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Original Article

IDENTIFICATION AND CORRECTION OF COORDINATE MEASURING MACHINE GEOMETRICAL ERRORS USING LASERTRACER SYSTEMS

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ABSTRACT
LaserTracer (LT) systems are the most sophisticated and accurate laser tracking devices. They are mainly used for correction of geometrical errors of machine tools and coordinate measuring machines. This process is about four times faster than standard methods based on usage of laser interferometers. The methodology of LaserTracer usage to correction of geometrical errors, including presentation of this system, multilateration method and software that was used are described in details in this paper.

Keywords: LaserTracer, Coordinate Measuring Machine, geometrical error.

INTRODUCTION

One of the main components that affect the accuracy of the measurement are errors of the kinematic system of the machine on which the measurement were carried out. First models of kinematic errors for coordinate measuring machines (CMMs) were created and implemented in practice in 1970’s [1], however, first attempts of eliminating the machine tools geometric errors were made at the second half of XIX century [2, 3]. Nowadays, in the era of costs minimization the majority of measuring and machining devices are equipped with geometric errors software correction systems because it is more profitable to produce parts (which built kinematic system of machine) that are more distant from ideal geometry and then compensate geometric errors influenced by these faults, rather than to produce expensive parts with very narrow shape and dimension tolerances.

There are few different models of CMM errors i.e. full rigid body, reduced rigid body which determines geometrical errors described by different number of geometrical components. More often models are supplemented with elastic errors of the machine. The most common model met in the coordinate metrology consists of 21 geometric error components, which include translation, rotation and squareness errors. All of them were presented in Figure 1.

Errors presented (Figure 1) significantly affect the indication error *e* of the measuring machine. Their impact can be written mathematically by the equation [5, 6]:

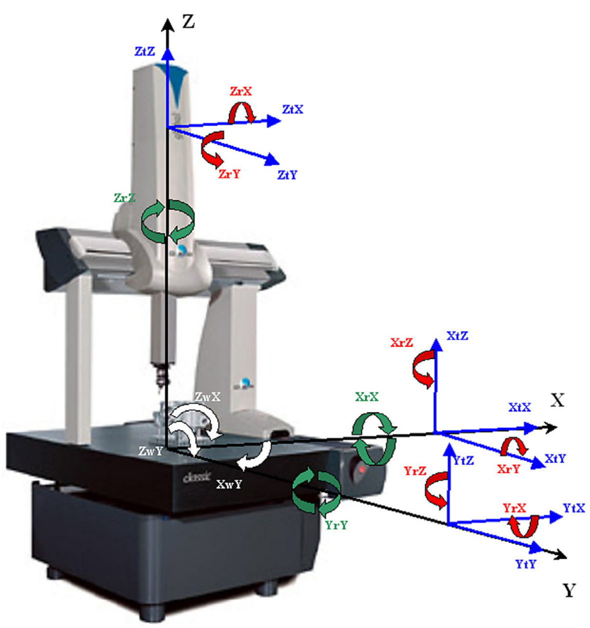

Fig. 1. Geometric errors of CMM [4]

$$e = k \cdot M \tag{1}$$

where: $e = [e_x, e_y, e_z]$ – indication error of the machine,

$k = [ywz, xwz, xwy, ytx, ypy, ytz, yrx, yry, yrz, xpx, xty, xtz, xrx, xry, xrz, ztx, zty, zpz, zrx, zry, zrz]$ – vector containing 21 geometric errors components,

$$M = \begin{bmatrix} -z & 0 & -y & 1 & 0 & 0 & 0 & z+z_t & -y_t & 1 & 0 & 0 & 0 & z+z_t & -y_t & 1 & 0 & 0 & 0 & z_t & -y_t \\ -z & 0 & 0 & 0 & 1 & 0 & -z-z_t & 0 & x+x_t & 0 & 1 & 0 & -z-z_t & 0 & x_t & 0 & 1 & 0 & -z_t & 0 & x_t \\ 0 & 0 & 0 & 0 & 0 & 1 & y_t & 0 & -x-x_t & 0 & 0 & 1 & y_t & -x_t & 0 & 0 & 0 & 1 & y_t & -x_t & 0 \end{bmatrix}^T$$

– weighted matrix which maps the impact of each element of the k vector on the x, y, z components of indication error.

This equation is a base for correction of geometric errors of CMM using CAA (Computer Aided Accuracy) matrix. The matrix is formed by measuring geometric errors in the evenly spaced reference points in measuring area of machine. After the data obtained during the machine tests is being uploaded to the controller, it is possible to correct on-line, particular errors at any point of the measuring volume using equation (1).

