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A NEURAL NETWORK MODEL 0OF A CMM APPLIED FOR MEASUREMENT ACCURACY ASSESSMENT

J. Sladek
Production Engineering Institute - Cracow University of Technology
Al. Jana Paw³a II 37, PL-31-864 Krakow, Poland

Abstract: The paper presents research on CMM virtual modelling applied for assessment of measurement accuracy and a method of CMM errors identification. The idea of the proposed method of error estimation is based on the measurement of a workpiece plate (hole or ball), placed in the CMM measuring area in such way, that reference points compose a spatial grid. The difference between co-ordinates of particular shape elements midpoints obtained from workpiece calibration and the co-ordinates given by the CMM creates the error grid. This grid is a basis for a matrix method of CMM error identification. The identification matrix corresponds to the reference points distribution. The matrix model for the CMM error identification is composed of two component parts: one - CMM errors depending on the position in the measuring area of the tested machine and the other - independent of this position. An idea of a virtual model is based on artificial neural networks. Results of comparative research into various virtual models of measuring machines have been discussed.

Keywords: CMM, neural network, virtual model

1 INTRODUCTION

Application of co-ordinate measuring machines (CMMs) in modern systems of quality assurance has to meet the basic requirement, i.e. the assessment of measurement accuracy. Both ISO9000 standards, and even stricter QS9000 system impose such requirement. It is then necessary to identify the accuracy of CMM itself. The concept of CMM accuracy assessment now is based on inspection procedure based on the measurement of length. The result of CMM assessment on the basis of length measurement is not sufficient for the given measurement accuracy evaluation (except simple tasks, like length measurement). So far there have been practically only two methods: by analysis of component errors or by comparison. However, CMM users claim that neither of these methods is effective in industrial practice [1,5]. From the literature [1,3,4,5,6] it follows that the problem of accuracy assessment for any measurement by means of CMM can be solved effectively on the basis of measurement simulation and calculating its errors by using a virtual copy of the given CMM. The research on these problems was started at the Cracow University of Technology in mid-eighties within CPBP 02.20 frame [2], however the problem that remained to be solved satisfactorily was identification, by experiment, of total error components, geometrical errors in particular. Only the method, worked out by Physikalisch Technische Bundesantalt - Braunschweig, by means of ball or hole plates made it possible to effectively use the idea of virtual machine [5]. Following this, a computer model of a virtual CMM was constructed at the Cracow University of Technology [1]. However, in view of measurement error assessment and choice of most efficient measurement strategy, the CMM virtual models mentioned above have a significant drawback, i.e. the errors have to be identified and assessed for each particular source. It is a complicated approach and needs extensive experience [1,5]. It was also stated that what should be searched for is error vectors for a point treated globally, without identifying the value for the components, e.g. geometrical. The research on new CMM virtual modelling method has resulted in a concept of the application of neural networks [6].

2 MATRIX METHOD OF CMM ACCURACY IDENTIFICATION

On the basis of a theoretical model described in [6] formulated was the CMM accuracy identification method. The concept of a method based on determination of accuracy mapping for an assumed set of reference points built in a form of a regular network is of the original nature. Fundamental for this method is measuring of a plate (hole or ball type) standard situated in CMM measuring space in such way as to create a three-dimensional reference points network with the dimensions and grid pertinent to the applied standard, as presented in Fig.1.

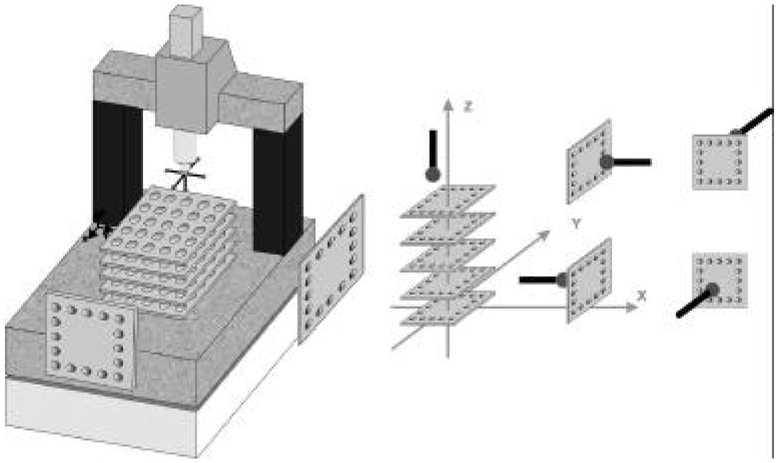

Figure 1. Practised positions of a model plate while creating the CMM error identification matrix

