Optimization of probe head errors model used in Virtual CMM systems

A. Gąska[1], W. Harmatys[1], P. Gąska[1], M. Gruza[1], T. Mathia[2], J. Sładek[1]

[1]*Laboratory of Coordinate Metrology, Cracow University of Technology, Poland*

[2]*Laboratoire de Tribologie et Dynamiques des systèmes, EcoleCentrale de Lyon, France*

Abstract

The development of manufacturing techniques and, in particular, increasing requirements on the accuracy of products, delineates new challenges for coordinate metrology. Currently used measuring systems are getting more accurate while measurement duration is decreasing. However, fast and precise estimation of measurement uncertainty, which is a measure of its accuracy, is still problematic. The so called Virtual Models of measuring machines are being developed in order to determine the uncertainty of a particular measurement task in quasi-real time. Such models typically consist of modules which are responsible for simulating a specific source of uncertainty. In the case of CMMs one of the most difficult tasks is to create a model which simulates errors arising from the operation of probing systems. In this paper authors describe such a model, which was developed in Laboratory of Coordinate Metrology in Cracow University of Technology, as well as an attempt to optimize its operation.

1 Introduction

Estimation of measurement uncertainty for CMMs is a challenging task, especially in the case of industrial conditions, where it remains largely unsolved. The usage of classical methods such as the substitution method and the multiple measurement method [1,2] require knowledge and experience, but more importantly they are based on multiple measurements of measured object and standards. For industrial measurements, their use may result in downtimes and generate additional costs. This incentives the development of simulation methods of uncertainty estimation, which are free of mentioned drawbacks. Operation of these methods is connected with the development of the so-called

Virtual machines, which allow multiple on-line simulation of measuring task. Results obtained in such a way can be then utilized during uncertainty estimation for example using methods of statistical analysis. Therefore, the main problem, is the development of adequate methodology for CMM examination which would give empirical information on errors that can occur during measurement on particular CMM specimens, especially insight into errors connected with machine kinematics and probing system errors. At present, there are several working models of Virtual CMMs, such as those developed in PTB [3,4] and Laboratory of Coordinate Metrology at the Cracow University of Technology (LCM) [5], however, existing solutions are being used, almost exclusively in research centres and calibration laboratories. There are at least few reasons for this state of affairs. Problems with ensuring constant environmental conditions in typical industrial applications is probably the most important issue. Surely, further research on the impact of ambient condition variation on the correctness of the simulation model operation is needed. Condition in stability also affects CMM testing procedures which should be fast enough to reduce the possible ambient influences to a minimum. This argument is also connected with economic reasons. Existing simulation methods often use multiple measurements of hole or ball plate standards in different locations of CMM. Such an approach may lead to the exclusion of the machine from its normal work even for a few days, which is hard to accept in an industrial condition, especially assuming that the machine operation should be checked frequently. Efforts to create the virtual machine that can be successfully implemented in industrial practice are currently being taken at LCM. The developed model called the Virtual MCM PK [6] is based on the Monte Carlo method, and it consists of two main modules: one responsible for simulation of errors connected with probing system and the second, which simulates errors arising from CMM kinematics. In this paper, authors present module for probing system error simulations. First, accuracy analysis of probing system is presented. Then the working principle of the model is described, as well as the methodology for acquisition of data needed for its operation. Next, authors describe an attempt to optimize the model for industrial application. Conclusions and recommendations for further research appear at the end.

2 Probing system errors

The measuring head is a crucial component of any CMM, because it provides the connection between the machine and the measured element [7]. Preparation of any probing system accuracy model should be preceded by an analysis which includes probing systems working principle as well as sources of errors which may occur during the probing process. Although basically probe heads can be divided into two groups based on how they operate: measuring heads and touch-trigger heads [7-10], the probing process may generally be presented in the form of a simple scheme (Fig. 1).