As it was mentioned above, machine errors are measured experimentally only in reference points. In order to make it possible to know the values of errors at any point of measuring area, the interpolation methods have to be used. Measurements can be made using a variety of methods and devices. They will be presented in next clause.

CLASSICAL METHODS FOR GEOMETRIC ERRORS IDENTIFICATION

Classical measurement of geometric errors of CMM involves using a laser interferometer (Figure 2). These devices are characterized by very good metrological features. Measurements carried out with these devices are performed at feed rates up to 1 m/s [7] with nanometer resolution (1 nm). Single-frequency laser accommodates the electronics used for interpolation, increasing stability and counting interference fringes. The laser frequency is calibrated using a reference laser. Additionally due to the influence of environmental factors which affect on the operation of the laser [8], there are systems for compensating the wavelength depending on the conditions under which the tests are carried out, for example, temperature, pressure and humidity. With the use of laser interferometer the following components of geometric errors WMP can be determined: positioning errors of particular machine axes, perpendicularity of axes errors, straightness errors and rotation errors. For determination of each component special optical systems are needed. During researches, reference points are designated in which all measurable geometric error components are determined. Information about them is then sent to the machine controller, for example, in a tabular format. They include information about various errors for each machine axis and also about the applied measurement interval.

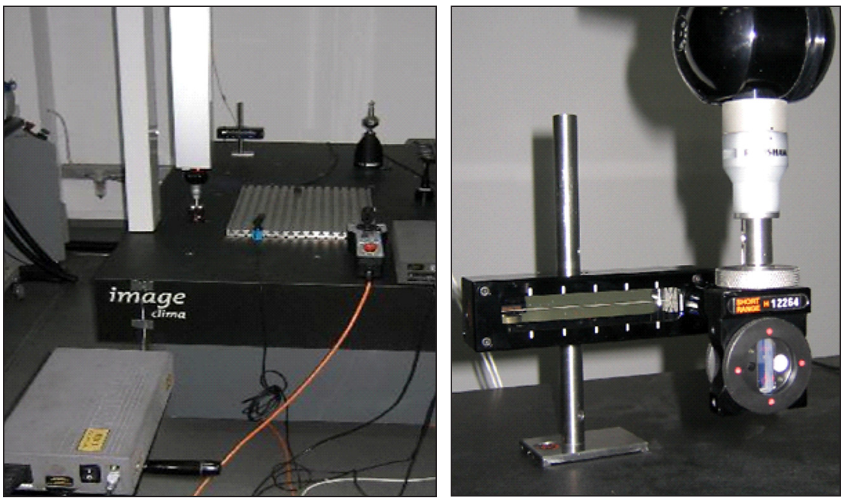

Fig. 2. Exemplary measurement of straightness errors using laser interferometer

Geometric errors can be also expressed using standards of length. Mainly 2D standards, such as a ball or hole plates are used here. One of the methods that uses this methodology is Novel method that was developed in a German laboratory PTB (Physikalisch Technische Bundesanstalt – Braunschweig). In this method, measurements of a two-dimensional standard are made to obtain information about the kinematic errors components, including the information about CMMs geometric errors. Although used standard is a two-dimensional plate standard it allows identification of errors in the entire three-dimensional measuring space by the successive arrangement of standard. The method raises a number of requirements that must be met during the tests. They refer mainly to the arrangement of standard position, the ambient temperature (20 °C), and variations of standard temperature during the measurements in one position. To estimate geometrical errors, standard plate must be measured at least six times in four predefined positions. The calibrated object is measured at three levels of the measuring area, each time using two oppositely oriented measuring tips, in the two different distances from CMM drive system guides. Every time the plate is set in parallel direction to the corresponding plane of machine coordinate system (Figure 3). It should be remembered that standard components (balls or holes) should be measured at the same points, which they were measured during the calibration. The measurements are carried out twice. The second measurement is performed in reverse order so it becomes possible to assess the reproducibility of the results. With this method the systematic changes in the dimensions of the standard in a specific direction (so called drift) can be eliminated [9].

As a result of the measurements, value and direction of a geometric errors vectors in all positions of the plate are obtained. The analysis of results involves comparing the coordinates of the holes or balls centers derived from the measurements to nominal coordinates which are known form earlier calibration. Thr information obtained from this analysis are the basis for the determination of 21 components of CMM geometric errors. With Novel method it is possible to define: the position error in each axis, straightness errors, squareness errors and rotation errors. The errors are defined as follows:

- position error is represented by the distance between points and calibrated lines,
- straightness error determined for each point is interpreted as the distance of the point from the best fit line,
- perpendicularity error is the deviation of angle between two nominally perpendicular best fit lines,
- rotation errors are divided into rotation of the axis errors and errors generated when turning in the direction of this axis.

