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Procedia Manufacturing 41 (2019) 1127–1134

Procedia MANUFACTURING

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th Manufacturing Engineering Society International Conference

# Algorithm to optimize measurement system location in a machine tool verification

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**Abstract**

Nowadays, machine tool accuracy is a competitive element. To improve it, machine tools are verified and compensate periodically reducing the influence of their geometric errors. As geometric errors have systematic behavior, their influence can be compensated after verification. However, verification itself is influenced by random uncertainty sources that affect verification results.

Within all influences on machine tool volumetric verification, laser tracker measurement noise is a random uncertainty source that is not usually considered. However, it should not be ignored and can be reduced through an adequate location. This paper presents an algorithm able to analyze the influence of laser tracker location, taking into consideration its specifications and machine tool characteristics. To do that, the developed algorithm provides a zone around MT to locate the measurement system using the Monte Carlo Method. Moreover, it provides the probability distribution function of laser tracker influence related to LT location zone. Therefore, if MT is used as a traceable measurement system, its uncertainty cannot be smaller than LT location uncertainty.



*Keywords:* Laser tracker; machine tool; uncertainty; Monte Carlo Method; verification.

**Nomenclature**

| | |
|---|---|
| LT | Laser Tracker |
| MT | Machine tool |
| MCM | Monte Carlo Method |

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Peer-review under responsibility of the scientific committee of the 8th Manufacturing Engineering Society International Conference.

## 1. Introduction

The main aim of machine tool verification is to reduce the influence of quasi-static errors, especially of the geometric ones; minimizing the lack of accuracy of machined parts. Currently, there are two different ways to obtain machine tool (MT) geometric errors. Direct measurement methods measure the influence of every individual error from each axis in a particular position of the workspace of the MT [1]. Alternatively, indirect measurement methods obtain the joint influence of MT geometric errors based on multi-axis movement and MT kinematic model.

Volumetric verification using a laser tracker (LT) as measurement system is based on indirect measurement of geometric errors of the MT; characterizing their combined effect though volumetric verification [2]. So, the accuracy of verification results depends, among others, on errors of the machine tool and measurement system used.

All measurements have a degree of uncertainty made up of systematic error sources and random ones. Laser tracker systematic errors, such as environmental conditions or components assembly, can be compensated by software. However, random errors cannot be compensated but can be reduced. So, the laser tracker should be appropriately located; improving verification results [3].

Laser tracker location problem requires: encoder uncertainty influence characterization and influence minimization taking into consideration machine tool characteristics [4], physical restriction as the range of laser tracking receiver [5], and even temperature variations [6].This paper presents a developed algorithm able to determine the influence of laser tracker measurement noise on verification result. It takes into consideration LT characteristic and MT workspace. In addition, developed software uses the Monte Carlo Method to provide the area where the LT should be located with its probability distribution function.

## 2. Laser tracker and machine tool verification

A laser tracker is a portable measurement system that provides, in spherical coordinates, the position of a measured point. It is often composed of a laser orientation mechanism by means of angular encoders, an interferometer block, a PSD sensor, optics responsible for the beam division, a reflector, and a control unit. Point coordinates are determined by comparing a measurement beam with a reference beam from the laser interferometer together with the combination of the azimuth and polar angle encoders of its head which provide two rotational degrees of freedom to LT.

### *2.1. Error sources on a laser tracker*

Like any other measurement system, laser trackers are affected by systematic and random errors. Gallagher [7] classified error sources as: angular encoders, tracking system, and components misalignments. Meanwhile, Knapp [8] divided sources of errors on: errors due to environmental factors, data captures, approximations, and simplifications.

*Errors due to interferometer and optics*

These errors are the result of environmental influences and laser tracker calibration. Atmospheric effects, variations in the speed of light, and turbulence affect the physical characteristics of the laser beam [10]. The environmental conditions, pressure, temperature, and humidity produce a variation of the refractive index of the air. This variation results on an error in the laser wavelength and finally, causes a variation of the measured distance [7]. Nevertheless, environmental conditions present a systematic behavior analytically described. So LT control unit can compensate for their influence due to its meteorological station.

