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Characterisation of volumetric error variation with temperature

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Abstract
A fast and automated solution for mapping volumetric errors in medium-sized 3-axis machine tools is presented. The solution enables calibration of a 1m3 workspace in less than an hour. The effect of temperature variations on the volumetric accuracy of the machine without prior knowledge of the temperature variations is characterized. Continuous measurements over seven days on a machine affected by different heat sources are performed and a volumetric error variation model is identified. Residual errors from the identification process are used to estimate the uncertainties of individual parameters and motion errors. Monte Carlo simulations are used to propagate these uncertainties to the TCP. The model is used to understand how the volumetric positioning error of the machine changes over time and how it is generated within the kinematic chain of the machine.

Machine tool; Thermal Error; Calibration; Uncertainty

1. Introduction

Volumetric accuracy evaluation is crucial for ensuring the quality of 3D parts produced by machine tools. The measurement and compensation of the geometric errors affecting volumetric accuracy have been widely addressed, as reviewed in [1]. For medium and large size machine tools, laser tracker and multilateration based solutions appear as the state-of-the-art technology for the characterization of the geometric errors of the machine, with a laser tracker placed on the ground on different positions [2], or with the tracker moving with the machine and some fixed reflectors on the ground [3]. Artefact based solutions, although being limited in range and measurable positions, represent a low cost alternative. Early approaches to volumetric error mapping were implemented by measuring with the machine a calibrated artefact or standard in different positions in its workspace. A good review of artefact-based machine error mappings can be found in [4]. These error mapping solutions usually look at the geometric errors of the machine, coming mainly from manufacturing errors in the guideways, assembly errors and flexibility of the structural elements [1].

Thermal variations in the machine structure, induced by the environment or by internal heat sources (e.g. bearings, gears, motors, fluids, etc.) are known to be large contributors to dimensional errors when machining 3D parts. Therefore, the volumetric error mapping and compensation strategies need to take into account the thermal condition of the machine.

In the following, a fast volumetric error mapping solution for medium size machine tools is presented, and it is shown how it can be used to analyse the variation of the volumetric accuracy of the machine due to different thermal influences. Measurements are used to obtain a model that can estimate the volumetric error of the TCP at any point within the measured volume, at a specific time step.

2. Experimental setup

An artefact based volumetric error mapping device has been built following the simulation strategy presented in [5]. It was shown there that a 1D ball array could be enhanced by introducing relatively small offsets in the position of the balls to break their alignment, resulting in the need of less measurements to achieve the same calibration uncertainty.

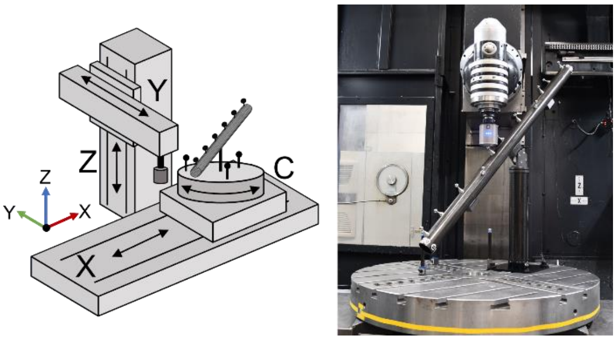

Figure 1. Machine and measurement system, with 1500 mm long ball array artefact. Left part shows a schematic view of the machine and the measurement setup with indicative sphere positions. Right part shows the actual setup, with ball #5 of the ball array being measured (numbering the balls from bottom to top).

A continuous measurement has been performed on the machine, running non-stop for 7 days (168 hours) with one measurement of the full volume every hour. Different thermal conditions have been induced on the machine, with three controlled heat sources. Two of them were hot air ventilators, focused on the lower part of the column, one on the side (Q1) and another one on the back (Q2), as shown in the left part of Figure 5. The third heat source is the climate control in the workshop (Q3). The diagram in the right part of Figure 2 shows when each of the heat sources is activated during the test. Three temperature sensors have been installed to get an indication of the temperatures in the machine, two on the column surface next to the heat sources, and another one out of the machine measuring the ambient temperature.

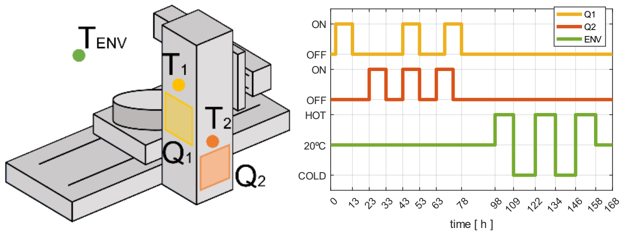

Figure 2. (left) location of heat sources and temperature sensors (right) timeline of the activation of each heat source.

