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Temperature effects in X-ray computed tomography

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Abstract
The aim of this research is to measure the time dependent temperature distribution and thermal time constant within a typical industrial X-ray computed tomography (XCT) system used for dimensional metrology. Temperature effects can significantly affect measurement results of XCT scans either by directly changing the dimensions of the measurement object, or indirectly by changing the geometry of XCT scanner. In either case, the effect is not known well enough to be used for correction of measurement results or estimation of measurement uncertainty. In order to determine these effects, traceable temperature measurements are performed during various stages of operation with a custom measurement system designed for this application. The influence of temperature fluctuations on length errors are determined by correlation of the measured temperature fluctuations with measurement deviations of a reference standard in repeated CT scans at different X-ray power levels.
Keywords: Length metrology, computed tomography, traceability, temperature measurement.

1. Introduction

The use of X-ray computed tomography (XCT) for dimensional metrology is becoming more and more widespread, with gradual improvements in measurement capabilities over recent years. However, traceability of XCT results is still not properly established and is usually established on case-by-case basis either by external calibration of appropriate features of the measured object (typically using a CMM) or by placing an externally calibrated reference standard into the scanned volume alongside the measured object. Other methods rely on traceable calibration of source-to-object distance (SOD), using a 2D hole standard [1], ball-bar standard [2], or through use of traceably calibrated encoders for direct measurement of SOD.

Typical approach to establishing traceability would be to ensure a complete measurement uncertainty budget is known and calculated according to ISO GUM. Several difficulties arise when this approach is analysed, such as definition of position of focal point, definition of detector plane, interaction of x-rays with different materials, etc. Influence of temperature on the measurement system is another typical factor in any uncertainty budget in length metrology. In the case of XCT, due to large amount of radiation shielding material we usually have a thermodynamically isolated system, which typically contains at least two heat sources: x-ray source and digital x-ray detector panel. Keeping a constant temperature in such system is difficult, and different manufacturers employ various strategies to achieve that effect. We investigated a standalone XCT scanner (cabinet type, NIKON XTH 225) which uses an external water cooler to directly circulate coolant through x-ray source, detector and air fan.

2. Methodology

Initial investigation of internal temperature distribution in XCT scanner was carried out using a thermal imaging camera (FLUKE T 660). Direct measurement of temperature was not attempted with this system, as the measurement results heavily depend on emissivity factors of various surfaces inside the XCT cabinet. However, these measurements did provide valuable insights into distribution of temperature inside the cabinet. Based on this information, 8 temperature sensors were placed at areas where most significant changes in temperature could be expected. Glass encapsulated NTC (negative temperature coefficient) thermistors were selected for temperature measurement. Their resistance values were calibrated in a temperature bath at 15 °C, 20 °C and 25 °C with a primary temperature standard, and Steinhart-Hart approximation was then used to correlate measured resistance with temperature values. Expanded measurement uncertainty of thermistor calibration was estimated at U = 10 mK, for coverage factor k = 2.

Thermistors were placed at the following locations (Figure 2):

- X-ray source: 3 thermistors, 1 as close as possible to x-ray focal spot, 2 at different positions above the focal spot size;
- Detector: 2 thermistors, placed above and below the outer edge of detector's active area;
- Air circulation: 2 thermistors, 1 placed at the exit duct of fan and 1 placed at the geometrical centre of the cabinet
- Measurement object: 1 thermistor placed in contact with the measured object (ball-bar standard).

Influence of temperature on measured length was investigated by measuring the distance between two spheres of a reference ball-bar standard (Figure 1).

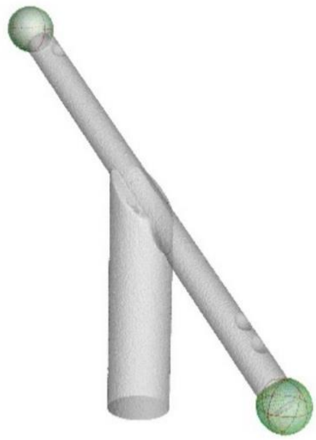

Figure 1. XCT scan of a ball-bar standard.

