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Evaluation of coordinate measurement uncertainty with use of virtual machine model based on Monte Carlo method

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ABSTRACT

Advances in modern manufacturing techniques implies more efficient production but also new tasks for coordinate metrology. The main of them is evaluation of accuracy of the measurement, because according to technological requirements, results of measurements are useful only when they are given with their accuracy. Currently used methods for uncertainty assessment are difficult and require knowledge and measuring experience. It is therefore important to implement correct and validated methods that will also be easy to implement and will not require broad metrological knowledge from the personnel. Presented here simulation method, based on Monte Carlo method is one of them. The article presents the conception, implementation and validation of this method.

1. Introduction

Developing production engineering implies more efficient production but also new tasks for coordinate metrology. Assessing of dimensional compliance with geometrical product specification (GPS) is becoming crucial task for the production engineering. Bearing in mind economic imperative, the danger of wrong decisions carry consequences that are observed as a wave of product complaints, especially in areas of automotive, domestic appliances and medical devices industries, etc. The importance here is given to the possibility of determining the accuracy of measurement, because according to technological requirements, results of measurements are useful only when they are given with their accuracy. In the case of coordinate measuring techniques (CMTs) it is a task particularly difficult and not always straightforward [1–3]. Therefore, users of this technique, as well as manufacturers of these measuring systems often overlook the problem of measurement accuracy giving in exchange the accuracy of measuring devices. This accuracy, is determined then, for the realization of the selected task as a measurement of distance (that is dimensionally similar to the dimensions of the measured object) and is given as the maximum permissible error (MPE). Thus defined, the accuracy is significantly different (sometimes twice!) from the accuracy of the real measuring task, and may lead to bad decisions in the determination of compliance with the specifications of the product [2,4–9].

It is therefore important to implement into practice of uncertainty estimation of coordinate measurement new, correct and metrologically validated methods. Currently used, are difficult and require knowledge and experience in the field of measurement [10,11]. It cause, that they are used only in the best laboratories. Considering the level of metrological expertise, their implementation is most advanced in the German industry, which is connected with the studies issued by VDI [12]. Analyzing the problem of assessing the accuracy of coordinate measurements, it can be divided into two main methods, substitution method and multiple measurement method – the best described and documented by normative establishments [10]. Descrip tions of their use can be found in [13–15]. Another group

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consists of analytical methods based on calculation of uncertainty of indirect measurement using the geometrical relations between them, performed similarly to the classical estimation of uncertainty of measurement done i.e. by micrometer. These methods are based on studies of Pressel and Hageney [16], Hernla [17,18] and others [19,20]. However, these methods are difficult to use in practice and they present approach similar to methods based on expert knowledge [10]. In recent years, the new methods called simulative methods were presented [10,12,15,21–28]. In practice, these methods require development of so-called virtual measuring machines used to assess on-line accuracy of measurement. Two concepts are dominating here, the first one – identification of sources of CMM errors (including kinematic errors) and errors of the probe head (as examples of this methods PTB Novel method [29,30] and analytical method invented in Cracow University of Technology [27] could be taken) and the second concept – developed by Sladek, based on a Matrix Method (MM) – identification of errors at selected reference points in machine measuring area and construction of CMM model using artificial neural networks [27]. Both concepts are continually developed. Area of modeled systems is expanded i.e. by measuring arms. MM is also implemented on large scale machines, here, a possibility of usage of LaserTracer (LT) and LaserTracker for the construction of reference points grid was noticed.

The consequence of the growth of industrial requirements regarding the accuracy of the Coordinate Measuring Systems (CMSs) is also improvement of error-correction software systems. This limits the participation of a systematic part of error, which shifts the problem of modeling of accuracy of coordinate systems in the area of residual errors and random errors [31]. Such a view about the importance of participation of random errors in uncertainty of measurements was expressed by Lotze when calculating it for the 2D measurements [32–34], he also claimed that it is possible to compensate systematic part of errors. The research on random part of accuracy of the measurement was realized by Sladek who focused on determining the area of uncertainty of spatial measurements in the shape of an ellipsoid [27]. So the new, effective methods of determination of the random part of errors were investigated in Laboratory of Coordinate Metrology in Cracow University of Technology. First experiences resulted in papers written by authors concerning the usage of Monte Carlo methods (MCMs) [14,15,25,26,35] – they are related to the substitution and multi-position methods, modeling of probe head errors and errors caused by thermal effects. Summing up these experiences, a new concept of a simulation system based on the use of Monte Carlo method was developed. Furthermore, the works under usage of this method in modeling of the selected coordinate measurement errors [1,2,23,36–40] were additional inspiration.

2. Conception of virtual machine model based on MCM

Nowadays, in the typical measuring machines the systematic errors are compensated for the kinematic system of CMM through use of CAA correction matrix, for probe head – an example of dynamic error correction matrix could be given, as well as for components originating from the environmental influences exemplified by the temperature correction (e.g. ACTIV). Therefore, the attempt was made to transfer the problem of modeling of accuracy of the CMM to the field of residual errors that remain uncompensated. This field includes random errors and systematic errors for which correction is not profitable or impossible. These errors can be treated as errors of random nature. Given the above facts, it is assumed that the presented simulative model is developed for modern metrological systems, equipped with a full, active error compensation. The described model of CMM will consist of two basic modules:

– module that simulates the residual and random errors dependent on kinematic system of CMM,
– module that simulates the workings of the probe head.

A key task in developing a virtual model of the measuring machine is to describe a measuring volume of CMM by a grid of reference points (Fig. 1).

Fig. 1 shows a grid of reference points, residual errors and the method of their identification. It is possible to build the first module of CMM model by describing each point on the grid of reference points with the probability distribution (the best in this application seems to be the *t* distribution) with which it is reproduced on a machine. But it is necessary to have a system that would allow experimental determination of distribution of errors in reference points, with the required accuracy. This is a key issue in the implementation of described concept. Currently, only LaserTracer (LT) meets these requirements. Cooperation between LT and CMM was presented in Fig. 2.

The use of LT, allows to determine the probability of reproduction of the measuring point and the designation of these probability distributions, showing the distribution of residual errors for the entire volume of CMM.

Having described the model of grid of probability distributions, the next problem has to be solved, which is obtaining the values between the nods of grid. It is obvious that during the measurement, majority of the measuring points are different than nodes of grid. It is therefore necessary to adopt a strategy of compaction of grid in such a way that it would be possible to simulate (with MCM) reaching of any point by the machine, anywhere in the measuring space. There are several ways to do this, for example method that uses a neural network for this purpose. The authors developed a method of compaction based on usage of a b-spline curves in conjunction with the nearest-neighbor method, which will be implemented using Monte Carlo simulations.

The second module forming part of the described measuring virtual machine is a module responsible for the simulation of probe head of CMM. To describe this system Probe Errors Function (PEF) has been used. The module gets the values of the individual errors of the PEF through Monte Carlo simulations.

Probe head was described by PEF [27,35]. This function is usually defined as follows. For all the possible directions of deflections of head, the error of probe head takes form of