Moreover, installation of laser tracker optics brings with a series of intrinsic errors such as Abbe error, cosine error, and depth error. If the reflector does not move parallel to the measurement axis, a cosine error will occur. In the same way, if the reflector does not move along the measurement axis of the interferometer, an Abbe error occurs. Similarly, an error of calibration between home and reflector provides the depth error that will be transferred to all measurement points.

*Errors due to PSD sensor*

The main sources of error in a PSD are its resolution and the calibration procedure that was used to determine the relationship between the sensor output and the offset of the beam from the center of the target used to calculate the measured point. It is minimized by the sub-system consisting of two stepper motors, two optical angular encoders, and a motion control card. The two motors produce the azimuthal and polar rotation of the beam tracking system, allowing the laser beam to go towards the center of the PSD target minimizing the offset. Depending on the resolution of the encoders used, a better adjustment of the offset will be done (Figure 1).

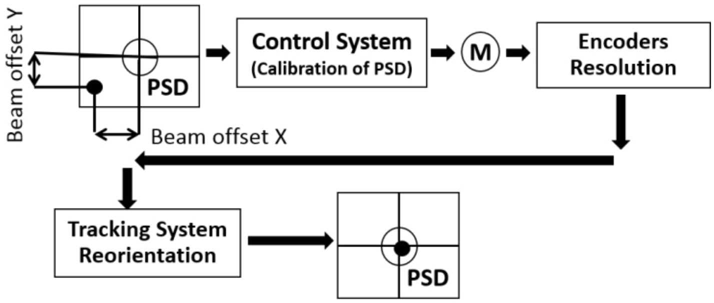


Fig. 1. Errors due to encoders and sensor

*2.2. Laser tracker on machine tool verification*

Currently, laser tracker is daily increasing its presence on machining and metrology companies as a tool to improve machine tool accuracy through verification. Although LT can be used to measure errors through geometric or pseudo-geometric verification, it is more frequently used on volumetric verification.

This way, the equipment should be located inside the MT kinematic chain in the same place as the workpiece. These are classified based on the movement of the workpiece and tool as *axis_that_move_with_part-F-axis_that_move_with_tool*, where F determines the fixed part of the machine. So, in a MT with XFYZ configuration, the workpiece move with X-axis and LT is located on it, while the tool moves with Y and Z axis. Similarly, in a MT with XCFZ the LT will be located on C axis (Figure 2) [9].

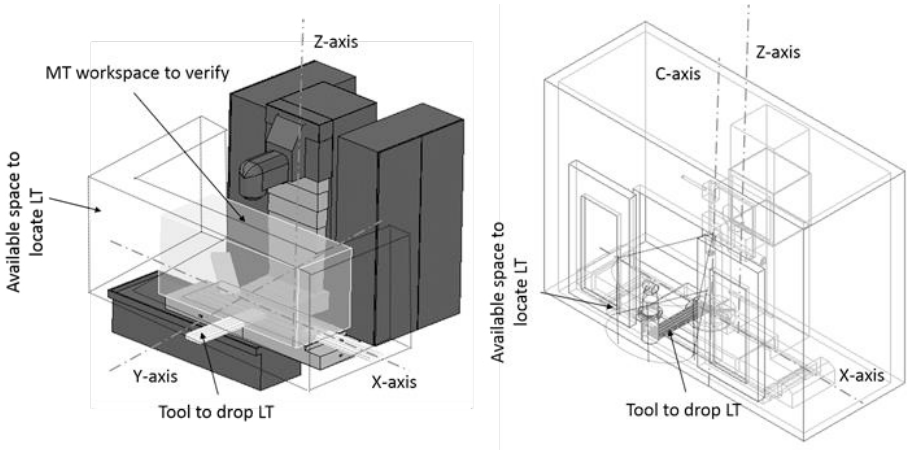


Fig 2. Machine tools with XFYC and XCFZ configuration

However, as shows figure 2 LT location will depend not only on laser tracker specifications (such as maximum and minimum azimuth and polar encoders, minimum and maximum measurement distance or height couplings) but on the workspace to verify and available space around MT to locate the laser tracker.