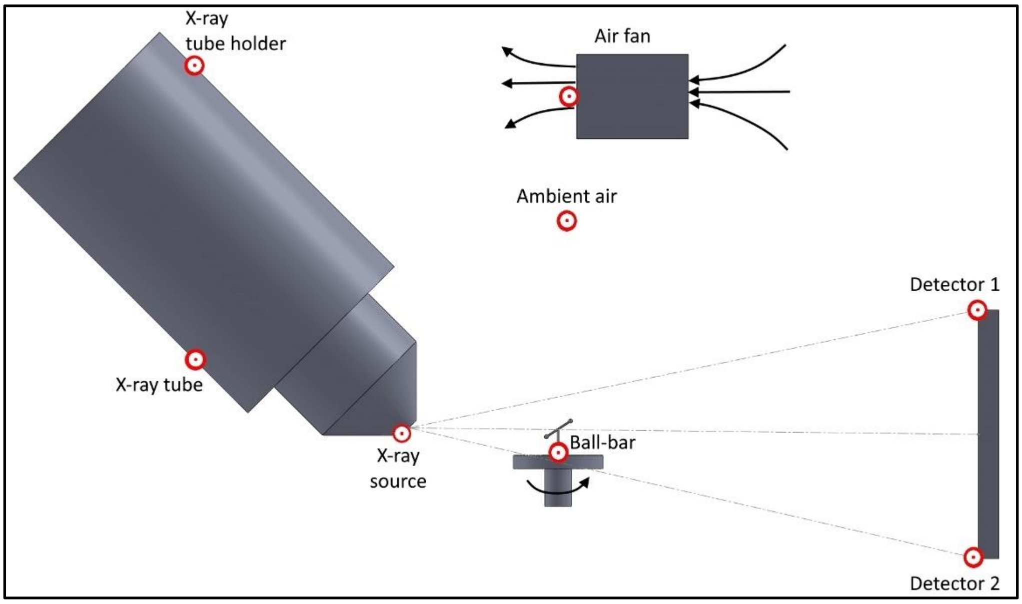

Figure 2. Schematic representation of XCT scanner, with placement of temperature sensors.

This is a fixed length standard which is externally calibrated with expanded uncertainty below 1 µm. Measurement object position was kept constant for all XCT scans, in an attempt to eliminate any influences which could arise from changes in geometrical magnification due to translation of the rotary stage of the XCT scanner. Preliminary measurements which are described here include two sets of XCT scans, performed at two distinct X-ray power levels: two repeated scans at 5 W and two repeated scans at 45 W of X-ray power. Different detector exposure times (333 ms and 708 ms) were used, to accommodate for increased X-ray flux at higher power level. This changed the scanning time and would consequently vary the amount of time that heat sources were active. Since the scope of research presented here is restrained to temperature effects at stationary thermal conditions, X-rays were turned on prior to start of each scan until stable air temperatures were obtained on temperature sensors. In this way, each XCT scan was acquired at stationary thermal conditions.

3. Measurement results

Data in Table 1 shows a summary of XCT scan parameters and measurement results obtained for distance between sphere centres of a ball-bar standard. A difference between average length results at different power levels equal to 7 micrometres is clearly visible from Table 1.

Table 1. XCT scan parameters and ball-bar length measurement.

Power	Scan duration /min:	Exposure time /ms:	Ball-bar length /mm	No. of projections
5 W	17	708	30.091	1440
			30.090	
45 W	8	333	30.097	
			30.098	

This is fairly typical when XCT parameters are changed in this manner, without some sort of voxel calibration strategy. To isolate the effect of temperature on this difference, all other measurement parameters were kept constant for all XCT scans, except for exposure time which was adapted for different X-ray flux at different X-ray power levels. Figures 3 and 4 show temperature measurements taken at 20 second intervals for all 8 temperature sensors, measured at 5 W power level and at 45 W power level. All measured temperatures appear to be constant at 5 W X-ray power, with a small increase of X-ray tube and source temperatures when X-rays are turned on. However, at higher X-ray power, X-ray tube and source temperatures show significant change when X-rays are turned on. Temporary peaks after X-ray on marker are attributed to regular start up procedure for higher X-ray power. A summary of absolute temperatures is given in Table 2.

