more than 1˚C variation. A typical tolerance for a coordinate measuring machine in this environment is in the range of 0.003+0.004L/1000 mm. Machines that have a tighter specification, but still allowed to work inside this environment, almost certainly have hardware to deal with temperature.

Temperature compensation is not a perfect solution to a poor environment but it is considered better than doing nothing. The best solution is to avoid the problem by having the environment as close to 20˚C as possible.

Why 20˚C

The nominal temperature of 20˚C (68˚F) is a temperature that was agreed upon for dimensional measurement in the early part of the 20^{th} century. Prior to April 15, 1931 there were different reference temperatures in use; Brown & Sharpe USA used 62˚F, Ludwig Lowe Berlin was 25˚C, Reinecker, Chemnitz used 14˚C, and the State Works of France was 0˚C. The definition of the meter prior to using the wavelength of light was a measurement at the melting point of ice which is probably why 0˚C was considered as a reference temperature.

The reasons that 20˚C was selected appears to be based on two main points:

1) Comfortable environment to work in. If the reference temperature was chosen to be 0˚C then you might need to have a room controlled at this temperature which would be very uncomfortable for the operator. Even 62˚F would be difficult for many people.
2) 20˚C has an equivalent integer temperature in the imperial system (20˚C = 68˚F). If, for example, the reference temperatures of 62˚F was chosen then the metric equivalent would be 16.666..˚C (an irrational number better described as sixteen and two thirds degrees Celsius).

Ideally all measurements are performed at the reference temperature to minimize problems related to material expansion coefficients. Having a dimensional lab at a non-reference temperature adds measurement uncertainty as the material expansion coefficients may not be precisely known.

References

Journal of Research of the National Institute of Standards and Technology. Volume 112, Number 1, January-February 2007. 20 °C—A Short History of the Standard Reference Temperature for Industrial Dimensional Measurements

ASME B89.6.2:1973 Temperature and Humidity Environment for Dimensional Measurement

Practical CMM Environments

With an agreed reference temperature of 20˚C why don't all companies install their coordinate measuring machines in an environment that is as close as possible to 20˚C?. Based on observations over the years the following are the most common reasons:

1) Maintaining an environment that is exactly 20˚C is too expensive.
2) A temperature of 20˚C is an uncomfortable environment to work in. If the temperature was closer to 22˚C the environment is more agreeable to most people.

For the first point striving to have a temperature controlled environment can be prohibitively expensive. The better the control of temperature the more elaborate and expensive everything becomes. In this case it becomes more a question of what is required so that the effect of temperature contributed errors end up below an acceptable limit. When temperature tolerances for the environment are really small then even minor things such as switching on (or off) a light bulb can be a significant problem since this is a heat source. The number of people allowed to enter the controlled environment must be limited for the same reason as each person generates heat. Heating and cooling must also have special considerations to eliminate rapid changes and localized hot or cold areas.

The second point really means the importance of having the environment as close as possible to the reference temperature is not really understood. It is assumed that errors from having the coordinate measuring machine in a non-standard environment are too small to be a concern for what the machine is measuring.

CMM Construction Materials

The materials used to construct a coordinate measuring machine are important as it contributes to accuracy and repeatability. The thermal properties of the construction material can have a big impact on the accuracy as thermal gradients usually create twists and bends in the shape of the material that cannot be removed with a standard geometric error compensation map. Some machines, such as shop floor models, have a dynamically generated geometric error map that can partially deal with the expected change in shape from changes in temperature.

The ideal material for the machine frame is something that has a zero expansion coefficient and high stiffness. If the frame has a zero expansion coefficient then it will not change shape or size with changes in temperature regardless of the environment. On the other hand if the frame is built from material that has a high expansion coefficient, such as aluminum, it will grow or shrink quite a bit with changes in temperature. If the material is too flexible (low stiffness) it will bend with acceleration or deceleration and this is virtually impossible to compensate for.