The difference between centres of the particular profile elements obtained as a result of calibration of a standard and centres indicated by CMM test piece generates a three-dimensional errors network, on which based is matrix method of CMM error identification [6]. Identification matrix is relevant to the reference points distribution. Furthermore, it is a sum of two components: one connected with CMM errors dependent on the position in a tested machine measurement space, and the other independent from such position. The former is mainly influenced by the position error vector $\boldsymbol{P_p}$ (depending on kinematics and errors of displacements measurement systems) whereas the other is influenced by errors vector of a probe $\boldsymbol{P_g}$ (systematic and random). In formulating of a summary model an assumption has been taken into account that for the occurrence of random errors responsible is greater part a measuring head. In the light of a years-long research such assumption is allowable [1,2], as well as assumptions of minimisation of thermal influences. As a result of operating of a model so created, we can generate a set (identified in a control area) of measurement points reproducibility errors vectors $\boldsymbol{P_a}$, which outline a matrix model of CMM errors identification, as presented in equation (2) This relation is mathematically described by equation (1) Now, if by application of the appropriate measurement strategy we can minimise influence of head errors (FBG$\Rightarrow$ min), while realising measurement in the particular points of reference (Fig.1), we shall practically determine error $\boldsymbol{P_p}$,, according to equation (3). So calculated values of errors in the particular points of reference allow to determine area of border errors for the particular identification surfaces. Then, after the analysis of obtained border values for all surfaces we reckoned the range of border errors for $\boldsymbol{P_p}$ for the whole control surface (cube). We calculate head errors as mentioned above for every probing point separately, defining head errors function *FBG (a)*, according to equation (4)

$$\overline{P}a = \left(\overline{P}p + \overline{P}g\right) = \overline{P}w - \overline{P}m \tag{1}$$

The method of notation of identification matrix is based on o 13 control positions of sphere (or hole) plate, when out of this 13 positions, 5 are parallel to the surface XY and each situated apart from the other by the section equal to the distance between the plate's balls (or holes), other 4 positions parallel to the surface XZ and 4 positions parallel to YZ, all those 8 located in the middle of the distance between the plate's balls (or holes), situated horizontally (surface XY) (Fig 1).

$$\begin{bmatrix} \overline{P}_{a(1,1,1,l)} & & \\ & \ddots & \\ & & \overline{P}_{a(9,1,5,l)} \end{bmatrix} = \begin{bmatrix} \overline{P}_{w(11,1,1,l)} & & \\ & \ddots & \\ & & \overline{P}_{w(9,1,5,l)} \end{bmatrix} - \begin{bmatrix} \overline{P}_{m(11,1,1,l)} & & \\ & \ddots & \\ & & \overline{P}_{m(9,1,5,l)} \end{bmatrix} \tag{2}$$

where: *i,j = 1...9 ,k = 1...5, l = 1...3*

$\overline{P}_{m(i'j'k1)}, \overline{P}_{m(i'j'k2)}, \overline{P}_{m(i'j'k3)}$ – coordinates of a $P_{i,jk}$ –th reference point, indicated by the machine

$\overline{P}_{w(i'j'k1)}, \overline{P}_{w(i'j'k2)}, \overline{P}_{w(i'j'k3)}$ – standard coordinates of a $P_{i,jk}$ *-th* reference point, corresponding with the real coordinates

$\overline{P}_{p(i'j'k1)}, \overline{P}_{p(i'j'k2)}, \overline{P}_{p(i'j'k3)}$ – CMM position error vector in a $P_{i,jk}$ *-th* reference point - cumulates kinematik system errors and linear encoders errors,