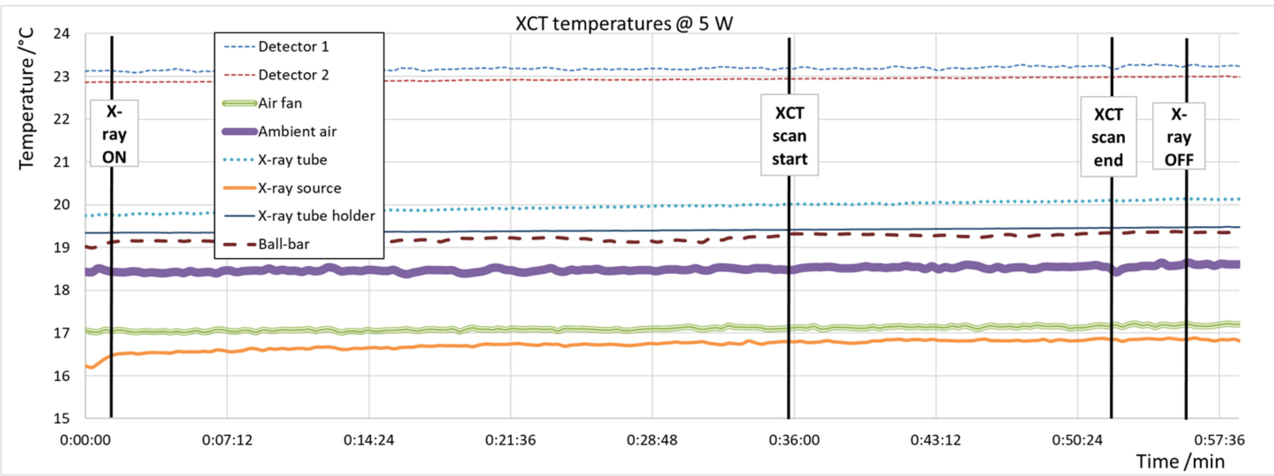

Figure 3. Temperature measurements at 5 Watt X-ray power.

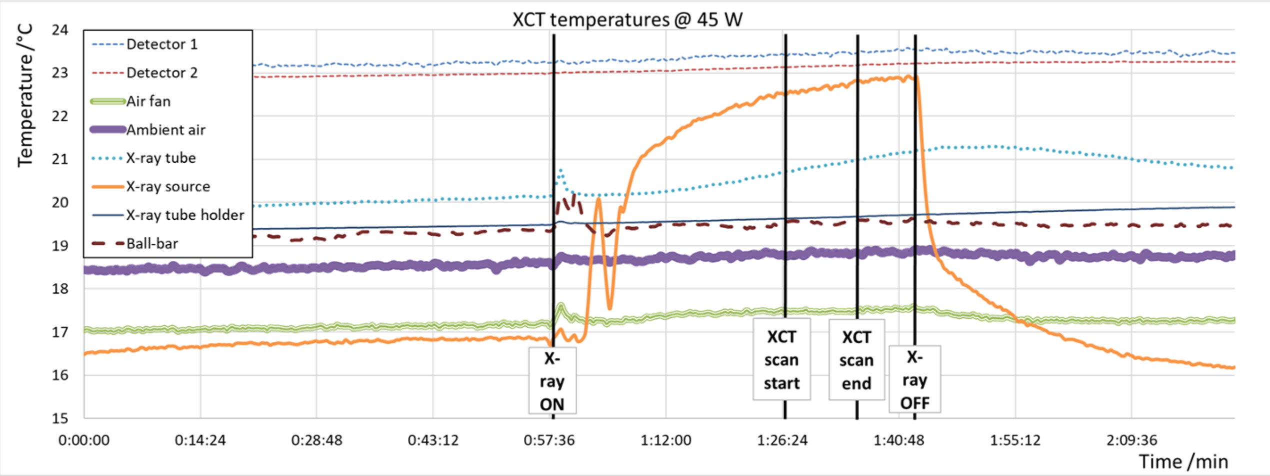

Figure 4. Temperature measurements at 45 Watt X-ray power.

