PAPER • **OPEN ACCESS**

Effect of ambient temperature on machine tool compensation functions

To cite this article: S Aguado *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1193** 012078

View the article online for updates and enhancements.

Effect of ambient temperature on machine tool compensation functions

S Aguado[1*], P Pérez[1], J A Albajez[1], J Velázquez[1] and J Santolaria[1]

[1] Department of Design and Manufacturing Engineering, University of Zaragoza, María de Luna 3, Zaragoza, 50018, Spain.

*Corresponding author: saguadoj@unizar.es

Abstract: Volumetric verification is increasing daily its relevance. However, as it is based on mathematical compensation, it does not model only the influence of the machine tool's geometric error to verify, but the total error of the data. Among all error sources, thermal variations due to changes in environmental conditions strongly affect MT position accuracy. This paper studies how verification changes affect compensation functions based on a modification of machine tool kinematic model and a generator of synthetic data. It takes into consideration the influence of the measurement noise on verification too. Moreover, the paper also studies how differences between verification and working conditions affect the accuracy of MT compensation functions. To do that, a brief explanation of the developed algorithm is presented.

Keywords: Temperature, Machine tool, Verification, Measurement noise.

1. Introduction

Nowadays, machine tool accuracy is a competitive element. To improve it, machine tools (MTs) are verified and compensated periodically, increasing MT working capability thanks ensuring the accuracy of its tool centre point (TCP) position.

Verification improves MT accuracy reducing the influence of its geometric errors. It results from the structural elements that make up the machine, which affect MT repeatability and kinematic precision [1]. To face it, the influence of each error on TCP can be measured independently, geometric verification, or all together, volumetric verification. Geometric verification characterizes the error's influence through its physical behaviour, only for the position where the measurement is done. Therefore, to characterize the influence of all MT geometric errors using conventional instruments like a laser interferometer, several setup phases have to be done. This implies a long verification time. However, as volumetric verification measures the influence of all errors together, the verification time is reduced [1]. Moreover, volumetric verification provides a non-physical compensation along MT's workspace. However, the TCP accuracy of a machine is affected by other error sources too. Ramesh, R [2] classified these into ten groups, including quasi-static (e.g., geometric and thermal errors) and dynamic ones. All these groups were rearranged in four bigger ones: geometric and kinematic errors, thermal errors, fixture-dependent errors and cutting force induced errors. As verification is carried out under no load, it is mainly affected by geometric and thermal errors.

Thermal influence has a non-negligible contribution. Different studies show that thermally induced error can account for around 40 ~70% of total error [3,4]. Within thermal influences, error sources have been classified as room environment, thermal memory from a previous environment, people, cutting process, machine and cutting fluid [5]. Moreover, the International Organization for Standardization (ISO) provides several standards to study thermal effects: temperature distortion of machine tools [6], machining centres [7] or turning machines [8]. Nevertheless, the MT is not cutting during a verification process. So, not all error sources have an influence on verification. The origin of these errors can be divided into internal and external influences. The main internal source of error comes from MT engines, which produces thermal deformation on MT structure. Its influence depends on the MT design and thermal behaviour of its components. Concerning external error sources, the main contribution comes from the environmental temperature variation error (ETVE). ISO 230-3 [6] shows how to setup different configurations to determine the influence of ETVE in MT spindles. However, although these standards can compare the thermal influence on different MTs, it is not enough to predict and avoid it. This problem has been faced in different ways. Some of them try to model the influence of temperature using information from sensors located along the MT, developing regression or neural networks algorithms [9]. Others use finite element methods to determine the thermal influence of MT components like bearings [10]. Nevertheless, it is not easy to apply these techniques on MTs that are not designed to include sensors on them, with standard control software and located in industrial workshops.

As verification is a frequent process, and volumetric verification is able to compare the nominal TCP with the real one (affected by geometric and thermal errors among others [11]). This paper links geometric error characterization with environmental error influence. It studies how the environment temperature on MT verification affects its accuracy. For this, it analyses how the functions that characterise MTs geometric errors are affected by temperature. Moreover, the paper also studies how the difference of temperature between verification and working conditions affects MT accuracy. To do that, it has been developed a series of algorithms able to model the influence of the temperature through the kinematic model of the machine simulating real measurements. Moreover, these algorithms provide the influence of temperature on the adequacy of compensation functions used too.