$\overline{P}_g$ – measuring head errors vector,

$\overline{P}_a$ – measurement points reproducibility errors vector – a sum of position error and head errors In the formulated model it is assumed, that:

$$\overline{P}p = \overline{P}w - \overline{P}m \tag{3}$$

when:
`*Pg* Þ **min** - assuming performance of the measurement in four permanent points located on perpendicular diameters of balls (or spheres) of standard plate

Pp - position error for single measurement points. For the estimation assumed is vector lenght $Pp_{i,jk,}$ and for calculation of border errors area (*MPE* for CMM) assumed is the maximum value for the whole control area. This allows to determine uncertainty $U_p = B(cube)$, however, the more appropriate shall be precise estimation of border errors area for the particular surfaces, which allows delimitation of this area.
and $\overline{P}g$ is determined subsequently separately as:

$$\overline{P}g = FBG_{PRB(i,l,r,k)}(a)\ Ug_{FBG(a)}$$
or (4)
$$\overline{P}g = FBG_{PRB(i,l,r,k)}(Nx, Ny, Nz)\ Ug_{PRB(i,l,r,k)FBG(Nx, Ny, Nz\ dx, dy, dz))}$$

where: $\overline{P}g$ – error vector of an i-*th* measuring probe *PRB(i,l.r,k)* dependant on a type of measurement (i.e. external or internal measurement - *k*) as well as on configuration (orientation, length of a mandrel *l*, diameter of a contingent ball *r,*), *FBG (a)* values of a function of head errors in a polar system
FBG (Nx , Ny, Nz) values of a function of head errors in a cartesian system
N_x, N_y, N_z – values of cosine of a tracking angle
$Ug\ PRB_{(i,l.r,k)}$– uncertainty of head measurement for an i-*th* contact probing point *PRB(i,l,r,k)*

Uncertainty $Ug\ PRB_{(i,l.r,k}$ in the assumed model is determined experimentally individually for each probing point, taking into consideration tracking direction, i.e. through a ring or ball standard measurement in n-points distributed evenly - n = (64) repeated m times m = (32) calculated as doubled value of a standard deviation cumulative for all deviations of a tested probing point, i.e. $2s_{n,m}$.
Deviations are calculated in relation to an mean square circle or ball [6].
Assuming that for the whole head (all probing points):

$$U_g = \max Ug\ PRB_{(i,l.r,k)} \tag{5}$$

Eventually, uncertainty CMM reckoned within the control area (cube):

$$U_{cube} = U_g + U_p$$
or practically: (6)
$$U_{cube} = A + B(cube)$$

And such formula is correspondent to the already known notation of accuracy error CMM estimated by the length measurement. With this important difference, that this relation has been calculated on the basis of accuracy error in the reference point and for the delimited control area (cube). So the defined space for uncertainty has a form of a ball. Such defining of accuracy error CMM allows to create the detailed error map within the control area by way of calculating the limits of errors. This also allows accomplishing of the more detailed comparative estimation of different machines, in relation to errors in particular reference points. Also possible is reference to the length model by application of calibration procedure for the ball or hole plate. The tested head is examined more in more detail than by application of other methods (e.g. ISO 10360 or VDI/VDE 2617), by increasing of measurement points and taking into account the particular probing points (also possible is the easy procedure of estimation for the scanning head). Although as the most important advantage of this method one should consider the possibility of using the accomplished results for creation of a virtual copy of estimated CMM helpful for the current assessing of the realised measurement task accuracy.

3 A NEURAL NETWORK MODEL OF CMM

On the basis of the above-described matrix method of error identification created was a concept of the virtual CMM model. After conducting of a series of examinations, the best results obtained so far have been achieved for a three-layer neural network with the reverse propagation of error and various functions of activation. In the course of executing of the neural network teaching process applied was a so-called tutoring method. It means that the neural network while learning of executing of the given assignment, seek the way to succeed by way of minimising mean square error resulting from comparing of expected values (output data - tutor) with the real values generated on the neural network's output in a process of self-programming. In Fig.2 presented is a scheme of CMM virtual model based on application of artificial neural networks. The important issue remains building of a separate neural network dedicated solely to a head. The final stage is superposition of both errors fields in a form of summary CMM virtual model based on neural networks.