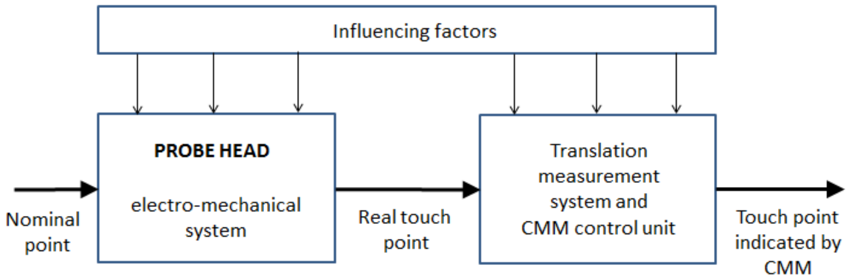


Figure 1: Scheme of probing process

Ideally, the coordinates of probing points which are indicated by the machine, should be the same as the actual point of contact of tip ball with measuring surface. The difference between these coordinates can be regarded as a total error of the probe head [10], which is caused by a number of factors. The first group of factors is connected with interaction of tip ball with the measured surface. This group includes, according to [10]:
x_r– measured surface condition (shape deviations, roughness)
x_{cd} – deformations of tip ball which occur during contact process
x_d – stylus deformation under the measurement force
x_{sd} – influence of tip ball shape deviations
the second group of factors is related to the probe head construction:
x_s – the switching path (pretravel, lobing) for touch-trigger probe heads
x_i – non-linearity and differences in characteristics of inductive transducers for measuring probe heads, depending on the direction of probing (*u*,*v*,*w*)
x_n – errors caused by uneven loading of the head (electronic balancing system)
x_c– change in the sensitivity of the transducers for probe heads with variable characteristics
x_{zk} – errors related to the change of the direction of probe head operation
Therefore, the total probe head error (*PE*) is defined as the sum of the subsequent components and can be written, for example for probing in direction of *x*-axis of CMM, using the following equation (1):

$$PE_x = x_r + x_{cd} + x_{sd} + x_s + x_i + x_n + x_c + x_{zk} \tag{1}$$

As the tip ball may approach a point of contact from any direction, the error of the probe head according to [10] could be summarized by the function of probe head errors (*PE 2D*), which links an probe head errors with the angle (α) of probe deflection:

$$PE\ 2D = (\alpha, PE) \tag{2}$$

Function (2) described in this way might be treated as a two-dimensional characteristic of the probe head. However, modern CMMs, perform measurements using 3 directional approach on measured surface so complete description of the probe head behaviour should use at least two tip deflection angles. Deflection can then be described in a manner similar to the definition of the coordinates in a spherical coordinate system. The probing system error model presented in this paper uses such a solution, which allows the description of probe head errors in three-dimensional space. The final probe head error function takes the following form (3):

$$FPE = (\alpha,\beta, PE) \tag{3}$$

3 Probing system errors model

Discussed probing system error model is a component of virtual CMM which enables multiple simulation of measurement of each measuring point. The coordinates of the points obtained in this way are determined by taking into account the residual errors of the machine kinematics, and the errors arising due to probe head operation. The main idea of the probing system error module is to link the errors of the probe head with the probing direction expressed by the direction cosines (n_x, n_y, n_z). Data required for a module is obtained experimentally through the measurements of a standard sphere. Multiple repetition of the measurement sequence allows to gather statistically representative sample describing error function in dependence on the angles of probe deflection (α, β). Evenly distributed measuring points whose location relates to the changes in probe deflection, create reference grid nodes. The mean form error in each point and its standard deviation can be determined and then used as a representation of systematic error (mean) and random error (standard deviation) of probe error depending on (α, β). Then for each grid node a Student's t-distribution of the parameters (x, σ, v) is assigned for each pair of deflection angles, where, x represents the mean value of the distribution, σ is the standard deviation, v represents degrees of freedom. For the points which constitute grid nodes, x is taken directly from measurements as well as σ expressed by standard deviation, while v is equal to the number of measurements taken during identification experiment minus 1. For deflection angles which have not been tested experimentally, parameters values are obtained using bilinear interpolation adapted for spherical system.

The value of the probe head error *PE* is simulated on the basis of assigned parameters (x, σ, v) using the Monte Carlo Method. *PE* is the vector of the direction which is consistent with the probing direction and the sense of direction depending on the value of the error. Therefore, at the end the module calculates the changes in the position of the simulated measuring point caused by the functioning of the probe head for each axis of the machine datum system (pe_x, pe_y, pe_z) using following formulas (4):

$$\begin{aligned} pe_x &= FPE \cdot n_x \\ pe_y &= FPE \cdot n_y \\ pe_z &= FPE \cdot n_z \end{aligned} \tag{4}$$

