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# Smart sequential multilateration measurement strategy for volumetric error compensation of an extra-small machine tool

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ABSTRACT

Research on machine tools has mainly focused, during these last couple of decades, on methods of error mapping and compensation techniques in aim of improving their geometrical accuracy. Over the last ten years, new measurement methods based on tracking laser (TL) multilateration have appeared. These methods have generally been applied to large machine tools or coordinate measuring machines. However, compact extra-small (XXS) machines have rarely been approached. The aim of this paper is to provide an optimal experimental strategy for estimating volumetric errors and then compensating these machine tools in the best possible manner. The method is based on the sequential multilateration technique, using a TL. This study focuses on the calibration of the translation axes of a five-axis machine tool. In this work, the accuracy of the machine is defined as the mean error vector measured in the entire working volume of the machine. The influence of a great number of factors (TL positions, offset size, acquisition time, temperature, etc.) that could affect the accuracy of the machine tool is then studied. For that purpose, a Design of Experiment (DOE) is carried out to discriminate the effect of these parameters. A Screening process is thus first used to refine the set of factors. This set is then retained to obtain the Response Surface (RS) with its Statistical Confidence Boundaries (SCB). Finally, these factors are optimized to derive the smartest strategy for providing the smallest reduced residual volumetric error after compensation. The results of this optimization are validated by an experiment.



## 1. Introduction

For more than a century, the industrial demand concerning the functionality and lifespan of workpieces has led to the enhancement of machine tool accuracy. During these last couple of decades, research on error mapping of Computer Numerical Control (CNC) machine tools has greatly contributed to improving the volumetric accuracy. This research work targets two fields. The first studies are dedicated to the volumetric error, which involves estimating the error vector in the entire working volume. This error vector is the deviation between the driven nominal tool position and the real cutter location. The second field deals with the compensation techniques, which correct the deviated tool path.

The errors of CNC machines with linear axes are linked to the kinematic errors of each axis, which include the positioning error, two straightness errors, and three angular motion deviations, called roll, pitch, and yaw. Squareness defects between axes are also to be considered. The defects of machine tools with three linear axes are finally represented by twenty-one kinematic errors. These errors come from various sources [1]. Mechanical and geometrical imperfections [2], as well as the misalignment of components in the structure, are the main sources of kinematic errors. Another source of error is the non-uniform expansion of the machine structure, which appears to be due either to different internal heat sources, such as drive motors, controller cards, or friction in the bearings, or to the specific environment of the machine tool. The weights of the different components or moving carriages of the machine tools also have a strong influence on the machine volumetric accuracy. Furthermore, it is well-established that geometric and thermo-mechanical errors represent the main sources of volumetric errors [2]. Once the sources of error are known, the errors can be defined thanks to an error model. Developing the error model requires different mathematical tools such as homogenous transformation matrices [3–5].

Generally the geometric and thermo-mechanical errors cannot be directly evaluated on CNC machine tools but are estimated using the measurement of distances. Laser interferometers are mostly used [6,7], especially Tracking Lasers (TL) [8–11]. For example, the devices and the software TRAC-CAL developed by Etalon AG,

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in collaboration with NPL and PTB [12], for more than ten years is able to provide reliable and accurate error maps. The TL, placed on the table of the machine, is able to track a spherical reflector which is bound to the spindle. The distance measurement resolution is of about 1 nm (Michelson interferometer principle). The coordinates of the reflector can be obtained using four TLs. In this procedure, four distances are measured simultaneously. Then, the location of the reflector in the reference frame of the machine tool can be estimated. This method is called multilateration [13]. However, a TL is quite expensive. In addition, a similar method called sequential multilateration can be used [14]: instead of employing four devices, only one TL is required but it is shifted three times. The measurements are carried out one after another. Once the kinematic errors have been estimated, a compensation matrix can be built. A Compensation matrix is the data which is the most used in order to compensate distorted tool paths. For that purpose, the working volume is meshed. The compensation matrix then provides the kinematic errors at each node of the mesh. The error vector, at any point in the working volume, is then derived from the kinematic model by using interpolated local kinematic errors. Two approaches are finally used to correct the tool path. Either the compensation is internal to the machine tool and the numerical controller compensates the tool path in real time [15], or a post processing procedure is added to the CAM software to define the corrected tool path [16]. This improves the volumetric accuracy.