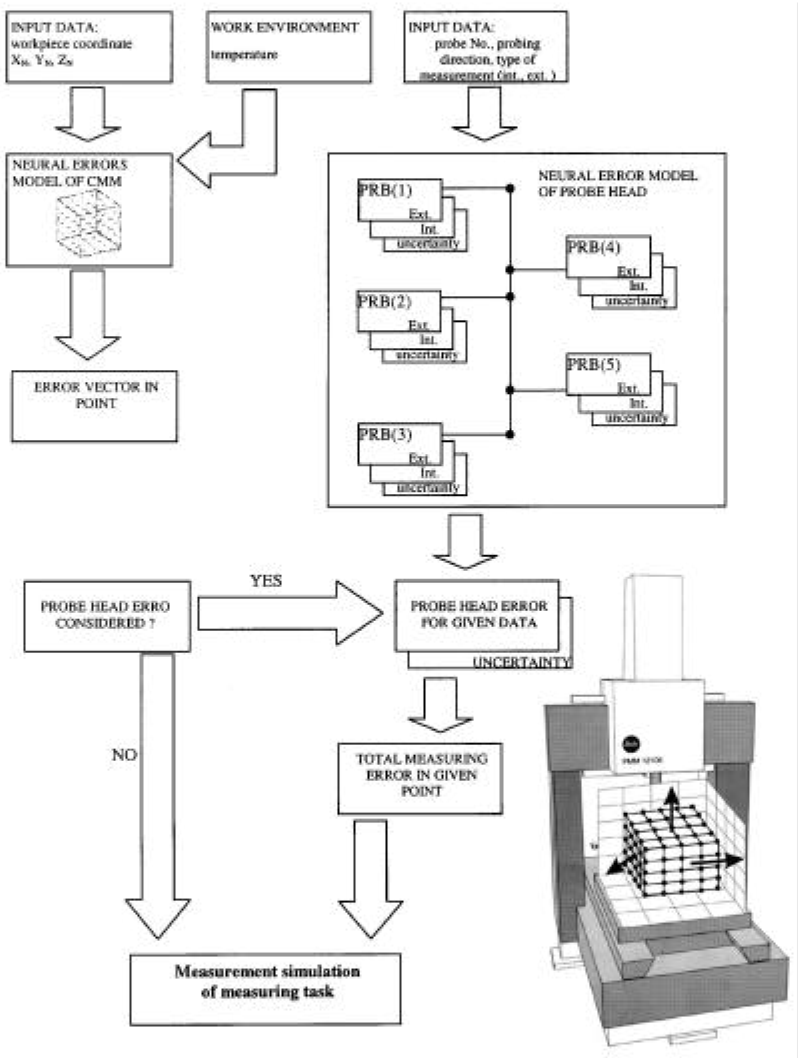

Figure 2. CMM virtual model based application of artificial neural networks

4 RESEARCH VERIFICATION OF THE VIRTUAL-NEURO-CMM MODEL

A neural model created for the machine PMM12106 has been tested on the basis of performed comparative research for the typical standard profile elements like: standard ring of a diameter $d=105_{0.002}$ mm, standard ball of a diameter $d = 100_{-0.001}$ and standard cylinder a diameter $d=100_{-0.001}$. Verification has been conducted according to the scheme presented in Fig. 3, with the use of the typical metrology software QUINDOS (according to the assumption given in the introduction). The model has been built for the extremely precise machine operating in the environment of strict air-conditioning (± 0.2 K) allowing to minimise of thermal effects, kinematic and head errors (in this case has been used an exceptionally precise head with the in-built measurement system).