2. Volumetric verification principles

2.1. Kinematic model and measurement equipment

All volumetric verification techniques have something in common; they require to model the sequence of movements of the MT. It is made up of guides, spindles, and other elements responsible for the movement of the machine, creating the MTs' kinematic model. It links the geometric errors of the axes with their sequence of movements, providing the MT equation of movement. Therefore, each MT configuration has its own equation of movement. Figure 1 shows the movement chains of a MT with an XFYZ configuration and its kinematic chain. Where $\bar{X}$, $\bar{Y}$, $\bar{Z}$and represent the translational vectors of the X, Y, and Z axes, respectively, including their geometrical errors and nominal displacements. $\overline{Rx}$, $\overline{Ry}$ and $\overline{Rz}$ are the rotational matrices of the X, Y, and Z-axes defined by their rotational errors [12,13].

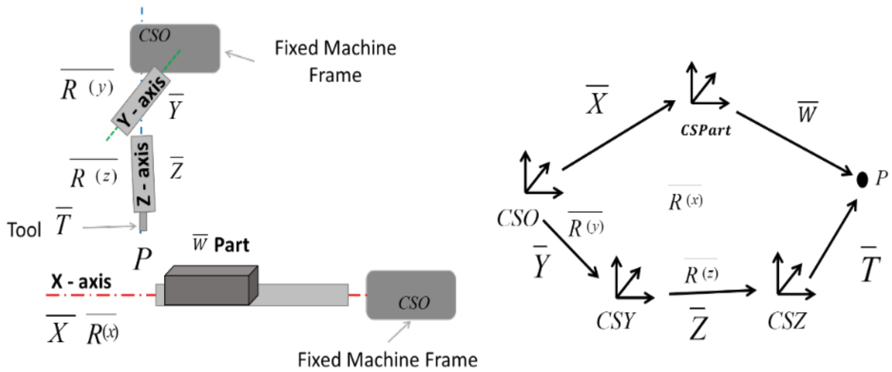

Figure 1. Machine tool and kinematic model of XFYZ milling machine.

IOP Conf. Series: Materials Science and Engineering 1193 (2021) 012078 doi:10.1088/1757-899X/1193/1/012078

However, as was presented previously, the verification of a MT is not only affected by its geometric errors. The mathematical equation that describes the MT sequence of movement, equation (1), can be modified to include these additional error sources on it [11].

$$\bar{X} + \overline{R(x)^{-1}}\,\overline{W} = \bar{Y} + \overline{R(y)^{-1}}\,\bar{Z} + \overline{R(y)^{-1}}\;\overline{R(Z)^{-1}}\,\bar{T} \qquad (1)$$

To study the influence of thermal variation, its influence has been modelled as a linear behaviour on each lineal axis, as shown in equations (2) to (4). Where $\delta_k(k)$ is the position error of axis k = x, y, z; $\delta_k(j)$ (with k ≠ j being the straightness error in the k direction) and s_{xy}, s_{xz}, and s_{yz} are squareness errors. $\alpha_{i=x,y,z}$ is the coefficient of thermal expansion from axes *x, y* and *z* respectively. T_i represents the value of the temperatures related to axis *i = x, y, z* . $T_{20º}$ represents the reference temperature at 20º Celsius. The assumption of temperature linear behaviour is based on real test observations done to determine a MT verification protocol [12].