One material that is commonly used for coordinate measuring machines is aluminum due to its weight. Aluminum is a good heat conductor so it is less likely to suffer effects from temperature gradients but this also means it can react quickly to changes in temperature. A situation where fast reactions to temperature is not preferred is when the machine frame grows and shrinks coinciding with the frequent cycles from the heating or cooling system.

Although aluminum is a good heat conductor there are materials with better heat conductivity such as; beryllium, lithium, gold, copper, silver, and diamond (listed in the order from better to best). Cost and rigidity are always a factor in the selection of the construction materials otherwise all machine frames would be made from diamond.

Based on observation of actual CMM's in the field it appears that machines manufactured with ceramic guide ways may be the best option. Ceramic is sufficiently light to allow high speed machines and ceramic has a low expansion coefficient so temperature has relatively small effects on the material shape. Ceramic is also a very rigid construction material so a coordinate measuring machine manufactured with a ceramic frame will have good repeatability as compared to similar machines constructed from other materials. Heavy machines made from granite are good if speed is not so important. Aluminum frames, where the scales are properly isolated, may be a good alternative if speed and cost is important provided the environment is stable.

Machine Scales

The scales used on a coordinate measuring machine are one of the most important items that determine the measurement characteristics. The type and resolution of the scale is always important but the installation can also be a critical factor.

Thin metal tape scales should have a good thermal bond to the mounting surface so they are not affected by rapid changes in air temperature. Glass scales have a low thermal conductivity so a poor thermal bond to the mounting surface will be less of a problem than something like a metal tape scale but it is always preferable to have a good thermal bond to the mounting surface.

For machine frames constructed from aluminum it is important to separate the scale from the frame so that the scale expansion is separate from the machine frame. Certain types of scales should never be installed on an aluminum frame CMM if there is any hope of accuracy with even small changes in temperature. Glass scales can be mounted on an aluminum frame provided the adhesive used to attach the scale allows some movement between the two materials. Even heavy oil can be used as an adhesive provided the scale is secured from moving.

Machine temperature sensors are usually attached to the frame and not directly on the scale which means there is some uncertainty in the measurement of the scale temperature particularly if there is a poor thermal bond between the frame and the scale. This can be a concern if relying on temperature compensation.

Errors From a Non-Standard Environment Temperature

When the environment temperature is not 20˚C there are a few sources of measurement error that should be considered. It is not a case where measuring with a CMM at a temperature other than 20˚C is completely wrong but it does mean that this measurement will have a bias or difference as compared to measurements performed at the proper reference temperature. If accuracy is paramount then this situation must be avoided.

Material Expansion Errors

All material expands or contracts with changes in temperature. All dimensional measurements are assumed to be results obtained at (or corrected to) the standard reference temperature of 20˚C. As the environment temperature moves away from the standard reference temperature all measurements require adjustment to produce a result as if it had been measured at 20˚C.

The example in illustration 1 shows a simplistic view of two lengths of material at 20˚C and 25˚C. The expansion coefficient of the two materials is such that both will grow or shrink at different rates and they are only identical in length when the temperature is 20˚C.

Temperature Compensation

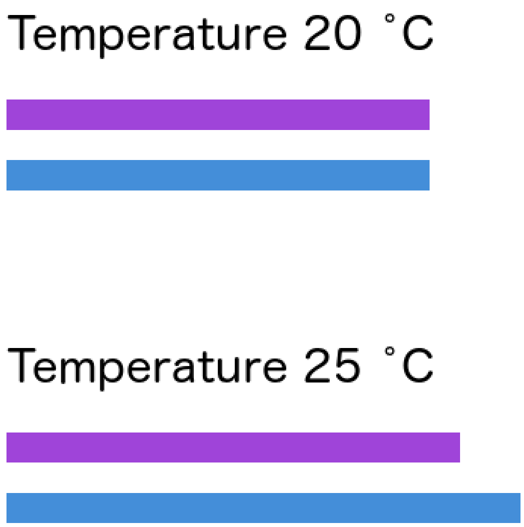

Illustration 1: Comparison of material with two different expansion coefficients at two different temperatures.