*2.3. Influence of laser tracker location on machine tool volumetric verification*

While systematic errors can be compensated by the LT control unit, other errors like incidence angle on the reflector, or errors on the PSD due to angular encoders and interferometer, provide a non-systematic error commonly known as measurement noise.

The influence of measurement noise on measured points can be modeled as shows equation 1. This equation links data from encoders and radial distance with their uncertainty; providing the uncertainty of a measured point on Cartesian coordinates. With $r$ radial measured distance, $u_r$ radial uncertainty, $\theta$ azimuth angle, $u_\theta$ azimuth angle uncertainty, $\varphi$ polar angle, and $u_\varphi$ polar angle uncertainty.

$$\begin{bmatrix} u_x^2 \\ u_y^2 \\ u_z^2 \end{bmatrix} = \begin{bmatrix} \sin^2\theta \cdot \cos^2\varphi & r^2 \cdot \cos^2\theta \cdot \cos^2\varphi & r^2 \cdot \sin^2\theta \cdot \sin^2\varphi \\ \sin^2\theta \cdot \sin^2\varphi & r^2 \cdot \cos^2\theta \cdot \sin^2\varphi & r^2 \cdot \sin^2\theta \cdot \cos^2\varphi \\ \cos^2\theta & r^2 \cdot \sin^2\theta & 0 \end{bmatrix} \cdot \begin{bmatrix} u_r^2 \\ u_\theta^2 \\ u_\varphi^2 \end{bmatrix} \quad (1)$$

As LT works with an absolute coordinate system and MT to verify too, nominal MT points are not in the same coordinate system when are measured. So, their real uncertainty depends on LT location around MT workspace to verify.

## 3. Working principles of location algorithm

The main aim of the developed algorithm is to provide a location area where measurement noise influence is smaller than an admissible error. It is obtained through optimization based on the Levenberg-Marquardt method; taking into consideration the following information (Figure 3):

1. Nominal machine tools points used to verify it.
2. Laser tracker characteristic. This includes maximum and minimum angles allowed by equipment as optimization restriction.
3. Limits of LT location. It consists of an available area around MT workspace to locate the LT. It can be defined as minimum and maximums parameters of translation vector that relate MT and LT along *x*, *y, z* axis.
4. Optimization criteria to minimize uncertainty influence.
5. Number of tests used to determine the location area.