$\bar{X}$ represents the linear error vector in the x-axis of the milling machine.

$$\bar{X} = \begin{pmatrix} -(x + x \cdot \alpha_x \cdot (T_i - T_{20º})) + \delta_x(x) \\ \delta_y(x) \\ \delta_z(x) \end{pmatrix} \qquad (2)$$

$\bar{Y}$ represents the linear error vector in the y-axis of the milling machine.

$$\bar{Y} = \begin{pmatrix} \delta_x(y) - y \cdot s_{xy} \\ (y - y \cdot \alpha_y \cdot (T_i - T_{20º})) + \delta_y(y) \\ \delta_z(y) \end{pmatrix} \qquad (3)$$

$\bar{Z}$ represents the linear error vector in the z-axis of the milling machine.

$$\bar{Z} = \begin{pmatrix} \delta_x(z) - z \cdot s_{xz} \\ \delta_y(z) - z \cdot s_{yz} \\ (z - z \cdot \alpha_z \cdot (T_i - T_{20º})) + \delta_z(z) \end{pmatrix} \qquad (4)$$

Additionally, other factors affect the equation of movement of the MT [11].The first one is the measurement system used. Currently, there are several measurement systems and artefacts able to measure the influence of all geometric errors jointly. The most common measurement systems used for MTs volumetric verification are ball bars [14], laser tracers (LC) [15], and laser trackers (LT) [11,12]. If a measurement system provides 3D coordinates related to its own reference coordinate system, such as LT, it should be included in the mathematical model, linking nominal coordinates with LT coordinates. Equation (5) shows how the LT is included modifying equation (1). Where $\overline{R_{lt}}$ and $\overline{T_{lt}}$ represent the rotation and translation matrix that links the MT with the LT and the coordinates of measured points $\overline{X_{lt}}$ on the laser tracker reference system.

$$\bar{X} + \overline{R(x)^{-1}}\,\overline{T_{lt}}\;\overline{R(x)^{-1}}\,\overline{R_{lt}^{-1}}\,\overline{X_{lt}} = \bar{Y} + \overline{R(y)^{-1}}\,\bar{Z} + \overline{R(y)^{-1}}\;\overline{R(Z)^{-1}}\,\bar{T} \qquad (5)$$

A laser tracker, like any other measurement system, affects the accuracy of measurement. Within all LTs error sources that make up its measurement uncertainty, the main contribution comes from its interferometer and angular encoders uncertainty. Their influence can be modelled as equation (6) to (9) show. With r radial measured distance, u_r radial uncertainty, θ azimuth angle, u_θ azimuth angle uncertainty, φ polar angle, and u_φ polar angle uncertainty. So, LT location affects substantially to verification results [16].

$$u_x^2 = u_r^2 \cdot \sin^2\theta \cdot \cos^2\varphi + u_\theta^2 \cdot r^2 \cdot \cos^2\theta \cdot \cos^2\varphi + u_\varphi^2 \cdot r^2 \cdot \sin^2\theta \cdot \sin^2\varphi \qquad (6)$$

$$u_y^2 = u_r^2 \cdot \sin^2\theta \cdot \sin^2\varphi + u_\theta^2 \cdot r^2 \cdot \cos^2\theta \cdot \sin^2\varphi + u_\varphi^2 \cdot r^2 \cdot \sin^2\theta \cdot \cos^2\varphi \qquad (7)$$

$$u_z^2 = u_r^2 \cdot \cos^2\theta + u_\theta^2 \cdot r^2 \cdot \sin^2\theta \qquad (8)$$

2.2. Geometric error identification

Isolating $\overline{X_{lt}}$ of equation (5), the MT kinematic equation provides theoretical points of verification mesh affected by its geometric error at different temperatures. Therefore, the approximation function for each error is obtained by reducing the difference between pair of points generated in optimization $P_{i,o}(x_{i,o}, y_{i,o}, z_{i,o})$ and real points $P_{i,r}(x_{i,r}, y_{i,r}, z_{i,r})$ measured by LT. The overall behaviour of the MT is estimated through its average volumetric error, equation (9). With *n* the total number of verification points evaluated.

$$v_e = \frac{\sum_{i=1}^{n}\sqrt{(x_{i,o}-x_{i,r})^2+(y_{i,o}-y_{i,r})^2+(z_{i,o}-z_{i,r})^2}}{n} \quad (9)$$

$$\overline{P_{i,o}} = \overline{R_{lt}^{-1}}\,(\overline{R(x)^{-1}}\,\big(\overline{R_y}\,(\overline{R_z}\bar{T} + \bar{Z}) + \bar{Y} - \bar{X}\big) - \overline{T_{lt}}) \quad (10)$$

To characterize the geometric errors using equation (10), non-linear optimization techniques should be used. The influence of these parameters on verification and identification processes is presented on [17]. These studies show that a correct design positively affects the achievable results in the identification of errors.