Measurement of length with a coordinate measuring machine is always done as a comparison against the machine scales. If the machine scales do not expand or contract at the exact same rate as the measurand then the difference between the two appears as an error in measurement length.

To perform a temperature correction of the measurement to 20˚C the following information is required:

- Expansion coefficient of the CMM axis.
- Expansion coefficient of the part.
- Temperature of the CMM axis.
- Temperature of the part.

Knowing the exact expansion coefficient of the part can be a problem. It is fairly easy to identify the material family (steel, aluminum, brass, …) but there are many variations and alloys for each family which may affect the actual expansion coefficient. For example, according to the Engineering Toolbox http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html the expansion coefficient of steel can be from 11e-6 to 12.5e-6 m/m/˚C. This variation is likely due to differences between common alloys of steel.

The expansion coefficient of the machine scale is usually known with more reliability but this is dependent on the type of scale and how it is mounted to the machine. Some scales, such as Renishaw tape scales, will have an expansion coefficient equivalent to the material it is bonded to so the resulting expansion coefficient of the machine axis depends more on what you know about the mounting surface than that of the scale.

Measurement of temperature becomes an increasing problem proportional to the expansion coefficient of the material. For example, a temperature measurement error of 0.5°C would represent a measurement length error of 6e-6 m/m for steel and double that, or 12e-6 m/m, for aluminum. To put it another way you would require a far better measurement of temperature for an aluminum part as compared to a steel version if all other considerations were identical.

Structural Expansion Errors

A common problem with a typical coordinate measuring machine is changes to the shape of the axis guide ways due to temperature gradients in the frame or base. The change in the shape is a result similar to how a bimetallic strips bend with changes in temperature except this change is unintentional. The change in shape from a temperature gradient is a function of the expansion coefficient and difference in temperature of each side of the bearing guide way.

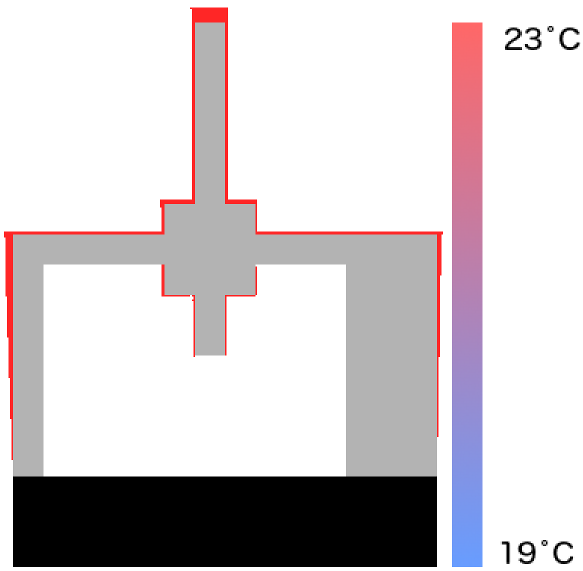

Illustration 2: Effects on a machine from temperature gradients in the machines environment.

The temperature gradient is a bigger concern when a coordinate measuring machine is installed in a room without a lot of ceiling clearance (and even worse when a ceiling pocket is needed to accommodate the machine). Fans can be used to circulate the air and reduce gradients if necessary.

Coordinate measuring machines constructed from material such as aluminum are still affected from thermal gradients even though aluminum is a good thermal conductor. Although the internal temperature gradient of aluminum should be less than that of material such a ceramic or granite the smaller temperature difference will have more effect due to the higher expansion coefficient of the material. Aluminum frames are rarely solid blocks of material so temperature gradients are more likely to exist.

A good way to avoid problems from temperature gradients is to have a suitable and stable environment for the coordinate measuring machine with lots of fans to mix and circulate the air around the machine.