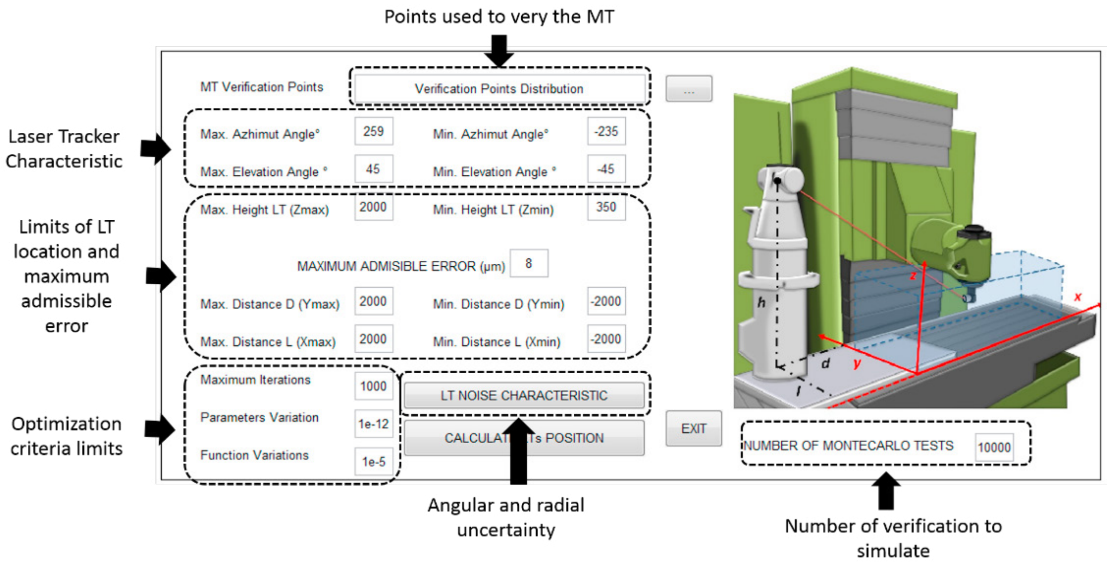


Fig 3 Components of developed algorithm

The working principle of developed algorithm is presented on figure 3. Location parameters are defined by a 1x6 vector [d, l, h, α, β, δ] that transforms coordinates from MT to LT coordinate systems. As shown in figure 3, parameters d, l, h represent a translation between MT coordinate system and LT coordinate system on x, y, z axis respectively. Meanwhile, α, β, δ are Euler angles that relates orientation of LT coordinate system with fixed machine tool one, rotating firstly around x-axis, then y-axis and ending on z-axis [3].

The objective function to minimize is a vector 1x3 made up with $[u_{max,x}, u_{max,y}, u_{max,z}]$; considering as admissible error the most restrictive criteria (all maximum uncertainty are at the same point). This way, the influence of measurement uncertainty in verification points will always be equal or smaller than optimization residual result.

Once objective function and optimization parameters are defined, the algorithm looks for initial optimization parameters. To do that, it divides available location space from *d*, *l*, *h* given by users as a uniform probability distribution function. Algorithm takes randomly a value of these optimization parameters and checks if those verification points angles are inside LT angles limits. If this restriction is not satisfied, other initial values are generated.