3. Generation and treatment of data

3.1. Synthetic data generation

The generation of synthetic data is based on the work presented in [13]. It is made up of several independent modules. The first one consists in a machine tool kinematic model generator. It is able to create the equation of movement of any machine tool with three of five axis of movement. The second module is able to define and discretize MT workspace to verify. This module has been updated compared to [13]. The new version includes a CNC generator able to generate and adapt verification code to the software of the machine. Moreover, the module takes into consideration the sequence of movement of the axis and the backlash error of the MT too. The following module is in charge of affecting verification points from module two with the geometric errors of the MT. Errors came from a previous real verification or are defined by the user. In both cases, the user introduced the functions that describe geometric errors manually as a deterministic error. The generator has an additional module to model the measurement system's influence, considering its measurement noise and location around the MT to verify. Measurement noise is modelled as a stochastic error The probabilistic distribution function that models its behaviour can be obtained from real data or introduced by user. The last two are the identification and compensation modules. The identification module is able to define different verification strategies considering errors to identify, measuring sequence, and functions used on identification (type and degree) [17]. Compensation is done offline; the software uses compensation functions obtained on the identification process to provide a new CNC program with a lesser influence of geometric errors.

This last developed version (figure 2) introduced a new module that allows us to model the influence of temperature variation as a linear deterministic error, considering the uncertainty of temperature sensors as a stochastic error modelled as a normal probability function [6]. The algorithm loads the information from the measurement sensors through a *.txt* file. As sensors measure continuously during all the verification time, the user should indicate the time of data capture of temperature sensors, the MT speed and its downtime while the measurement system takes information or verification points. This way, it is possible to determine the temperature that each sensor has on each verification point. If there is no information for a specific moment, it is calculated by linear interpolation. As data of each sensor can be linked with MTs axes, the temperature value for each point on each axis can be introduced on equations (2) to (4). Moreover, the software provides a summary of sensors information with their average, maximum, minimum and standard deviation values. In addition, the algorithm allows the user to introduce the uncertainty of each sensor, the ETVE value, and the coefficient of thermal expansion of each axis, calculating the influence of drift on each axis [6]. The algorithm can be used with real and synthetic data. However, it is a bit slow to carry out cascade real tests. Thus, general synthetic tests have been added as an option that allows to discretise a range of temperatures to each axis and their step fixed by the user. This way, all tests are generated using the same configuration file with different temperature and measurement noise errors.