Localized Expansion Errors

Coordinate measuring machines can be affected by localized heating or cooling. A machine placed in a location near a cooling vent will be subjected to frequent localized changes in temperature. Illustration 3 shows an example of a typical air conditioner mounted on the wall next to a machine. The air conditioner will produce cool air at 15°C and if this is directed at the machine it will result in a cold spot on the machine frame. This scenario is particularly bad because the cooling cycles are frequent and the temperature swings can be very large.

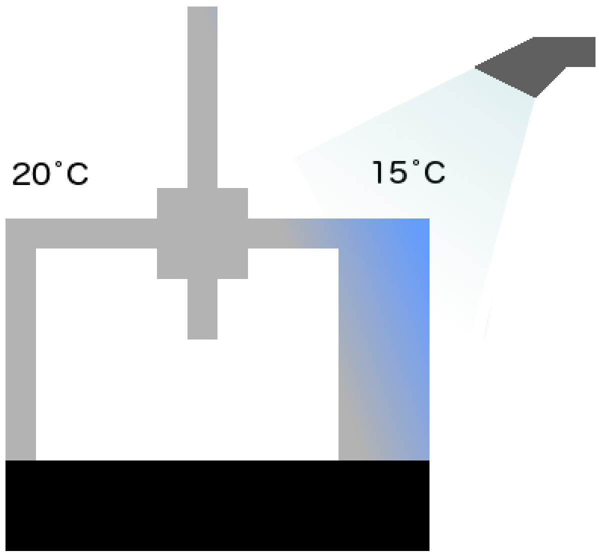

Illustration 3: Temperature effects on a machine from a localized heating or cooling point.

The change in temperature of localized areas will alter the shape of the machine in very unpredictable ways. Often calibration technicians will add deflectors to the exhaust vents when they run into this situation due to the impact it has on the machine and measurement.

Part Expansion Errors

Most parts are machined shapes consisting of holes and other structures with internal stresses that result in unpredictable changes in shape with changes in temperature. Temperature compensation does not take this into account at all as this is completely unpredictable.

The only way to properly measure a part in this situation is to do so at the reference temperature of 20°C after allowing the part to acclimate to this environment.

Machine Temperature Sensors

Coordinate measuring machines can be equipped with temperature sensors at key points of the frame. The absolute minimum would be three sensors on the machine and one for the part. A more typical machine will have two or more sensors per axis and two or more mounted on key areas of the CMM frame for correction of expected structural changes due to thermal gradients.

One problem with machine temperature sensors is that these are rarely calibrated. A typical machine manufacturer will purchase pre-calibrated sensors and this is often the only time they are calibrated. Proper calibration of the sensors after machine installation is a bit of a problem as this would require removing them from the machine (see note 1).

Temperature Compensation

Performance testing using certified artifacts such as a step gauge require the use of temperature compensation for best results. When running measurement tests on a machine with hardware temperature compensation any problems with sensors should be obvious. This is a big difference as compared to the ball bar standard ASME B89.4.1:1997 since this standard is more focused on repeatability of length then measurement of a known length. Take, for example, a machine that has the axis calibrated using a laser then a ball bar test to verify geometry. The laser (with its own temperature sensors) updates the scales of the axis which are not temperature compensated by the software (note 2). The length repeatability doesn't care about a nominal length of the ball bar but instead focuses on how well the ball bar length is repeated through out the volume of the machine. This entire process manages to skirt any problems with the temperature sensors of the machine.

Note 1: One point of view is that the machine temperature sensors are considered part of the equipment and the performance test of the machine is enough to ensure the equipment is working as expected (where the machine is a system that includes all temperature sensors).

Note 2: One solution to this problem with ASME B89.4.1:1997 is to use temperature compensation in the inspection software that is tied to hardware temperature sensors on the machine. The expansion coefficient of the laser is set to zero in this configuration which is the effective expansion coefficient of the axis when temperature compensation is enabled.

Temperature Compensation of Length

Temperature correction for the measurement of length, when the measurement method is to compare an unknown to a known, is reasonably straight forward. All measurements of length are a form of a comparison between a known and unknown quantity (with one exception for an NMI where the reference length is a theoretical value such as the distance light travels in some period of time).