3. Test results

The results obtained in the test are summarized in Figure 3. Measured position deviations are expressed in the same coordinate system as the machine, as indicated in Figure 1 and vertical grid markers were added at time steps where the local heat sources were switched on/off or when the ambient was forced to heat up or cool down.

The position of the three fixed balls varies significantly in X, Z and Y directions following the changes in the heat sources. The three balls show similar variations, almost the same for B1 and B2, and larger for B3, which indicates that the positioning error is dependent on Y axis position.

Since a large number of distances between balls in each artifact orientation are measured at each measurement cycle, the distribution of the variation of these distances is represented through their quartiles: minimum, maximum, median and first (Q1) and third (Q3) quartile. Variations in measured distances are in the same order of magnitude as in the fixed balls, showing that both measurements are relevant.

Measured temperatures, position deviations and the heat source activation timeline show an apparent good correlation which indicates that the machine thermal errors have been perturbed significantly.

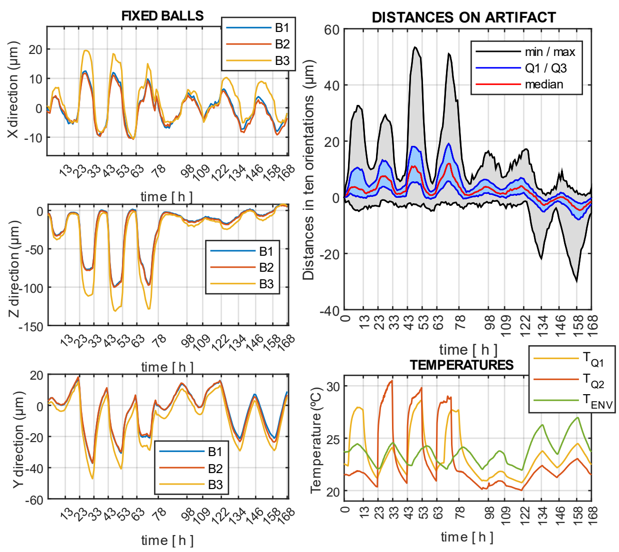

Figure 3. (Left) Measured position of fixed balls; (right, top) distances measured on the artifact; (right, bottom) measured temperatures.

3. Volumetric error variation

A kinematic error model based on evaluating the volumetric error for every volume measurement (1h) is fit on the test results. This model can be used then to analyse the propagation of thermal errors along the kinematic chain and at any point in the working volume. As an example, the model is evaluated in the tool centre point (TCP) while performing a linear motion of the Z axis at midrange of X and Z axes. The variation of X, Y, Z error components with the seven-day test is shown in Figure 4.

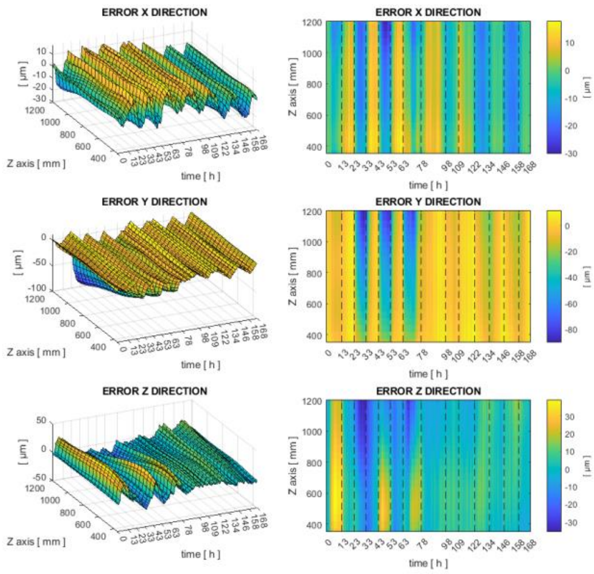

Figure 4. Simulated TCP positioning errors within trajectory TZ.

4. Conclusions

A volumetric error mapping method for medium size machine tools has been presented. The measurement procedure is fully automated and fast enough to characterize most of the thermal effects on the machine with a relevant volumetric variation. Controlled thermal perturbations have been induced while measuring on a machine during a seven-day test. The obtained data have been used to fit a volumetric thermal error model that fits sufficiently well the measurements, and the analysis of the model output while following certain trajectories in the workspace shows results that are consistent with the thermal loads that have been applied on the machine.

References

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