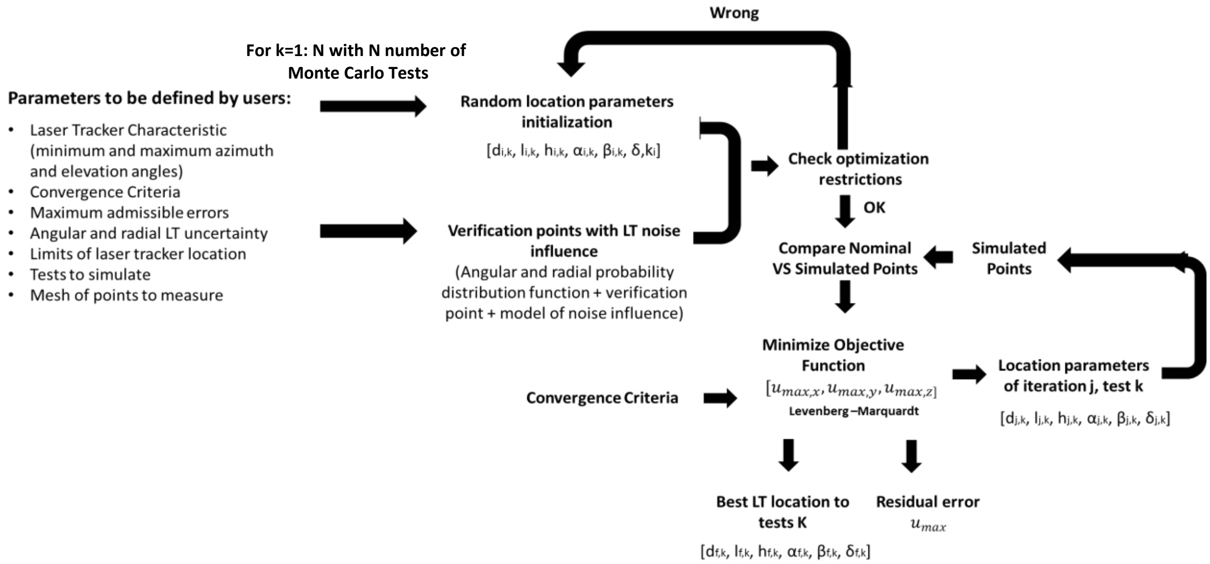


Fig 4. Working principle of location algorithm

After that, the algorithm loads the probability distribution functions that define angular and radial uncertainty of LT taking a value of each uncertainty for each verification points, which does not change during the optimization. Then nominal points are introduced on MT kinematic model with LT without considering MT geometric errors; providing points at laser tracker coordinates systems. Thus, $r$, $\theta$, and $\varphi$ coordinates are known for each point and can be affected by measurement uncertainty through equation 1. Software looks for $u_{max,x}, u_{max,y}, u_{max,z}$ and defines optimization functions. Optimization modifies $d$, $l$, $h$, $\alpha$, $\beta$ and $\delta$ (optimization parameters) changing $r$, $\theta$, and $\varphi$ spherical coordinates of each point, minimizing uncertainty influence (Figure 4).

When optimization is over, the algorithm returns optimization parameters, the residual error of the objective function, and checks the angular LT restriction. Finally, it provides the maximum error introduced by LT on verification points as shows equation 2. If $u_{max}$ is smaller than the admissible error introduced by the user, as shows figure 3, the algorithm stops. If it is not, the software halves the verification area; changing a location that meets admissible error restriction for each one.

$$u_{max} = (u_{max,x}^2 + u_{max,y}^2 + u_{max,z}^2)^{1/2} \quad (2)$$

Nonetheless, at this point, there is a LT location for a single test with an specific laser tracker noise influence. To obtain an LT location area, the software uses Monte Carlo method simulating the same verification points with different noise error on each point for each test. This way when all tests are analyzed together, the software provides different areas where the influence of measurement error on verification is probabilistic smaller. Moreover, the algorithm provides probability distribution functions that define uncertainty behavior depending on LTs location.

## 4. Test and results

Tests carried out allow to analyze how laser tracker location affects to verification of a machine tool with an XFYZ configuration (figure 2 left). Taking into consideration: distribution of verification points on workspace to verify, number of verification points, and number of tests carried out. All tests have as common simulation conditions:

- Workspace to verify. Defined by its limits of movement 0 mm ≤ x ≤ 1500 mm, 0 mm ≤ y ≤ 600 mm and 0 mm ≤ z ≤ 400 mm.
- Available workspace around MT to locate LT (figure 4 left).
- Angular laser tracker limits. Azimuth angle $\theta$, -235 º ≤ $\theta$ ≤ 235 º. Polar angle $\varphi$, -60 º ≤ $\varphi$ ≤ 77 º.
- Limits of admissible location. Available space around MT was divided into two areas, narrow and wide. Narrow side has as available location parameters 350 mm ≤ h ≤ 2000 mm, -500 mm ≤ d ≤ 2000 mm and -2000 mm ≤ l ≤ -500 mm. Wide side has as available location parameters 350 mm ≤ h ≤ 2000 mm, -2000 mm ≤ d ≤ - 500 mm and -500 mm ≤ l ≤ 2000 mm. As additional restriction, the algorithm does not allow to locate the LT inside the verification workspace.
- Uncertainty of radial and angular encoders. Probability distribution functions that define their behavior are normal distributions with μ = 20 μrad and σ = 1.5 μrad on angular encoders and 4 μm ± 0.8 μm/m for radial one.
- Optimization criteria limits. Maximum iterations 1000, minimum parameters variation 1e-12 and minimum objective function variation 1e-5.

Firstly, tests carried out study the influence of laser tracker location around MT with previous conditions using as verification points a cloud of 178 points. On each test the LT is located on an initial position and points are affected by its random errors. Values of radial error $u_r$ and angular ones $u_\theta$ ,$u_\varphi$ to each point of the cloud are obtained of probability distribution functions (PDF) shows previously. These are fixed along optimization which modifies LT location parameters *d, l, h, α, β* and *δ.* As $u_{r,i}$, $u_{\theta,i}$ , $u_{\varphi,i}$ with $i$ number of point of the cloud follow a PDF the test should be redone with different $u_{r,i}$, $u_{\theta,i}$ , $u_{\varphi,i}$ values applying MCM. So, each test will provide a best LT location depending on initial values $u_{r,i}$, $u_{\theta,i}$ , $u_{\varphi,i}$, if number of tests are big enough, the best LT location area is obtained.