Referring to illustration 1 the required information for temperature compensation is the following:

- Expansion coefficient of the part and the scale.
- Temperature of the part and the scale.

In the case of a coordinate measuring machine the reference length is the axis scales.

Assuming the following conditions:

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Expansion coefficient of the machines scales is 10e-6 m/m/˚C
Expansion coefficient of the part is 12e-6 m/m/˚C
The temperature of the part and the scale is 25˚C
The length is 1,000 mm
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The real length of 1,000 mm of the machine's scale at 25°C is:

$$Scale_{Length} = Length + Length * CTE_{scale} * (Temp_{Scale} - 20)$$
$$Scale_{Length} = 1000 + 1000 * 0.000010 * 5$$
$$Scale_{Length} = 1000.050$$

The real length of the part at 25°C is:

Temperature Compensation

$$Part_{Length} = Length + Length * CTE_{Part} * (Temp_{Part} - 20)$$
$$Part_{Length} = 1000 + 1000 * 0.000012 * 5$$
$$Part_{Length} = 1000.060$$

The expected measurement without any correction for temperature:

$$Measurement_{Uncorrected} = Length_{Nominal} + (Part_{Length} - Scale_{Length})$$
$$Measurement_{Uncorrected} = 1000.000 + (1000.060 - 1000.050)$$
$$Measurement_{Uncorrected} = 1000.010$$

The temperature corrected measurement would be:

$$Measurement_{Corrected} = Measurement_{Uncorrected} * (1 + CTE_{scale}(Temp_{Scale} - 20) - CTE_{part}(Temp_{part} - 20))$$
$$Measurement_{Corrected} = 1000.010 * (1 + 0.000010 * 5 - 0.000012 * 5)$$
$$Measurement_{Corrected} = 1000.010 * 0.99999$$
$$Measurement_{Corrected} = 1000.000$$

Software Temperature Compensation of Length

Illustration 4 shows an example of a temperature compensation dialog used by PC-DMIS™. The dialog in this example is setup for manual temperature compensation which is a common configuration for machines without temperature sensors and associated hardware.

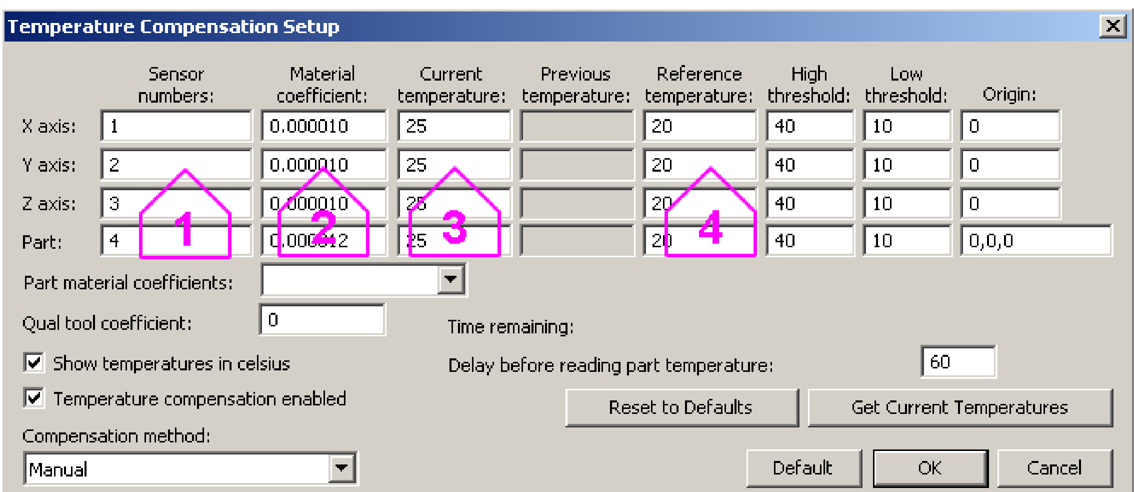

Illustration 4: Manual temperature compensation dialog in PC-DMIS.