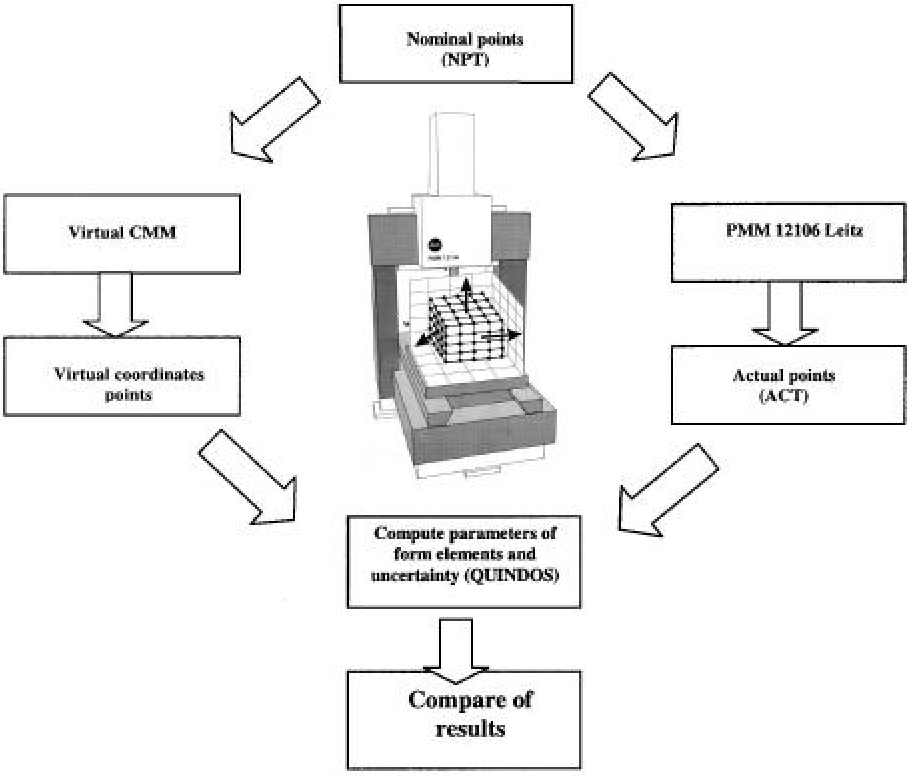

Figure 3. Scheme of the comparative research verifying the neural-CMM virtual model

The examination began with placing of standard elements in CMM measurement space, then performed were measurement identifying the elements location, with the use of QUINDOS software generated were the values of coordinates of nominal points on the surface of both standards. Then for the selected points have been generated errors with the use of a virtual model VN-CMM built according to Chapter 3 based on the NeuroSchell program [4] and, as presented in Fig.3, imported to the QUINDOS software. At the same time have been performed, on the machine PMM12106 Leitz, measurements of profile elements exactly in the generated points. The results obtained for both objects in a form of positions of centre and diameter and profile errors are presented in Fig.4. Elaborated virtual model WMP based on the use of neural networks has been compared to the other virtual models for the same CMM and to the results obtained for the real machine. For this comparation have been used the results obtained for: virtual model WMP - Megakal PTB [3,5] – created in Phisikalish Technische Bundesanstalt – Braunschweig; Virtual PK - created in PK ; classic virtual model WMP [mmm] Symbols K1,K2,K3 used in Fig. 4 relate to the results obtained for the ring model; symbols SPH 1SPH2 and SPH3 relate to the results for sphere model; and CYL1 CYL2, CYL3 for the cyllindric model. While analysing of those results, one can observe semblance results for the real machine and neural virtual model and the model created in PTB. The purpose of application of a virtual model is assessment of uncertainty for the performed measurement task. Uncertainty for a 30-fold repetition of measurements obtained experimentally on PMM12106 and 32-times repeated simulation with the use of a virtual model gave very much comparable results.