First tests carried out study uncertainty of locating a laser tracker on narrow and wide areas using 1000 tests. As shows colormap of figure 5, when LT is located on the wide area the error range goes from 33.6 µm to 68.1 µm.That is to say, the test with lest influence of LT noise with specific values of $u_{r,i}$, $u_{\theta,i}$ , $u_{\varphi,i}$ with $i$=1..178, provides a maximum uncertainty value of 33.6 µm to optimal values of *d, l, h, α, β* and *δ*. Meanwhile, optimal parameters *d, l, h, α, β* and *δ* on test with the most maximum uncertainty provide a value of 68.1 µm. All other tests results are between these values.

Moreover, as shows figure 5, when LT is located on wide area there is a zone with cone shape where tests present a high concentration of optimal locations with uncertainty values between 33.6 µm and 68.1 µm. So, LT should be located on the wide area between -830 mm ≤ d ≤ -500 mm, 500 mm ≤ l ≤ 1000 mm and 700 mm ≤ h ≤ 850 mm where the cone is registered. If LT is located on other are, the uncertainty due to LT location will be higher than this value.

When LT is located on narrow area as shows figure 6, noise uncertainty due to LT location increases from 56.2 µm to 141.0 µm. However, when LT is located on narrow zone there is an area to locate the LT with rectangular shape with l = -500 mm, 350 mm ≤ h ≤ 600 mm and 0 mm ≤ d ≤ 600 mm where uncertainty is smaller than 115 µm.

More than location areas and maximum or minimum uncertainty is necessary to define the PDF that fit results to be able to estimate LT location influence. It is similar in narrow and wide zone looks like a lognormal distribution as shows figure 6 right, but cannot be ensured. Might be due to definition of optimization objective function (eq2).