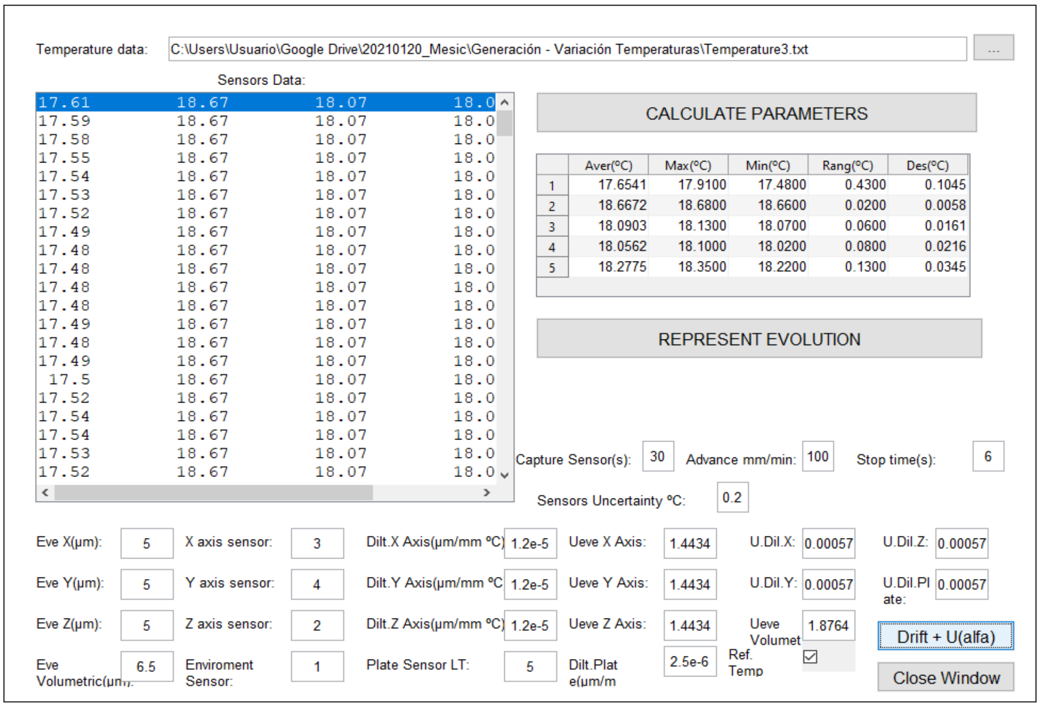

Figure 2. User interface of thermal influence on generation algorithms.

Summing up, the developed program allows simulating the volumetric verification process of a MT with a laser system under different thermal conditions to study how verification strategy, measurement system, geometric errors, and other uncertainty sources affect the compensation of different machine tool configurations.

3.2. Treatment of data results

To study how temperature affects to verification, another program has been developed to load and work with all the tests together. It is formed by three modules: general information, behaviour of approximation at different temperatures, and adequacy of approximation functions outside verification conditions.

Figure 3 shows the visual display of the first module. It presents to users the initial and final information of all tests (average, final and minimum error in micrometres), which behaviour can be represented independently or joint together. Moreover, it allows to show limits and average values of MTs geometric errors for each axis.

The approximation functions module represents all the approximation function of each geometric error jointly at every temperature. It is a quick way to see how temperature variation affects geometric compensation functions (figure 4(a), figure 4(b) and figure 4(c)). This module also has an option to study the error of a single verification point at different temperatures affected by different geometric errors. The last module is able to study the adequacy of approximation functions obtained at verification temperature on working conditions (figure 4(d)). To do that, the algorithm uses information from the first module to calculate the new errors of the machine through its kinematic model (figure 3).

