Comparison of different interpolation methods, used for modelling of probe heads errors

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Abstract. Virtual CMMs allow user to estimate the uncertainty of measurement using multiple measurement simulations. Most often the Virtual CMMs consist of several modules responsible for main errors sources modelling. These modules utilizes different interpolation methods in order to model the error values in any point in machine's measuring volume. Thus the proper functioning of Virtual CMM depends on chosen interpolation method. Experiment described in this paper is aimed to assess which interpolation method would give the best results for newly developed probe head errors model for the articulated probe heads.

1. Introduction

One of the most important demands formulated by the industry is the reduction of the quality control duration. To meet this requirement new measuring methods are developed while the acclaimed ones are constantly improved. This trend is present also in Coordinate Measuring Technique. One of the latest solution is usage of articulated heads in so-called five-axis measuring systems, which enable measurements to be performed using rotational movements of head with limited influence of machine’s kinematics. Such approach significantly reduce the measurement duration especially in case of circular features measurements.

Of course development in field of Coordinate Metrology entails a series of challenges and problems. Probably the most important one is question about accuracy of newly developed systems. The expression of measurement uncertainty, which is a quantitative measure of the measurement accuracy, in case of Coordinate Measuring Technique is never a simple task [1-5]. Users often try to omit this problem, giving the information of machine maximum permissible errors, but such approach is questionable [3]. The problem become more urgent with continuous miniaturization of measured elements and with tolerances getting narrower. The so-called classical methods of CMM uncertainty estimation are based on multiple measurements of standards. Additionally they require experienced stuff which assure that measurement would be performed in accordance with the guidelines, and the results would be correctly analysed. This is why various research institutions through the world work on simulative methods of measurement uncertainty estimation which are free of mentioned drawbacks [3, 6-8]. These solutions most often utilize the numerical models of machine accuracy called Virtual CMMs. Such models are used for multiple simulations of measurement process. Then the measurement uncertainty can be estimated using basic statistical analysis. The Virtual CMM should model the impact of main uncertainty sources on the measurement result. Most of currently available Virtual CMMs consist of at least two modules, responsible for kinematic errors simulation and for probe head errors modelling. Each module is based on the empirically gathered information about the
errors distribution. Developed models use different experiments to assess the errors characteristics. Often the experiments are based on material standard measurements. Of course it is impossible to check machine functioning in all points in machines measuring volume so the errors are determined only in limited number of points and for all points not included in experiments the values of errors are interpolated. It is clear then that functioning of the Virtual CMM is strongly dependent on chosen interpolation method. Then it is significant issue to determine which interpolation method would be the best for the newly developed model of probe head errors for articulated probe heads used in five-axis measuring systems. Three methods was chosen for experiment: trilinear interpolation, nearest neighbour method and artificial neural networks.

2. Newly developed simulative model
The model of probe head errors for articulated probe heads used in five-axis systems is based on the PEF (Probe Error Function). In this approach the probe head error is treated as a sum of many components [3], among others: errors connected with tip ball shape deviations, stylus deformation under the measuring force, deformations of ball during contact process, the pretravel, differences in sensitivity of the transducers etc. Because The probe error depends strongly on the approach direction on the measured point, the PEF can be formulated, which carries information about Probe Error value in relation to approach direction. The probe head discussed in this article can rotate about two mutually perpendicular axes named A and B which are marked in figure 1.

![Figure 1. The articulated probe head used in five-axis systems with marked axes of revolution A and B.](image1)

![Figure 2. The verification measurements in one of chosen ring positions.](image2)

Such probe heads allow to perform measurements using rotational movements of a head. Rotation about the A axis is limited and it can be realized in range (-105°, 105°), while rotation about B axis is unlimited. The probe head is oriented vertically when A and B values equal to 0°. The experiment was conducted to check if the accuracy of the head depends on its angular orientation. For this purpose the standard ring of 20 mm diameter was measured with different orientation of probe head. The arrangement of standard was changed using swivel and tilting vise and it was set in such a way that axis of reference ring would be align parallel to the actual probe head orientation. Measurement setup is presented at figure 2. The PEF was determined for 24 positions which can be defined using the A and B angles. The A angle changes at 30° in range between 0° and 90°, while the B changes at 60° in range between -120° and 180°. The measurements were performed on the Zeiss WMM850S machine, located in the air-conditioned room at Laboratory of Coordinate Metrology. During whole experiment the ambient conditions were monitored and the temperature varied between 19,3°C – 20,7 °C. The machine measuring volume is 1000×1200×500 mm. During the measurements the machine was equipped with Renishaw PH20 probe head, with touch trigger TP20 probe. The obtained results
indicates that PEF significantly varies with a change in orientation of the head. On the basis of obtained results it can be assumed that values of A and B which are used during point coordinates measurements can be the input values for newly developed model. However because the certain probe orientation can be achieved with the limitless number of approach directions the third input should be used, which would give the information about used approach vector. This information can be obtained using \( \alpha \) which is defined on the plane perpendicular to the probe when it is oriented using A and B angular positions, and has its zero indication in the direction in which the probe rotates along the A axis in the positive direction. Finally the PEF can be written as equation (1):