The key items for manual temperature compensation using PC-DMIS™ are described in the following table:

Item Number	*Description*
1	The input sensor numbers. For machines with actual temperature hardware this would represent the assigned sensor number(s). For machines without temperature hardware arbitrary values must be entered into each axis field.

Item Number	Description
	The requirement for the sensor numbers in this particular software is unique to PC-DMIS™.
2	Expansion coefficient of each machine axis and the part. The input value is in m/m/°C.
3	Actual temperature values of each scale and the part in Celsius.
4	Reference temperature is 20°C. *The reference temperature should always be 20°C. Not sure why it is an option and really perplexed why the default is 0°C in this software.*

Structural temperature compensation

This kind of temperature compensation is not so straight forward. In order to compensate for changes in shape you must know in advance what the changes in shape will be from changes in temperature. The predicted shape change might be based on theoretical data or determined by direct measurement from testing in an environment chamber. Testing in an environment chamber is the preferred method since it is not susceptible to subtle errors that may affect the theoretical results.

Simple Structural Changes

Simple structural changes are changes that can be easily predicted. For example, some coordinate measuring machines have active table pitch compensation and this compensation is based more on the properties and size of the granite base then anything else.

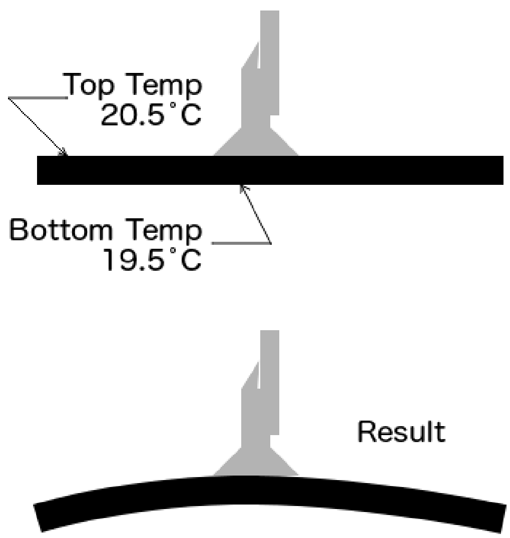

Illustration 5: Example of pitch error introduced into the long axis of a CMM from thermal gradients in the granite.

An example of active pitch compensation for a coordinate measuring machine is shown in illustration 5. The expansion coefficient of granite is in the area of 8e-6 m/m/°C and the top and bottom surfaces at different temperatures. Since the expansion coefficient is not zero the shape of the granite will change as the difference between the top and bottom surface changes. This is an example of an effect from temperature gradients on material.

Machines that have the ability to actively compensate for this change in shape will have temperature sensors mounted near the top and bottom of the granite. This feature is fairly common on certain models of CMM's.

Due to the predicable change in shape it is possible to estimate the change by only knowing the dimensions of the granite, the expansion coefficient of the granite, and the difference in temperature between the top and bottom of the granite.

Complex Structural Changes

Machine assemblies often consist of complex shapes welded or bolted together and these assemblies often contain different types of material in the construction. As a result it is nearly impossible to determine the change in shape from changes in temperature without performing a complex simulation or by direct testing.

Direct testing is done by placing a coordinate measuring machines inside an environment chamber and measuring one or more geometric errors at different temperature points. This method is suitable for specific models or sizes of coordinate measuring machines but has one disadvantage where future substitutions or alterations to the construction of the CMM would require repeating the measurement tests as changes invalidate previous data.

Changes of shape may not be linear so they are often described as a series of coefficients for each parameter of the machines dynamic compensation error map. For machines with parametric temperature compensation the actual error map is a combination of the static error data and the dynamically calculated error data based on temperature.

The reference temperature for some of the parameters of a parametric compensation map may not be the standard reference temperature of 20°C. If, for example, the angular pitch error of the long axis is measured in an environment where the temperature is actually 21.5°C then it is preferred to have no dynamic adjustment of the error map when the temperature is 21.5°C. Using a reference temperature other than 20°C does not apply to the scale axis of the coordinate measuring machine if scale correction is part of the parametric temperature compensation (which is often true).