To ensure proper functioning of the model, the spherical standard used for experiments has to meet several requirements. It's form deviation should be less than 0.2 * P_{FTU} defined according to [11], and sphere diameter should be small enough so that the influence of machine kinematics on the measurement results can be regarded as insignificant (diameter of sphere should be less than 30 mm). Also, the position in measuring volume in which the standard would be measured, should be chosen precisely, as it could have considerable impact on the measurement results. The Virtual MCM PK was prepared for CMMs, that uses kinematic error correction (CAA matrix) so the main investigation in field of machine kinematics should focus on residual errors, that means, errors which cannot be compensated or their compensation would be inviable. Therefore it can be assumed that in order to minimize their impact on the measurements, the spherical standard ought to be placed in such position in machine volume so that the sum of residual errors for all sampling points is the smallest. Another important element is the appropriate distribution of points on the surface of the sphere. A grid of reference points which covers the upper hemisphere of a standard sphere, is created by uniformly increasing the α and β angles, where alpha varies between 0° and 360°, and beta changes within 0° and 90°. While a larger number of points, provides a more accurate representation of reality, it increases the measurement time. Therefore, researches should be taken on the model optimization, so the experimental procedure can be as fast as possible without loss of accuracy.

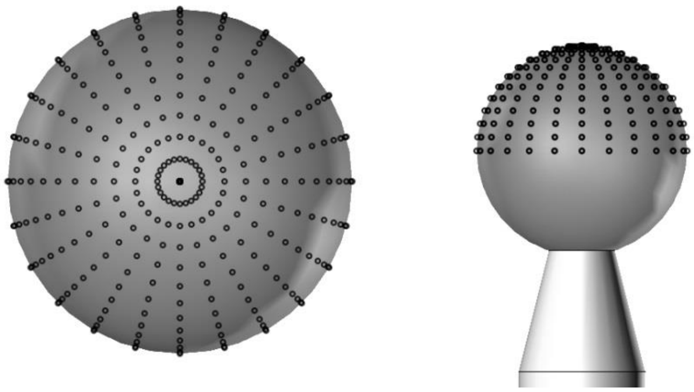
4 Performed experiment and results

Successful usage of the presented model in the case of measuring probe heads has been confirmed, and described in [12]. In this case, the model was based on 163 reference points. The authors decided to check the correctness of model's operation for touch-trigger probe heads, which are more commonly used in the industry.

Measurements described in this paper were performed on the Zeiss WMM850S machine, located in the LCM at the Cracow University of Technology. Before machine was brought to the university and retrofitted, it had been used in the industry for many years, so it is well suited to the research purpose. The measuring volume of this machine is 1000\1200\500 mm. The temperature during measurements was at the level of 19,7°C ± 0,4 °C. The machine was equipped with Renishaw PH10 with TP20 probe. For all the measurements, the same stylus length of 20 mm and tip ball diameter of 3 mm combination was used. During measurements, the probe head was oriented vertically along the machine *z*-axis. The standard sphere with diameter of 24,9946 mm, which meets requirements pointed out in a previous section, was mounted in the machine volume so that the kinematic errors influence was reduced to minimum.

As the touch trigger probes are considered to be less accurate than measuring probes, it was decided to perform the initial measurements using twice the amount of points than in the case described in [12]. The α angle was changed by

15° degrees, and the β angle by 7.5°. It gave a total of 289 measuring points distributed evenly over the surface of the upper hemisphere of the standard (Fig. 2). Measurements were performed ten times. Each time the *FPE* was determined for each point.



a) b)

Figure 2: Grid of 289 reference points a) top view; b) front view

Obtained measurement results allow to link each node of reference grid with the mean radial error and the corresponding standard deviation. Table 1 presents data obtained for the first two levels of reference grid.

Table1: The results of measurements of spherical standard for angles α Є <0; 340>, β Є <0; 7,5>. The mean error (x) and standard deviation (σ) in mm, α and β in °