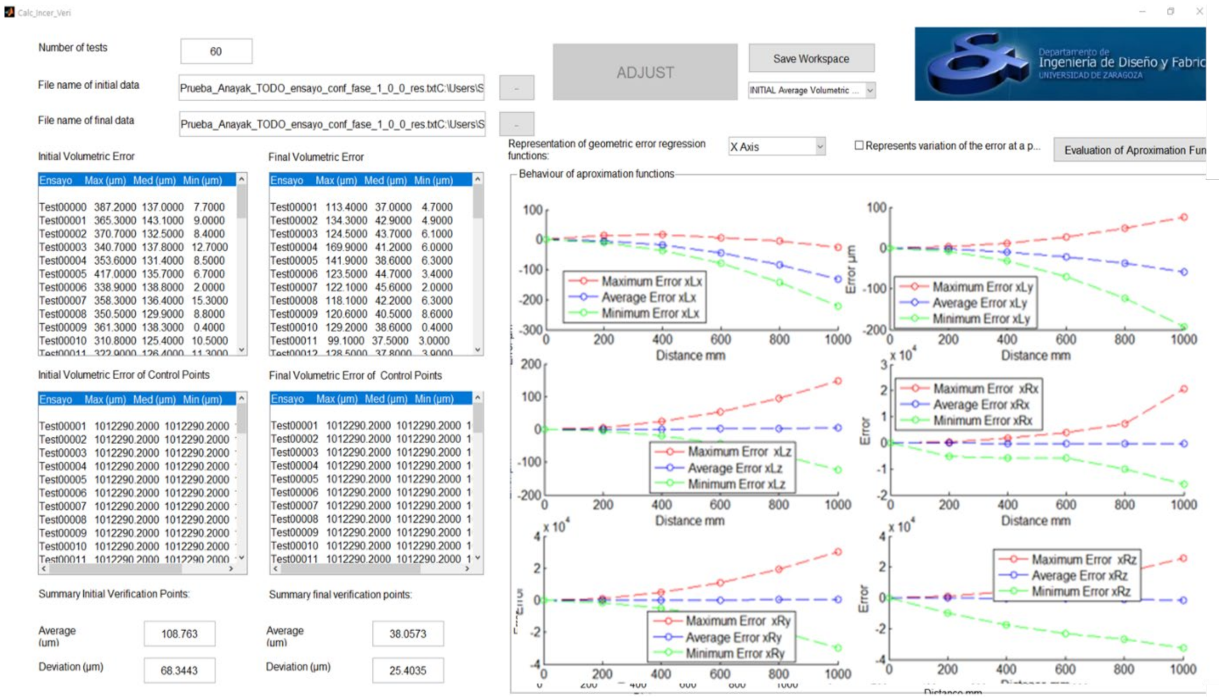

Figure 3. User interface – general information of verification results.

4. Results and discussions

The main aim of this section is to analyse how approximation functions are affected by environmental temperature changes. To do that, it has been performed a virtual verification process of the MT with XFYZ configuration presented in the second section.

Tests carried out have been done in three series, but all of them have in common, the geometric error of the MT, the verification mesh od points, the temperature ranges from 15°C to 27°C in 0.2°C steps, the optimisation method: Levenberg-Marquardt algorithm uses one phase optimisation with sequence squareness-translation-rotation from all axes together [17], the convergence criteria, and regression functions (second degree polynomials).

The first series of tests is only affected by environmental conditions; The MT has no geometric errors, and the measurement system does not generate measurement noise. Figure 4a) shows how the identification process models a thermal effect as a position error of the X-axis, although this error is zero. The approximation function adapts its behaviour to the temperature model. The function obtained at 15ºC (blue line) models the effect of maximum contraction, and the red line (27ºC) models the effect of maximum thermal expansion. Grey lines do not cross each other, adapting all of them to each intermediate thermal behaviour simulated.

On the second series of test, the MT is virtually affected by geometric error functions at reference temperature (20ºC) and environmental conditions. Figure 4b) shows that verification temperature affects geometric error identification again. If there is no thermal influence, the generated geometric error (yellow line) and the final approximation (green line) are almost the same. Thus, verification strategy can characterise errors generation accurately. However, if verification is affected by thermal influence, approximation functions move away from the actual error behaviour creating curves with different slope for the error with the same origin at different temperatures. It is the result of adapting the linear coefficient of x-position polynomial error to thermal variations.

The last series of tests adds another uncertainty source, the influence of measurement noise for a laser system. It is modelled as the combination of an angular error normally distributed with $\mu = 24$ µrad $\sigma = 8$ µrad and a radial error normally distributed with $\mu = 4$ µm + 0.8 µm/m $\sigma = 2$ µm using equations (6) to (8). In this case, figure 4c) shows that approximation functions obtained at different temperatures cross each other and the limit functions are not those of the most extreme temperatures. This is because approximation functions include the measurement noise influence misleading the identification process. So, this influence is not negligible.

Moreover, verifications are carried out on a specific day at certain temperature conditions. However, the MT works all days with varying conditions over time. Figure 4d) shows how TCP's accuracy changes when the MT verification was done at 18ºC and MT works at different temperatures. To do that, approximation functions obtained from the third series of tests at 18ºC are used to compensate errors at different working temperatures from 15ºC to 27ºC. The trend of the average error after compensation (blue line) in figure 4 c) shows a linear behaviour reducing the accuracy of compensation used. This may show how using a compensation outside verification conditions could deteriorate the MT's accuracy at working conditions instead of improving it.