Table 2. Average temperature values and their standard deviations (shown in parenthesis) during XCT scans, in °C.

Scan ID	X-ray source	X-ray tube	Ambient air	Detector
5 W	16.3 (0.05)	19.8 (0.01)	18.5 (0.03)	23.0 (0.01)
5 W	16.8 (0.04)	20.0 (0.02)	18.6 (0.03)	23.0 (0.01)
45 W	22.5 (0.08)	20.7 (0.08)	18.8 (0.02)	23.3 (0.03)
45 W	22.8 (0.08)	20.9 (0.07)	18.8 (0.03)	23.4 (0.02)

It is evident from above data that an increase in X-ray power results with an increase in the temperature of significant structural parts of XCT scanner. X-ray source spot position is directly involved in the XCT metrology loop, therefore a change in temperature of X-ray source can directly influence magnification and length measurements which are calculated from its value.

As noted before, stationary thermal conditions were desired so that "fixed" temperature differences can be determined at different X-ray power levels. If temperatures measured during a single scan are analysed (Figure 5 and 6), it is obvious that some variation in temperature still remains within the duration of a single XCT scan. This variation is also visible in standard deviation

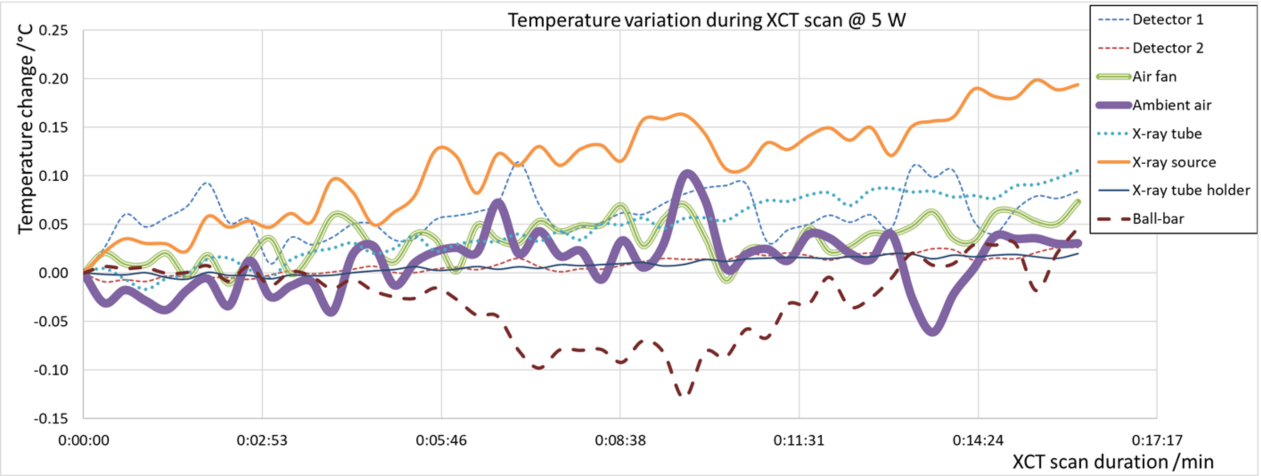

Figure 5. Temperature variations at 5 Watt X-ray power.