Next method, which had been gaining a lot of interest lately, is determining the geometric errors using laser tracking systems. These machines determine the coordinates of measuring point on the basis of distance from the retro-reflector to interferometer, taking into account tracking system position angles read from angular encoders. The first attempts with tracking devices aiming in identification of geometric errors were made in the 1970's, but because of low accuracy of the trackers at the time, the results were not satisfactory. Now, when some tracking systems are able to achieve uncertainties of length measurements less than 1 micron, it is possible to successfully determine the geometric errors using this devices. The idea of determining the geometric errors is analogical to the Novel method. The biggest dif-

Fig. 3. Measurements of a hole plate in one of the positions recommended in Novel method [9]

ference is that instead of centers of reference elements at 2D standard, as a basis to the computation, the coordinates of points at which the retroreflector mounted on the CMM probe head (or instead of it) stopped during measuring sequence are taken.

IDENTIFICATION OF GEOMETRIC ERRORS USING LASERTRACER SYSTEM

LaserTracer (LT) system is one of the laser tracking devices mentioned in the previous section. LaserTracer (Figure 2) is an interferometric device, which allows tracking movements of the reflector mounted on the probe head of measuring machine or on tool holder of machining tool [10]. The accuracy of this device is given by:

$$U = 0.2 + 0.3 * L / 1000 \mu m \qquad (1)$$

where: L – is measured length given in mm.

So high accuracy can be achieved thanks to novel solution in its construction based on reference sphere, which form errors do not exceed 30 nm. This sphere lays in the center of rotation of LT rotary system.

Application of LaserTracer for determination and correction of geometric errors of CMM is based on measuring the distance between a retroreflector mounted at the machine probe head and the LaserTracer. With laser tracking mechanism LT follows the reflector while the machine moves along a prespecified grid of points. LaserTracer works together with metrological software Trac-cal developed by Etalon company to facilitate experiment set-up (planning the mapped volume, setting the measuring path, establishing connections between devices) and processing the results. This software allows also to generate a geometric error correction matrix in a format suitable for machines offered by different manufacturers.

The described method needs to use multilateration technique as LaserTracer is able to measure only the distance (from itself to center of reflector) while determination of geometric errors requires knowledge of points coordinates in measuring volume of the machine. Multilateration is the method that uses only distance measurements from several different positions in order to determine the position of the localized object. This method was primarily used in GPS satellite navigation systems. It has also been used for many years in the so-called Internal GPS measurement systems to measure large objects, and more recently also used to correct the accuracy of the measuring machines and to create a coordinate measuring systems with a very large range.

Next part of the paper shows the exemplary usage of LaserTracer combined with Trac-cal software for geometric error identification done on Leitz PMM 12106 machine located in accredited Laboratory of Coordinate Metrology (LCM) at Cracow University of Technology.

Planning experiment with Trac-cal software

The first thing that has to be done is planning the experiment, including measuring paths. Figure 4 shows the definition of machine parameters and its measuring volume.

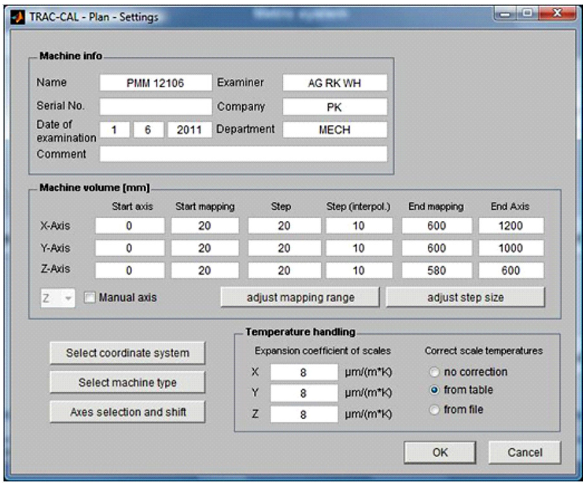

Fig. 4. Configuration of experiment

After that, the generation of measuring paths takes place. In this step, the shape of measuring paths, positions of LaserTracer in machine volume and offsets at which the retroreflector is mounted have to be determined (Figure 5).