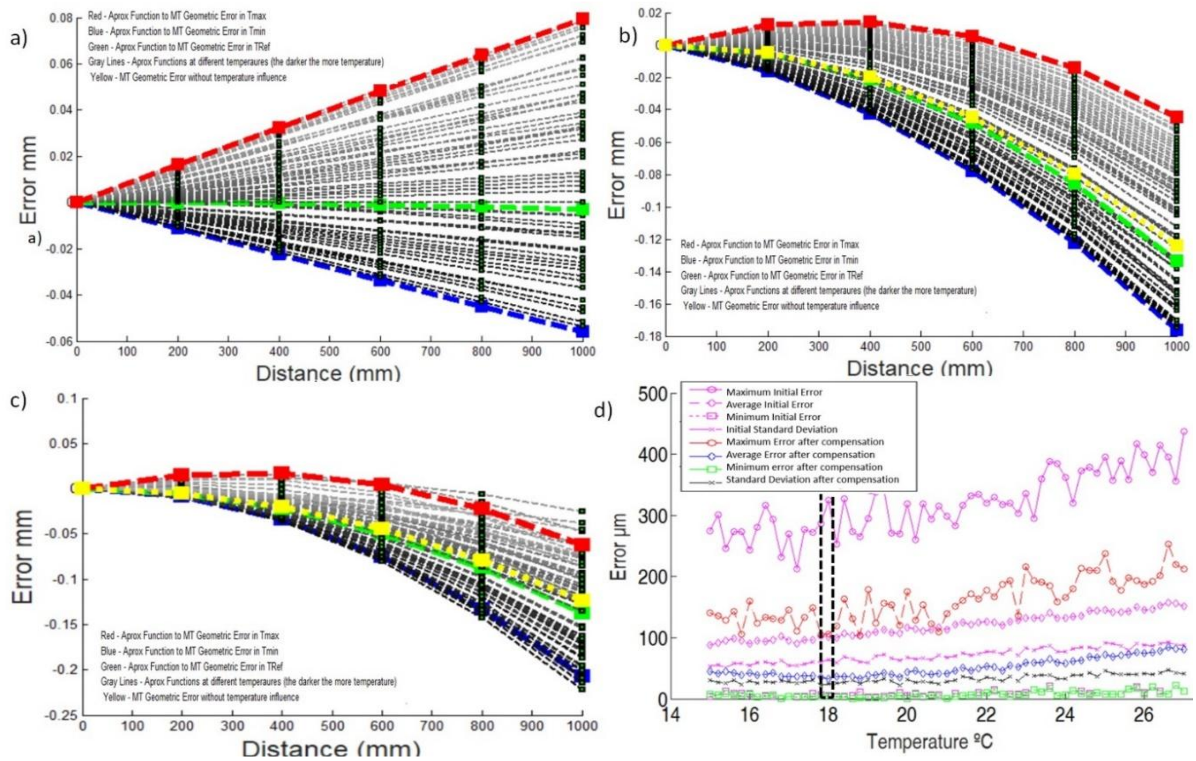

Figure 4. (a) X position error identification results due to temperature variations. **(b)** X position error characterisation results due to temperature and geometric error influences. **(c)** X position error characterisation results due to temperature, geometric error and measurement noise influence. **(d)** adequacy of compensation functions obtained at 18ºC use at different verification temperature.

5. Conclusions

The developed programs allow to study how environmental temperature changes affect approximation functions obtained on a volumetric verification. To do that, the kinematic model of the machine has been modified to add the effect of temperature on its axis as a linear behaviour. The software allows users to link the temperature of verification with the measured point considering the location of the sensors and their uncertainty. Moreover, the adequacy of approximation functions outside verification conditions can be analysed. This allows estimating the accuracy of TCP taking into consideration verification and working conditions.

Test results show that the effect of temperature on TCP has an influence on the characterization of MT geometric errors, affecting all of them. Even when the MT position geometric error has been nulled, the identification process models the thermal influence as a geometric error. This is done mainly through the linear coefficient of the polynomial approximation functions. It has also been observed that environmental variations affect approximation functions, creating almost piecewise parallel curves for the error with the same origin at different temperatures. This behaviour increases its relevance with distance and difference between real and reference temperature. The measurement noise also affects approximation functions and compensation of the MT. It has been observed that this influence strongly affects the identification process modifying the systematic behaviour of approximation functions obtained at a different environmental verification temperature. Thus, compensation functions obtained from approximation ones by MT verification may not work properly on working conditions due to changes between verification and working environmental temperature and/or measurement noise.