α	β	x	σ	α	β	x	σ
0	0	0,00107	0,00014	0	7,5	0,00063	0,00030
15	0	0,00073	0,00024	15	7,5	0,00079	0,00023
30	0	0,00099	0,00035	30	7,5	0,00011	0,00016
45	0	-0,00041	0,00022	45	7,5	0,00003	0,00017
60	0	0,00017	0,00039	60	7,5	0,00109	0,00043
75	0	0,00003	0,00016	75	7,5	-0,00022	0,00012
90	0	0,00029	0,00034	90	7,5	-0,00047	0,00021
105	0	0,00031	0,00018	105	7,5	-0,00066	0,00025
120	0	0,00070	0,00035	120	7,5	0,00027	0,00024
135	0	-0,00010	0,00036	135	7,5	-0,00045	0,00028
150	0	0,00004	0,00023	150	7,5	0,00047	0,00018
165	0	0,00062	0,00026	165	7,5	0,00097	0,00031
180	0	0,00049	0,00039	180	7,5	-0,00013	0,00020
195	0	0,00055	0,00029	195	7,5	0,00065	0,00017
210	0	0,00108	0,00023	210	7,5	0,00107	0,00020
225	0	0,00064	0,00026	225	7,5	0,00085	0,00019
240	0	0,00003	0,00019	240	7,5	0,00087	0,00031
255	0	0,00061	0,00021	255	7,5	0,00053	0,00023
270	0	-0,00066	0,00021	270	7,5	-0,00055	0,00018

285	0	-0,00073	0,00023	285	7,5	-0,00060	0,00032
300	0	0,00070	0,00038	300	7,5	-0,00081	0,00034
315	0	0,00062	0,00020	315	7,5	0,00028	0,00034
330	0	0,00071	0,00018	330	7,5	0,00069	0,00027
345	0	0,00102	0,00019	345	7,5	0,00086	0,00029

The data grouped in a way showed in Table1 define the verifying data set for the models based on a smaller number of points. Therefore, three such models have been developed: first model included 163 reference points, where α changes by 20°, β by 10°; the second model was based on 82 reference points, where α changes by 40°, β by 10°; the last model consisted of 46 reference points, where α changes by 40°, β by 20°.The measuring sequence was repeated 10 times for all the models, without changing the position of standard or other measurement settings. Then, using each model, errors values were simulated for 289 points that corresponds to the points from the verifying data set. So obtained simulated values could be compared with data gathered empirically. The *FPE* value was considered correctly simulated if it differed from the corresponding value obtained experimentally by not more than ± 3 * σ (standard deviation) which were assigned to the considered point. Table 2 shows the number of points which do not comply with this requirement per each model.

Table2: The number of faulty simulated points per model

Number of points used in model	Number of faulty simulated points (out of 289 points, which were simulated)
163	5
82	17
46	10

Figures 3 - 6 present *PE* values in relation to α, obtained through measurements (in case of 289 points) and simulation (using developed models) for different values of β, respectively, $\beta = 0°$, $\beta = 30°$, $\beta = 60°$, $\beta = 82{,}5°$.