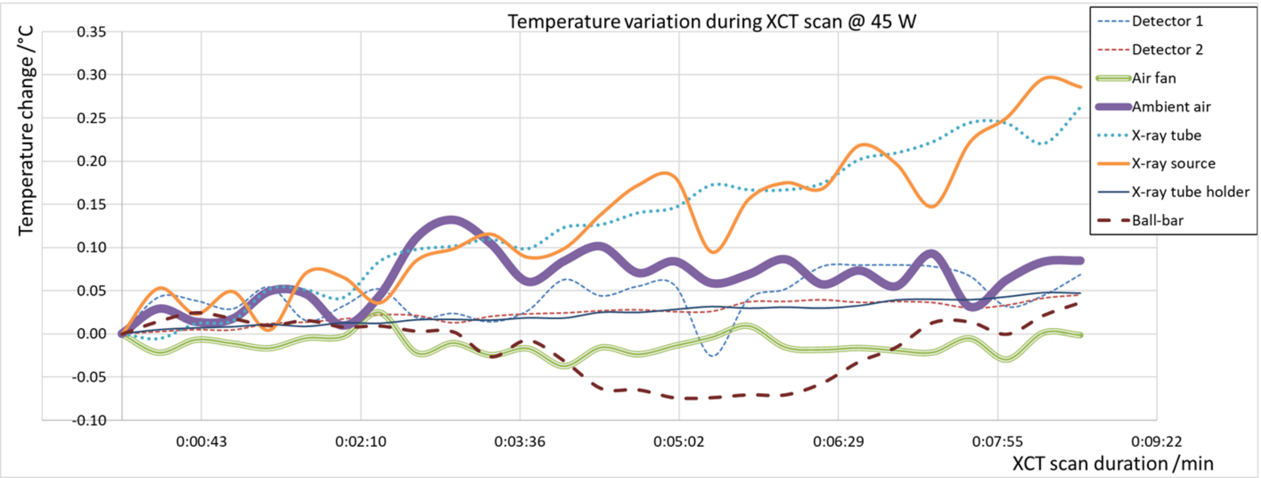

Figure 6. Temperature variations at 45 Watt X-ray power.

values in Table 2. Temperature differences shown in Figure 5 and Figure 6 were calculated by subtracting initial temperature measurement at the start of XCT scan from each subsequent temperature measurement during the scan.

When this is also taken into consideration, it appears that two separate thermal effects need to be investigated:

1. Temperature change between different X-ray power levels;
2. Temperature variation during an XCT scan.

These effects influence XCT measurement accuracy by very different mechanisms. Stationary difference in temperature of components which make up the XCT metrology loop can cause a change in their position because of thermal expansion. Such effects could be corrected by scaling the voxel size of an XCT scan. On the other hand, change in temperature during an XCT scan would influence individual projections, so they would therefore need to be accounted for at the projection-level, before reconstruction of an XCT scan volume.

Data acquired for 5 W XCT scans shows that first effect is negligible, as there is no significant increase in average temperature of relevant XCT components when X-rays are turned on. This is not the case for 45 W scans, where both effects are present.

Additionally, standard deviations of temperatures (Table 2) are also increased when X-ray power is increased from 5 W to 45 W. This can be caused either by variability of water cooler performance, or by fluctuations of electrical parameters of high-voltage generator.

4. Summary

Influence of temperature on measurement of length in a cabinet type industrial XCT scanner was investigated. XCT scans of a reference ball-bar standard were obtained at two distinct X-ray power levels (5 W and 45 W) and a 7 µm difference in measured length was determined. Temperature measurements, made at 8 different location within the XCT scanner cabinet, show that significant temperature differences exist at different X-ray power levels. Significant temperature variations during XCT scans (during constant X-ray power) were also determined. These results indicate that temperature variations during XCT scans, as well as temperature differences between different X-ray power levels, can be correlated to measured length changes in XCT scans. Further research will be focused on adding more XCT scans with increased scan times to determine warm-up time necessary to achieve stationary thermal conditions as a function of selected X-ray power. Additional power levels should also be added. Finally, further research will be directed at development of corrections for thermal effects on measurement accuracy and uncertainty.

5. References

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