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Use of coordinate measuring machine to measure angles by geometric characterization of perpendicular planes. Estimating uncertainty

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ABSTRACT

The purpose of this paper is to estimate the uncertainty of angle measurements using a Coordinate Measuring Machine (CMM), through the geometrical characterization of two concurrent sides of a steel angle gauge block with four perpendicular sides.

For the calculation of the uncertainty associated with the measurement and investigating the errors of the CMM associated with orientation and length in the work volume, two models: linear statistical model behavior of CMM and the *Mitutoyo* model behavior are used and compared. After having established two behavioral models for the CMM we have determined the values of the angles and their uncertainty by using Monte Carlo Method. The results show that the proposed methods are suitable to investigate CMM hardware performance and determine the contribution of machine variables to measurement uncertainty. We can affirm that the statistical model behavior is more immediate and less laborious in terms of calculation and implementation time than the *Mitutoyo* model.

1. Introduction

In the past ten years numerous scientific works have arisen related with angle measurement in order to respond to growing demands in certain industrial sectors with increasingly strict tolerances tied to the production of mechanical pieces [1–4].

Research in this field has addressed the analysis of different instruments and methodologies able to provide adequate solutions to the problems of industries [1,2]. The first major classification distinguishes between direct and indirect measurements (Fig. 1). The definition itself can be derived from its name, and further explanations are not necessary in this context. It must be noted, however, that indirect measurements require an algorithm for calculation that relates the input values, measured, and the output value, calculated.

Likewise, three aspects that determine the choice of the measurement methodology can be: the dimensions and shape of the measurand, the requirement for precision and uncertainty and the costs associated in each case.

The Coordinate Measuring Machine (CMMs) are devices that make it possible to meet the previous requirements [5,6]. Said instruments allow us to obtain data in an indirect manner quickly and easily from pieces of different shapes and dimensions with maximum permissible errors (MPEs) that are reasonably compatible with the most demanding tolerances in the mechanical field (e.g., for the case of angular measurements in the range of a ±5''). Its degree of automation allows us to reduce times and hence costs associated with the measurements performed. These machines measure in a way that involves taking the coordinates of a set of points on the surface of an artefact and then combining them to evaluate the desired geometric feature. So a CMM measurement requires some processing of the combination of measured values to

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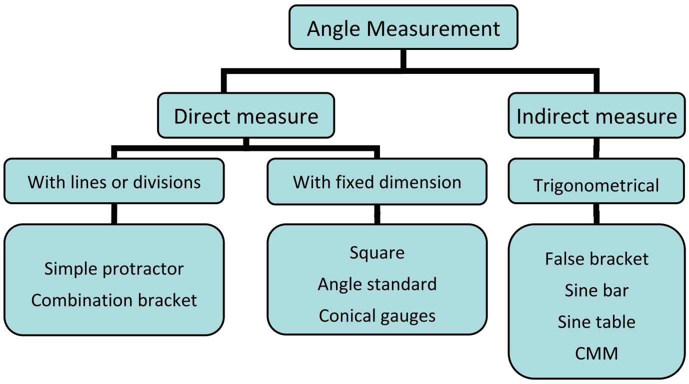

Fig. 1. Classification of methods for angles measurement and used instruments.

produce an estimate of the measurement [7,8]. Clearly then, the outputs from a CMM measurement will depend on the way in which this processing is performed (the algorithm), and the properties of the points chosen to sample the surface of the artefact [9]. Naturally, for critical measurands with strict tolerances, *ad hoc* instruments and methods with greater precision have been developed. The scientific literature contains numerous works that provide evidence of this [1,10–12].

The measurement uncertainty of the coordinate measuring machine has been determined by mathematical modeling, comparison, and performance test methods [7–9,13–15]. The mathematical modeling method involves the verification of CMM geometric errors to build a theoretical model and predict the uncertainty for any measurement made according to the model's assumptions [16].

Numerous studies in the field of coordinate measuring machine uncertainty have been conducted in the past. Wilhelm et al. [17] provided an excellent review of techniques developed to model and estimate the uncertainty of the coordinate measuring system. Schwenke et al. have developed a virtual CMM to aid in the evaluation of the CMM measurement uncertainty [18,19]. Likewise, another method of calculating the uncertainty associated with a measurement is described in the standard ISO 15530-3 2011 [7,8], which provides us with two methods based on the use of calibrated pieces or standards.

In this paper we discuss how the verification of the CMM affects the results of a measurement, and how the measurement uncertainty is a powerful tool for reflecting this. We do this by presenting an approach to determine, with the CMM, the angle measurement, formed by two perpendicular planes, and its associated uncertainty, using the Monte Carlo simulation method following the guidelines provided to us by Supplement 1 of the GUM [20] and employing the performance tests mentioned in ISO 10360-1 [21], ISO 10360-2 [22] and ISO-10360-5 [23].

In order to achieve what is stated above, we use two behavioral models for the CMM, which allow us to determine the uncertainty associated with the measurement, and also to study the errors of the CMM associated with orientation and length in work volume. Using these models, it is possible to evaluate the angle's value and its associated uncertainty, using the Monte Carlo Method [18,20,26].

The first model called "Linear statistical model behavior of CMM" [24], corrects the raw coordinates obtained by the CMM and takes into consideration the geometrical errors and the errors due to the CMM's dynamic behavior. The second, called "MITUTOYO model behavior of CMM" [25], is a method for statistical simulation with a strong correlation. Said correlation is verified among the coordinates of the measurement points, and decreases as the probing points become more distant.

Once the results obtained have been compared, we can ascertain which method provides a procedure for calculating uncertainty that is simple and reliable.

2. Measurement methodology

A case study was performed using a Moving Bridge CMM "TESA Micro-Hite® 3D" at the Dimensional Metrology Laboratory of Technical University of Madrid, with a field of measurement $X \times Y \times Z$ equal to 450 mm × 500 mm × 460 mm and with a resolution "R" equal to 1 µm.

The CMM was located in a temperature-controlled environment of 20 ± 1 °C. The part used for the study has been a steel angle gauge block with four angles with a nominal value equal to 90° marked with the letters *A*, *B*, *C*, and *D* (Fig. 2).

The values of the standard, certified by an accredited laboratory, are indicated below in Table 1.

In order to obtain indirectly the values of the standard's angles it is necessary to characterize the measurement planes of the angle gauge block taking 75 points in each plane, as shown in the schematic representation of Fig. 3. These points are characterized by the coordinates *x*, *y*, and *z*.

The angle gauge block measurement planes are located nearly parallel to the axes *X*, *Y*, *Z* of the CMM.

The measurement strategy for each plane has been as follows: the points have been distributed equally on three lines parallel to each other and perpendicular to the *Z* axis, as is shown in Fig. 3.

Once obtained the coordinates of the points, for each side, we proceed to the mathematical representation of the planes

$$ax + by + cz + 1 = 0 \quad (1)$$