Acknowledgements
This research was funded by the Ministerio de Economía, Industria y Competitividad with project number Reto 2017-DPI2017-90106-R, by Aragon Government (Department of Industry and Innovation) through the Research Activity Grant for research groups recognized by the Aragon Government (T56_17R Manufacturing Engineering and Advanced Metrology Group). Project JIUZ-2020-TEC-01: Aumento de las capacidades operacionales de los sistemas de fabricación convencionales mediante modelado computacional

References
[1] Schwenke H, Knapp W, Haitjema H, Weckenmann A, Schmitt R and Delbressine F 2008 Geometric error measurement and compensation of machines-An update. *CIRP Annals - Manufacturing Technology* **57** (2) pp 660–675
[2] Ramesh R, Mannan M and Poo A N 2000 Error compensation in machine tools — a review: Part I: geometric, cutting-force induced and fixture-dependent errors. *International Journal of Machine Tools and Manufacture* **40** (9) pp 1235–1256
[3] Mayr J, Jedrzejewski J, Uhlmann E, Alkan Donmez M, Knapp W, Härtig F, et al. 2012 Thermal issues in machine tools *CIRP Annals - Manufacturing Technology* **61** (2) pp 771–91
[4] Aronson R B 1996 War against thermal expansion. *Manufacturing Engineering* **116** (6) pp 45–50
[5] Bryan J B 1990 International status of thermal error research *CIRP Annals - Manufacturing Technology* **39** (2) pp 645–56
[6] International Organization for Standardization ISO 230-3:2010, Test Code for Machine Tools — Part 3: Determination of Thermal Effects
[7] International Organization for Standardization ISO 10791-10:2007, Test Conditions for Machining centres—Part 10: Evaluation of Thermal Distortions
[8] International Organization for Standardization ISO 13041-8:2004, Test Conditions for Numerically Controlled Turning Machines and Turning Centres, Part 8: Evaluation of Thermal Distortions
[9] Zhang Y, Yang J and Jiang H 2012 Machine tool thermal error modeling and prediction by grey neural network *International Jorunal of Advanced Manufacturing Technology* **59** (9–12) pp 1065–1072
[10] Min X, Shuyun J and Ying C 2007 An improved thermal model for machine tool bearings *International Journal of Machine Tools and Manufacture* **47** (1) pp 53–62
[11] Aguado S, Pérez P, Albajez J A, Santolaria J and Velazquez J 2019 Study on machine tool positioning uncertainty due to volumetric verification *Sensors* **19** (13) p 2847
[12] Aguado S, Santolaria J, Samper D and Aguilar J J 2014 Protocol for machine tool volumetric verification using commercial laser tracker *The International Journal of Advanced Manufacturing Technology* **75** pp 425–444
[13] Aguado S, Velázquez J, Samper D and Santolaria J 2016 Modelling of computer-assisted machine tool volumetric verification process *International Journal of Simulation Modelling* **15** (3) pp 497–510

[14] Lee E S, Koo S S and Park D G 2014 A Study on the Ball-Bar Artifact for the Volumetric Error Calibration of Machine Tools *Transactions of the korean Society of Mechanical Engineers, A* **28** (7) pp 986–991
[15] Zha J, Wang T, Li L and Chen Y 2020 Volumetric error compensation of machine tool using laser tracer and machining verification *International Journal of Advanced Manufacturing Technology* **108** (7–8) pp 2467–2481.
[16] Aguado S, Pérez P, Albajez J A, Santolaria J and Velázquez J 2020 Configuration optimisation of laser tracker location on verification process *Materials (Basel)* **3** (2)
[17] Aguado S, Santolaria J, Samper D, Velazquez J and Aguilar J J 2016 Empirical analysis of the efficient use of geometric error identification in a machine tool by tracking measurement technique *Measurement Science and Technology* **27** (3) p 035002