This state of the art intimates that TL techniques are generally applied on any Coordinate Measuring Machine or CNC machine tool. However, the error mapping of a compact extra-small (XXS) machine tools involves some real difficulties. This is due to the small size of the working volume (about $200 \times 200 \times 200\,\text{mm}^3$) and its reduced accessibility. In fact, these specific problems were existing for the machine tool used in this study. This machine is a very compact CNC bridge type machining center. First, measuring the tight working volume of this extra small machine tool requires some special fixture. The tracking laser cannot be placed on the cradle of the machine tool which does not support the appliance weight. Then it needs to be placed on a plate bound to the machine tool bed, which avoids collisions between the TL and the reflector. Second, the small size of the working volume ($200 \times 200 \times 200\,\text{mm}^3$) and its reduced accessibility impose a different approach: the reflector locations cannot be spread equally around the spindle during the sequential measurement process; the same constraint also applies to the positioning of the TL. This reinforces the necessity to improve the calibration process. Of course, other technologies to calibrate a XXS machine tool exist, like the *R*-test for example. But the advantage of the TL is to be able to estimate the mapping error in the whole working volume and to acquire a large number of data.

In consequence, this paper describes the optimization of the experimental calibration strategy of the translation axes for an extra-small CNC bridge type machining centers, using the TL sequential multilateration technique. A Design Of Experiment (DOE) will be used as an analysis tool. This study is organized around three major points: the introduction of the experimental procedure, the analysis of the experimental strategy using DOE and its optimization.

## 2. Experimental process

### 2.1. Error mapping procedure for an extra-small machine

#### 2.1.1. Case study environment

The studied measurand is the extra-small CNC bridge type machining center, shown in Fig. 1. This machine tool is placed in a temperature-controlled room. In order to avoid the impediments due to the thermal drift, the machine environment has been customized. Three heat sources are controlled: the drive motors of the axes, the numerical controller cards and the specific environment of the machine. A heat exchanger and a cooling system are used to evacuate the heat. Another heat exchanger is dedicated to controlling the temperature of the coolant. Finally, an air conditioner system regulates the temperature in the room at a precision of $\pm 1.5^{\circ}$.

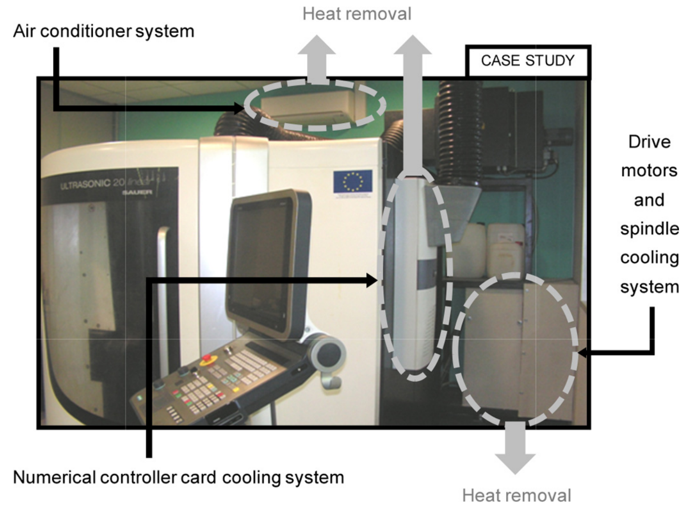


**Fig. 1.** CNC machine environment.

The studied machine is a five-axis milling machine. It is dedicated to high precision machining of small workpieces. 5 μm is the accuracy specified by the manufacturer. The working volume is limited to $200 \times 200 \times 200\,\text{mm}^3$ and its accessibility is reduced.

#### 2.1.2. Volumetric error estimation using the TL technique

The TL used in this study is an ETALON Laser Tracer. A preliminary study, focusing on repeatability, was conducted to validate the use of the TL. A set of length measurements was repeated thirty times. These measurements involved characterizing the distance between the TL and the reflector fixed on the spindle of the machine. After each measurement, the three axes were moved and put back into the initial fixed position. The repeatability was estimated to a tenth of a micron, which is much lower than the order of magnitude required for the compensation.

The TL shown in Fig. 2 is a reliable device for measuring the kinematic errors of the machine tools. The measuring technique employed is sequential multilateration. A toolpath trajectory is therefore defined to join up the different nodes of the mesh used to map the working volume of the machine. When a given node of the mesh is reached, the TL characterizes the length between the reference sphere of the TL and the reflector. Due to the dead zone of the interferometer, the acquired data does, however, not match the real measured distances. The same sequence is repeated three times, by shifting the TL position. After computation, an error vector is deduced for any node of the trajectory. The set of error vectors is finally used to determine the compensation which has to be applied to the machine tool.

This error vector can be written in function of the kinematic errors of the machine. To deduce these errors, the kinematic model of the machine tool was required. The machine tool is a bridge structure that was assumed to be perfectly rigid. In Fig. 3, which shows the machine tool under study and its structure, M refers to the reference point of the spindle and P represents the center of the reflector. During a machining step, P would refer to the cutting edge location. The error model was deduced from the structure of the machine tool. It is based on general homogeneous transformations and small angle approximations.