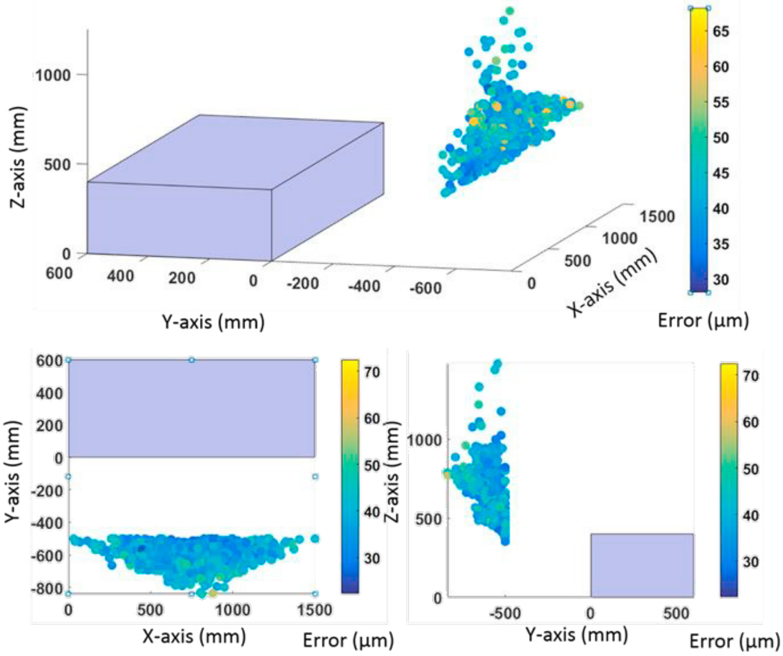


Fig 5. Error and laser tracker location area on wide zone using a laser tracker

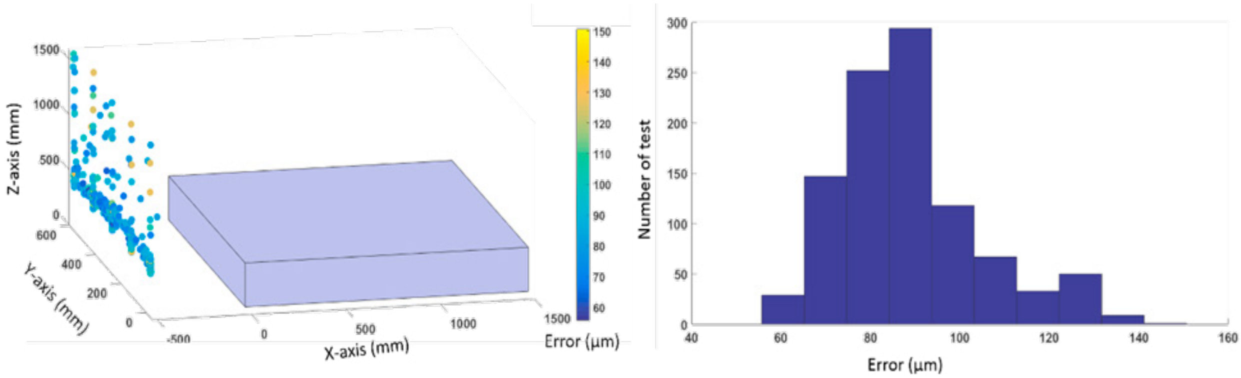


Fig 6. Error and laser tracker location area on narrow zone using a laser tracker

When the result is higher than the admissible error introduced by users, the algorithm halves the verification area in x = 750 mm. Then, the software analyses the influence of LT on these halves as independent workspaces keeping location conditions. Table 1 compares maximum and minimum error when MT workspace to verify is divided. The division favors placement on wide zone; reducing its minimum and maximum error respect a unique space.

This reduction is really relevant inside the new workspace near to LT on narrow zone, where minimum influence is reduced from 56.2 µm to 25.7 µm and maximum one from 141.0 µm to 53.0 µm on workspace1, approximately 55%. On far zone, workspace 2, the reduction is not meaningful, around 5%. If two LT are located on wide zones, the influence of LT uncertainty reduces its minimum influence from 28.1 µm to 21.6 µm and 22.5 µm and its maximum one from 68.2 µm to 50.7 µm and 51.4 µm on wokspace1 and workspace 2 respectively, around 20 %-25 %.

Table1. Influence of LT uncertainty depending on location and number of devices

| Zones | Workspace divides in two zones = 2 LTs | | | | Workspace 1 zone = 1 LT | |
|---|---|---|---|---|---|---|
| | Minimum Error (μm) | | Maximum Error (μm) | | Minimum Error (μm) | Maximum Error (μm) |
| | Workspace 1 | Workspace 2 | Workspace 1 | Workspace 2 | Unique Workspace | Unique Workspace |
| Narrow | 25.7 | 60.2 | 53.0 | 134.0 | 56.2 | 141.0 |
| Wide | 21.6 | 22.5 | 50.7 | 51.4 | 28.1 | 68.2 |

## 5. Conclusions

The developed algorithm allows to study the best area to locate a LT to verify a MT; taking into consideration parameters such as verification points to measure, LT characteristics, and available space around the MT. Tests carried out show that there is not a unique position. As LT uncertainty is defined by a probability distribution function, same verification points will be affected by different values on each test. Therefore, MCM should be used to obtain the location area, the probability distribution function of laser tracker influence, and its maximum influence on verification process.

Tests results show that when using only one LT to verify the whole MT workspace, its influence range is reduced depending on LT location zone. Moreover, a Monte Carlo analysis carried out provide an optimal location area. In this case, if only a LT is used to verify the MT, the LT should be located on cone shape of wide area, because it assures an uncertainty influence smaller than 68.2 μm. If not, probability of having a major influence is very high.

Besides, the solution to divide the MT workspace on longest side to reduce laser influence does not provide an homogeneous result in both zones. On wide zone, the influence is reduced around 25%, but, uncertainty of narrow zone is reduced around 55% on zone next to LT and 5% on the farther one. In addition, the probability distribution function of LT uncertainty influence, obtained through Monte Carlo tests, allows to determine a value limit from which accuracy of MT cannot be ensured.

### Acknowledgements

This work was supported by Ministerio de Economía, Industria y Competitividad de España with project number Reto 2017 - DPI2017-90106-R., and 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).

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