Properties of Scale Only Temperature Compensation

Machines that actively compensate for scale errors have an effective expansion coefficient of zero. This is a common configuration for a shop floor model of CMM.

Machines with active parametric compensation often have this feature active by default even without the users knowledge. As a result observed errors when measuring parts in a changing environment will appear to be much larger unless the operator applies compensation to the part.

A common mistake when calibrating this kind of machine is to ignore the parametric scale compensation and calibrate the machine like any other machine. Machines that use parametric temperature compensation are often installed in shop floor environments and the environment temperature are rarely constant throughout an annual calibration cycle.

An example of a temperature compensation dialog for machines with parametric temperature compensation is shown in illustration 6. The controller is actively compensating for the machine axis so the inspection software must handle the compensation of the part.

Temperature Compensation

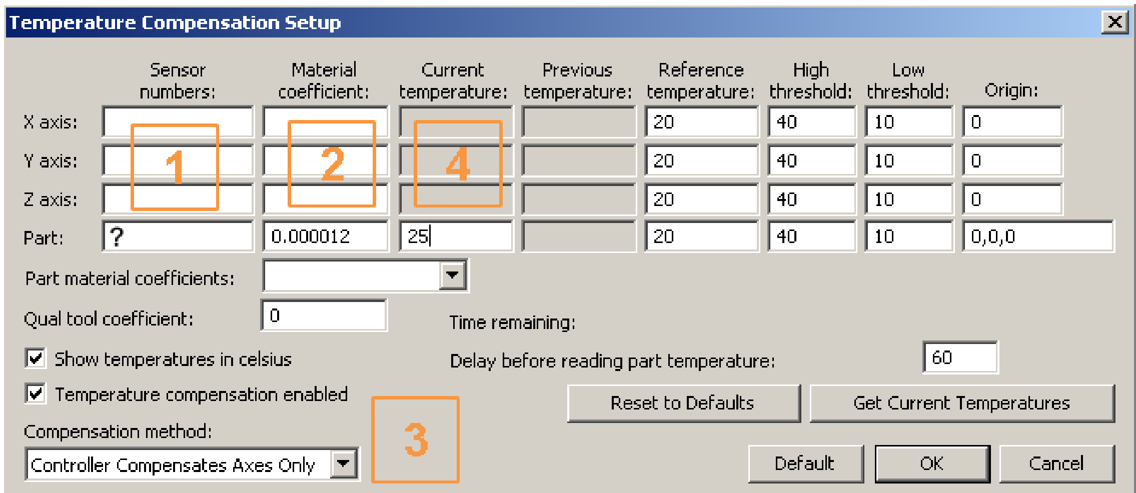

Illustration 6: Example of part only compensation in the inspection software.

The options highlighted in illustration 6 are described below:

Item Number	*Description*
1	The part temperature sensor number. Machines with parametric temperature compensation will often have a built in part sensor. The number of the part sensor should be used as assigned in the controller. The sensor numbers for the axis are not required but can be present if a record of the axis temperatures is required.
2	Expansion coefficient of the part. The input value is in m/m/°C. Assuming steel for the part the input would be 0.000012.
3	Compensation method is set to *Controller Compensates Axis Only.* The description is misleading as it indicates that the controller is already compensating for the axis and only the part needs to be corrected by the inspection software.
4	Actual temperature values of the part in Celsius. This value is read by the controller and can be updated by pressing the *Get Current Temperatures* button.

Long Term Effects of Temperature

It has been observed that frequent changes in the machine environment require regular changes to the machines compensation error map to keep it accurate. Machines that are in a stable environment often settle down so that changes to the compensation error map are small. When a machine is subjected to a change in temperature it seems to never fully recover when returned to its original environment.

Revision History

Date	*Version*	*Changes*
Oct 11, 2017	1.0	Initial Release