\[
PEF = PE(\alpha, A, B) \tag{1}
\]

where: \( \alpha \) – angle in which probe is working, A – the angle around the horizontal axis of probe head, B – the angle around the vertical axis of probe head, PE – Probe Error

The model is based on the results obtained during measurements described above. For all measuring points in each of chosen ring positions, the mean values of PEF and the standard deviation were calculated. Then the scaled and shifted t-distributions was assigned to each point, with parameters \((x, s, \nu)\), where \( x \) is the mean radial PE, \( s \) is the standard deviation associated to \( x \) and \( \nu \) is the number of degrees of freedom equalled to number of measurements minus one. These probability density functions are used by Monte Carlo Method during errors simulation.

3. Comparison of different methods of interpolation used for probe head errors modelling

In this section the three different interpolation methods will be compared: the trilinear interpolation, nearest neighbour method and the artificial neural networks. The trilinear interpolation needs values in eight nodes to determine the values for considered point. Firstly the surrounding values of A and B angles are found, then for each of chosen four nodes the two nearest values for given \( \alpha \) values are searched and the linear interpolation is applied in three steps for each input parameter. In case of nearest neighbour interpolation the closest A and B values included in reference grid are searched for model inputs. Then the PE value is taken directly from closests \( \alpha \) value for chosen position. The third of compared method utilizes artificial neural network. The structure of the network was determined experimentally by observing the network behaviour for various settings. Best results were obtained for three layer neural network with back-propagation and the various activation functions. The first and third layers utilizes three neurons while second layer uses ten neurons.

\[\text{Figure 3. The comparison of experimentally and simulative obtained results for A equal 30° and B equal to -100°.}\]
In order to check how they interpolate the values of PEF for any chosen input values, the additional experiment has to be taken. The reference ring used in measurements described in section 2, should be measured in additional positions that are situated between positions included in the model. The results obtained empirically can be compared with results given by different interpolation method. Figure 3 shows the results obtained for verification position for A equal to 30° and B equal to -100°. Then the interpolation errors understood as the absolute value of difference between the measured value and simulation result can be calculated for each position included in experiment. Table 1 shows the results obtained for different methods for positions included in verification experiment.

| Interpolation method          | Maximal Interpolation Error (μm) | Mean Interpolation Error (μm) |
|------------------------------|----------------------------------|------------------------------|
| Trilinear                    | 0.444                            | 0.092                        |
| Nearest Neighbour            | 1.117                            | 0.159                        |
| Neural Network               | 0.447                            | 0.152                        |

4. Conclusions
Results presented in table 1 proves that selection of proper interpolation method for probe head errors model is important task and should be considered during model preparation. This selection can be done by comparing the experimentally obtained data with results given by the simulative model working with chosen interpolation method. On the basis of obtained results it can be concluded that trilinear interpolation provided the best results. Both the maximum interpolation error and mean interpolation error values were smallest in case of this method. The nearest neighbour method and interpolation with artificial neural networks gave similar results, however additional conclusions can be drawn for these methods. The nearest neighbour interpolation is susceptible to occurrence of single peaks which can significantly differ from majority of values. In such case those peaks are almost directly transferred to the modelled output. At the same time it is worth to mention that distribution of PEF given by nearest neighbour interpolation is congruent with distributions obtained through measuremnt. The last tested method utilized artificial neural networks. Development of the network is largely dependent on the experience of the person responsible for this task, additionally it can be observed that the PEF distribution given by the model that uses artificial neural networks averaged the experimentally distributions given by measurements. Although maximal interpolation error obtained with artificial neural networks was noticeably smaller than once observed with nearest neighbour method, it appears that the artificial neural network is the least suitable method for modelling probe head error.

5. References
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