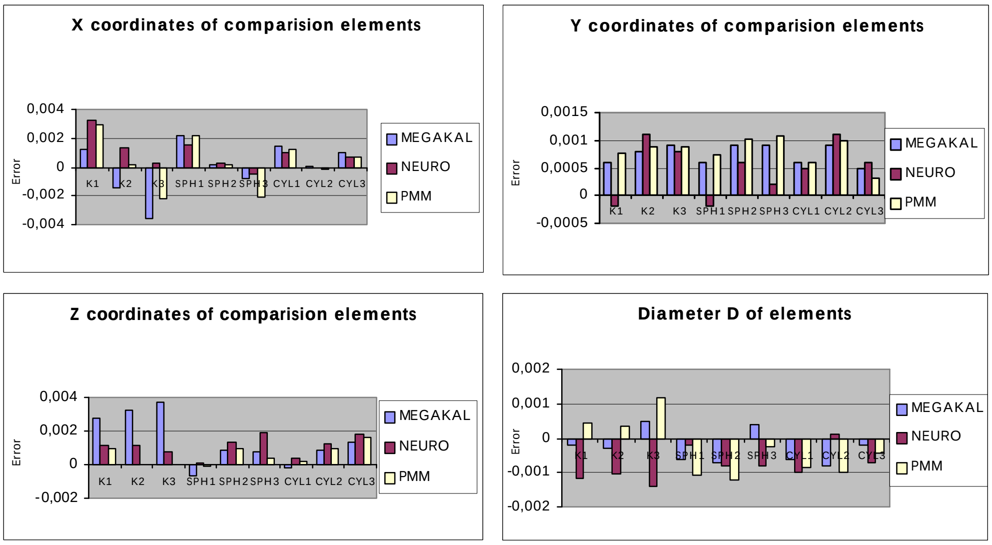

Figure 4. Comparison of results of testing different objects obtained for the created virtual model based on neural networks, other virtual model and a real CMM.

5 CONCLUSION

The results of comparative tests confirm the applicability of methods which provided the basis for the construction of a training set, particularly in the part of area where reference points grid was made, the plate workpiece used as a reference point. In the areas where reference points neural network was developed the accuracy is slightly lower, which is obvious since in these areas the error values have been added by the network itself. The matrix identification method presented is based on a typical plate workpiece, which has become standard for CMM evaluation. This method, if combined with the possibility of building on its basis a CMM virtual model can be a basis for of a coherent measurement accuracy assessment system. The applied matrix method of error identification allows the precise error estimation in the particular CMM reference points, taking into consideration the head errors and facilitating determination of the new, more adequate guidelines in relation to CMM accuracy assessment. The further research towards the full integration of the on-line CMM and a virtual model should be continued.

REFERENCES

[1] Kowalski M, S³adek J,: Opracowanie wirtualnej wielowspó³rzê dnoœciowej maszyny pomiarowej z zastosowaniem do badañ i korekcji bê dów obiektów rzeczywistych i optymalizacji pomiarów Reasult of scientifical research PEI of CUT in frame PB 1367/T07/95/08
[2] Nawara L, S³adek J, Kowalski M.: „Badania metrologiczne maszyn pomiarowych i urz¹dzeñ ze szczególnym uwzglê dnieniem dok³adnoœci geometrycznej, pozycjonowania i strategii pomiarów" Reasult of scientifical research PEI of CUT in frame CPBP 02.20
[3] Schwenke H., Bedienanleitung MegaKal, Kalkom, Tkal- PTB, Braunschweig 1996.
[4] S³adek J,Rakoczy R, Szwajkowski A.: Application of Neural Networks for Modelling Coordinate Measuring Machines.-In:Progress in Precision Engineering and Nanotechnology –Edited by H.Kunzmann F.Waeldele,G.Wilkening,J.CorbetP.MacKeow,M.Weck,J.Huemmler vol.1s.323-326 – PTB- Braunschweig u. Berlin P.u.Oe.1997 ISBN 3-9801433-9-2
[5] Trapet E.Waeldele F:The Virtual CMM Concept, In: Ciarlini, P, Cox, M.G.,Pavese, F.,Richter,D. (Editors): Advanced Mathematical Tools in Metrology II World Scientific, Singapore 1996
[6] J.S³adek Errors Identyfication and measurement accuracy assessment of coordinate measuring machines (CMM) – Advances in Technology of Machines and Equipment – Kw.PAN Vol.23/4 1999

AUTHOR: Jerzy S£ADEK, PhD.Eng. Ass.Prof. Production Engineering Institute, Cracow University of Technology, 31-864 Kraków Al. Jana Pawla II 37, Poland
Phone++48126480130, Fax ++48 12 6482010, Email: sladek@mech.pk.edu.pl