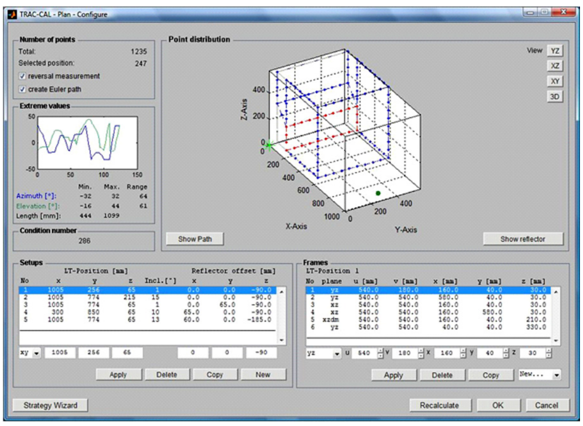

Fig. 5. Planning of the measuring sequences and LT positions

PERFORMING THE MEASUREMENTS

When the experiment is already planned, the required measurements in all specified LaserTracer positions have to be conducted. At least four positions of LT should be planned, but more positions could facilitate determination of all geometric error components. It is also important to change the offsets at which the retroreflector is mounted. The offset specifies the distance of reflector center to reference point at the machine probe head. If, for example, all of the sequences from all positions would be measured with reflector pointing in direction Z (when Z is a vertical axis of the machine) then determination of some rotation errors will be impossible. Figure 6 presents measurements done at LCM.

Fig. 6. LaserTracer performing the measurements at the PMM machine

RESULTS

Results could be computed after all planned measurements are finished. Trac-cal software solves the system of equation describing the multilateration method, determines the coordinates of points at which center of reflector stopped during measuring sequence and using methodology similar to that known from Novel method determines components of geometric errors. Results could be presented both in graphical and textual way (Figure 7).

Described software gives also opportunity to create automatic reports from performed inspections and generate compensation matrices for different types of machines, depending on producer and machine controller. This matrix can be then uploaded into the controller and used to compensate the identified vectors.

CONCLUSION

Increasing number of usages of laser tracking systems like LaserTracers to geometrical error compensation and results shown in many papers, including this one, proves that these kind of systems could be successfully used in that field. They can be also regarded as an helpful improvement reducing time and costs of identification and compensation of CMMs and machine tools geometrical errors. User friendly software and comparably small dimensions of LT (whole unit including its driver and cables fits into one case) makes it even more comfortable device for geometrical errors investigations.

Results obtained using LT system are comparable to those obtained using other methods

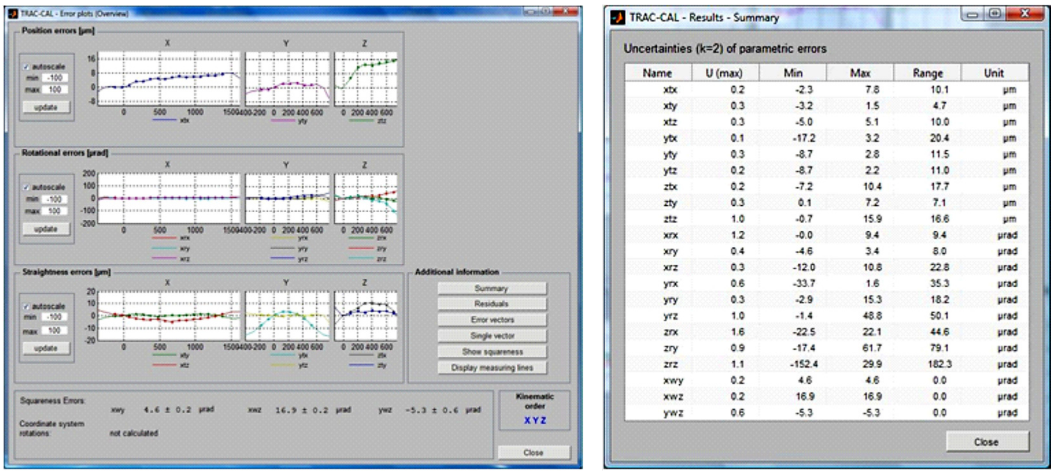

Fig. 7. Results of geometric errors identification using LaserTracer system

mentioned in this paper. However, there are still fields in which the standard laser interferometer shows its advantage. This situation happens, for example, during compensation of high-accuracy machines. On the other hand, LaserTracer is an invaluable tool for compensation of large volume CMMs and machine tools.

LaserTracer system could also be used for other purposes. One of them is CMMs calibration and checking, which is also simplified comparing to standard methods. The other usage is determination of point reproduction error, which can be then used for uncertainty evaluation using Virtual CMMs models. LT is surely not a common device and its further abilities should be tested in near future as it has a lot of potential.

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