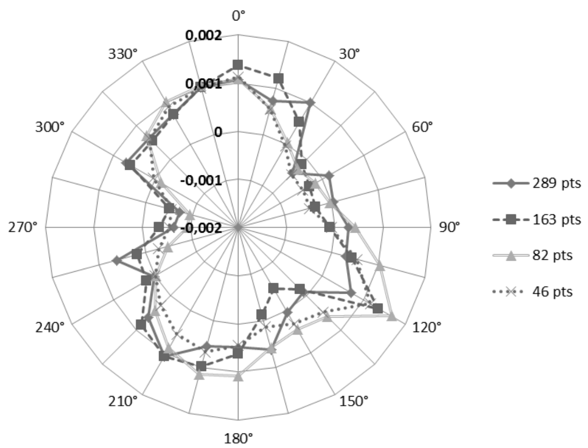


Figure 3: *PE* values (in mm)dependence of α (in °), β = 0°

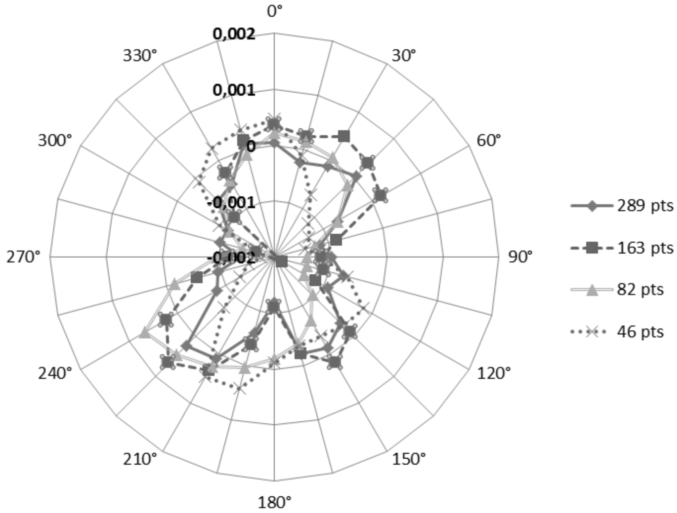


Figure 4: *PE* values (in mm) in dependence of α (in °), β = 30°

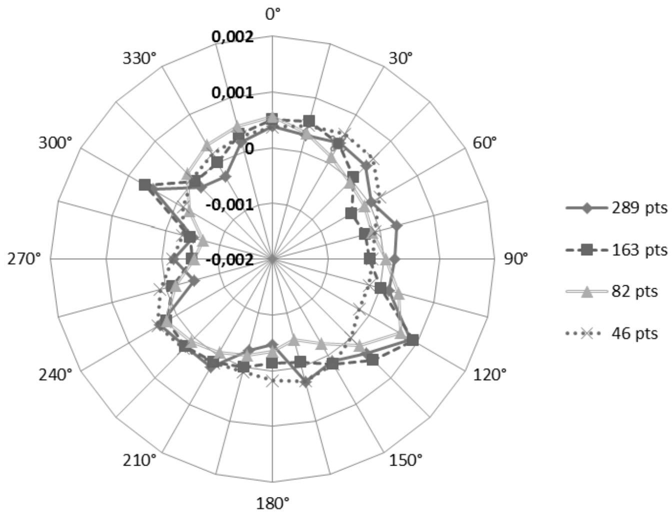


Figure 5: *PE* values (in mm) in dependence of α (in °), β = 60°

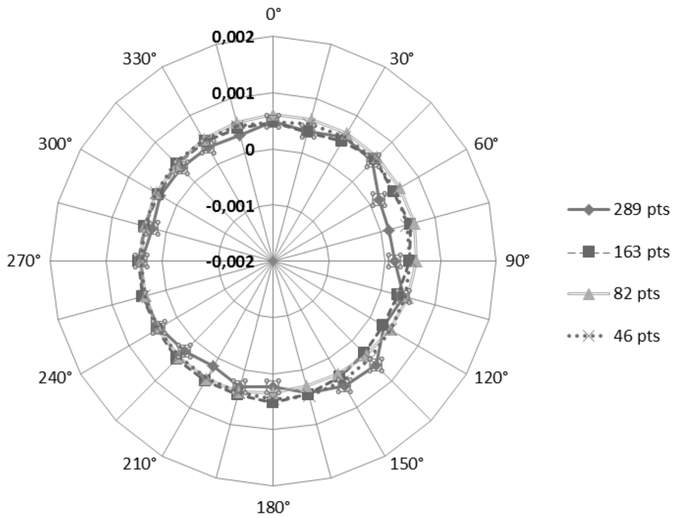


Figure 6: *PE* values (in mm) in dependence of α (in °), β = 82,5°

5 Conclusions

Presented results show that the developed models reflect the actual functioning of the probing system in a satisfactory manner. Especially, the last of the prepared models seems to have a chance of being applied to industrial conditions, because it allows for frequent monitoring of the probe head operation. Presented experiment should be repeated for all styluses used during measurements on considered machine in order to create probe head errors model for all of them. This is why it is so important to reduce the number of reference points on which the model would be based. If the number of points that has to be measured is relatively small, the data needed for the model functioning could be collected once or twice a month, which would contribute to the better performance of the virtual machine.

Of course, the model still requires further improvements. Measurements were made only with the stylus orientated along the z-axis. In the case of articulated probe heads the influence of stylus orientation on a PE should be checked. Also, the problem of standard sphere and tip ball form errors influence remains unsolved. From the practical point of view, the model presented in this paper should be constructed each time the considered probe is qualified, as after the qualification of the probe, the characteristics connected with the effective probe radius could be slightly changed, what may influence the PE. It is also true that the standard used during described researches is characterized by the form errors, whose values could be regarded as negligible from the perspective of studies purpose. However, during the measurement, disrupting interactions between the spherical standard surface and measuring ball surface which could distort the results may occur.

To sum it up, presented model, based on the Monte Carlo method and multiple measurements of spherical standard prove to operate correctly also in case of touch-trigger probes. The simplicity of test procedure should allow its application in industry where it could contribute to a more throughout uncertainty assessment of the coordinate measurement.

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