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Strategy of applying co-ordinate metrology in quality assurance systems with regard to a measurement accuracy

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Abstract

The paper presents research in the following fields: assessment of CMM measurements accuracy, application of standards in the form of ball and hole plates for the purpose of CMM errors identification, modelling and simulation of CMMs, developing a concept of a virtual CMM for forecasting accuracy of CMM measurements and setting its link with design and manufacturing systems. A concept of a developed system is presented which allows for interactive measurement planning, creation of a measuring program basing on CAD data and accuracy assessment using a simulation model of a CMM.

1 Introduction

Continuous improvement and demand for increasing effectiveness of quality assurance systems make it necessary to apply quick and universal measuring systems to match accuracy and flexibility of manufacturing systems. These requirements are to a large extent met by co-ordinate measuring machines (CMMs). Due to their key position in quality assurance systems a strategy of taking a full advantage of them becomes an essential issue.

The above mentioned strategy includes:

1. CMM's link to the whole manufacturing process in informatics and logistics terms,
2. assuring possibility of assessing accuracy of performed measurements,
3. planning of measurements.

The first and the last issue are now satisfactorily well developed whereas the second one still presents a lot of problems and has not yet been fully resolved.

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From technical and economic point of view it is very important to estimate the accuracy of performing specified tasks before actual measurements take place. Such information is necessary at the product and process design stage.

Rapid development of CAD/CAM/CAPP/CAQ systems makes it necessary to elaborate methods of comprehensive analysis of accuracy of measurements carried out by a CMM which would address all kinds of measurement tasks performed by CMMs. Achievements and problems encountered during research carried out in this field at Cracow University of Technology are presented in this paper. The most promising, however, is the method using special artefacts (standards) for error identification in conjunction with a simulation model of a CMM in the form of the so called virtual CMM, linked to measurement planning systems based on CAD files.

2 CMM accuracy assessment

Methods of assessing accuracy of CMMs are described in national and international standards or guidelines.They are intended to be used in receiving inspection and acceptance tests of CMMs allowing only to assess conformance of CMM parameters with its specifications included in technical documentation, brochures or in an agreement with a purchaser.

A real assessment of accuracy of measurements carried out by a CMM can be made with one of the following methods:

- comparison method
- analysis of component errors.

In case of the first method measurement accuracy is determined by measuring a calibrated artefact identical to a workpiece to be measured.

The second method is an accuracy analysis method which determines component machine errors, i.e. 21 geometrical components for three axes and errors of probing point acquiring system. Having these errors evaluated it is possible to anticipate measurement errors for selected measurement tasks. Due to a great complexity of a CMM error model this approach tends to be very complicated for more complex measurements. Superposition of effects of these component errors depends on a measurement task or even for a given measurement task - on a measurement strategy (it is reflected by a disperse of measurement results for the same dimension). Results of analysis made according to this method can only be valid for one defined measurement task which makes the method useless in industrial practice.

3 Mathematical model of a CMM

Due to a need of creating a flexible method of defining and identifying CMM measurement errors for any geometrical element, a mathematical model of errors has been elaborated.

A mathematical description of such a model has been realised [1,3] with an assumption that a full description of CMM accuracy is based on evaluating a field of error vectors. It means that each point in a measuring volume of a machine has an error vector assigned. A set of those vectors forms an error vector field $\vartheta = f(n)$ which, according to [1,3] can be defined as:

$$\vartheta(n) = i\vartheta_x(n) + j\vartheta_y(n) + k\vartheta_z(n) \tag{1}$$

or

$$\vartheta(x,y,z) = [\vartheta_x(x,y,z) + \vartheta_y(x,y,z) + \vartheta_z(x,y,z)] \tag{2}$$

where: $\vartheta\,(n)$ - position error field vector in point n in measurement volume of a CMM

$\vartheta_x, \vartheta_y, \vartheta_z$ - coordinates of the field ϑ in certain coordinate system $O_{x\,y\,z}$,

i, j, k - unit vectors of the coordinate system.

In order to describe $\vartheta_x, \vartheta_y, \vartheta_z$ errors a so called stiff error model has to be assumed (it refers to a mechanical structure of a CMM. This model is defined by nine functions ϑl_{ij} describing translational components of an error and by nine functions describing rotational errors, i.e. caused by angular rotation errors β_{ij}. Adding component errors in the same directions a following formula for geometrical errors can be obtained:

$$\vartheta l_i = \sum_j \left[\vartheta l_{ij} - \frac{1}{2}(x_i - x_j)\sum_k \beta^2_{kj} \right] - \sum_{l,kj} (x_j - x_{jk})\beta_{lk} \tag{3}$$

where

$$\vartheta l_i = \left[\vartheta l_x, \vartheta l_y, \vartheta l_z\right] \tag{4}$$

$$x_i = \left[x, y, z\right]$$

$$\vartheta l_{ij} = \begin{bmatrix} \vartheta l_{x1} & \vartheta l_{x2} & \vartheta l_{x3} \\ \vartheta l_{y1} & \vartheta l_{y2} & \vartheta l_{y3} \\ \vartheta l_{z1} & \vartheta l_{z2} & \vartheta l_{z3} \end{bmatrix} \tag{5}$$

$$x_{ij} = \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{bmatrix} \tag{6}$$

$$\beta_{ij} = \begin{bmatrix} \beta_{x1} & \beta_{x2} & \beta_{x3} \\ \beta_{y1} & \beta_{y2} & \beta_{y3} \\ \beta_{z1} & \beta_{z2} & \beta_{z3} \end{bmatrix} \tag{7}$$

where

x_{ij} - matrix of characteristic points related to locations of length standards of CMM displacement measurement systems (linear transducers). Components of these matrices are functions (g) of displacements respectively in x, y, z, i.e.:

$$\begin{aligned}&\vartheta\, l_{x1}=g_1(x),\ \vartheta\, l_{x2}=g_4(x),\ \vartheta\, l_{x3}=g_7(x)\\&\vartheta\, l_{y1}=g_2(y),\ \vartheta\, l_{y2}=g_5(y),\ \vartheta\, l_{y3}=g_8(y)\\&\vartheta\, l_{z1}=g_3(z),\ \vartheta\, l_{z2}=g_6(z),\ \vartheta\, l_{z3}=g_9(z)\end{aligned}\tag{8}$$

$$\begin{aligned}&\beta_{x1}=g_{10}(x),\ \beta_{x2}=g_{13}(x),\ \beta_{x3}=g_{16}(x)\\&\beta_{y1}=g_{11}(y),\ \beta_{y2}=g_{14}(y),\ \beta_{y3}=g_8(y)\\&\beta_{z1}=g_{12}(z),\ \beta_{z2}=g_{15}(z),\ \beta_{z3}=g_{18}(z)\end{aligned}\tag{9}$$

In addition, besides the above described 18 components of rotational and translational errors there are 3 more errors ($\Theta_{xy}, \Theta_{yz}, \Theta_{xz}$) arising from perpendicularity deviations of actual coordinate system of a CMM. In total there are 21 component geometrical errors. Functions included in (8), (9) can be identified through measurements of a given CMM. During a measurement process an important role is played by a measuring probe. Its errors are described by a function FBG = $f(d, \alpha)$ where d - radial deviation of a measuring head error, α - angle defining a contact point of a probe with a surface of a workpiece in a spherical or polar coordinate system. They also take into account a configuration of probe pins. A method of determining FBG and its relation to other CMM errors is described in [3]. Considering an effect of a head one should note that it is a source of both random and systematic errors. Accuracy error of a CMM is a superposition of effects of an error vector field $\vartheta = f(n)$ and a random error field $\zeta = f(n)$.

Thus, a superposition of component errors and measuring probe errors is performed basing on a mathematical model, which makes it possible to evaluate a resulting error vector in each point of a measuring volume of a CMM and for each measuring direction. Determined in this way error vectors comprise three main components [2,3,1]:

- known systematic errors (21 component errors of a CMM and systematic errors of a measuring head),
- random errors of a measuring head resulting from e.g.: interpolation errors, dynamic effects or a hysteresis,
- unknown systematic errors caused by e.g.: uncertainty of artefact calibration, neglecting an influence of temperature, simplification of a CMM error superposition model, excluding a problem of a workpiece influence.

4 Software-based modelling of CMMs

Realisation of a simulation model of a CMM (virtual measuring machine - VCMM [4]) is a difficult task, therefore in practice it is handled with the usage of defining of functions built on characteristic points obtained through actual measurements. Analysing these functions it is possible to evaluate errors for any measuring points.

Using a virtual machine it is possible to simulate a given measurement task in order to determine its measurement uncertainty without a need to analyse an error propagation problem by a CMM user. A prerequisite to create a virtual machine is developing a method of determining component errors of a CMM given by formulas (8), (9). A few methods can be applied, they use interferometer level systems and 2D or 3D standards. The most effective however are methods using ball or hole plates because they are already well known and analysed and easy to use [4]. *(according to [8] an obtainable uncertainty U of determining sphere or hole distances is* $U=0.6\mu m+0.9x10^{-6}L$ *for steel plates and* $U=0.6\mu m+0.4x10^{-6}L$ *for Zerodur plates at a confidence level 95%)* Besides geometrical errors describing a deformation of a measurement volume of a CMM, errors of a measuring point acquiring system (measuring heads) are also determined through measuring a calibrated ring or sphere standard. It is necessary to take into account a strategy of measurements and used software when analysing accuracy of measurements. Based on this data an identification of a vector error field is carried out $\vartheta = f(n)$ and then a superposition of measuring points for an ideal shape element $F = f(n_1 \ldots n_i \ldots n_m, x, y, z)$ and for an error vector field $\vartheta = f(n)$ is performed. A virtual shape element $\widetilde{F} = f(\widetilde{n}_1 \ldots \widetilde{n}_i \ldots \widetilde{n}_m, x, y, z)$ is thus obtained . Taken into account are also random errors by generating measuring points coordinates with random effects imposed on them according to ranges of variability of all components. Simulations are performed many times until a stable range of variability is achieved. A measurement error being in fact a set of errors of parameters for a given element is given as follows: $\Delta = n - \widetilde{n}$ taking into account a standard deviation 2s of determining parameters of a given element.

Researches carried out at the Cracow University of Technology are supported by a software package from PTP-Braunschweig (being a practical implementation of a VCMM concept: Kalkom, Tkal, Megakal-[4,5]) and our package - SymCMM [1,7].

4.1 Application of neural networks for modelling of CMM errors

Being aware of both advantages of a "traditional" comparison method and its drawbacks (described in clause 2) such a modification of a VCMM method was sought for that it would be capable of identifying errors for any measuring points in a measuring space of a given CMM (by comparing actual points with "reference" points and applying a "black box" rule). As a result of performed analysis the application of neural networks has been proposed for the purpose of modelling CMMs errors.

A neural network is a very simplified model of one kind of human mental process. It consists of a large number of elements which process data. These elements are called neurones although their functions compared to a human mind neurones are trivial. Neurones are connected forming a network, each connection featuring its ”factor” which can be modified during a learning stage. Topology of connections and their parameters form a program of operation for a network whereas signals appearing at an output as a response to a specified input are solutions of a given task.

The main differences between conventional computer systems and neural networks are employing a multiprocessor system , as it was mentioned above, of a large number of elements (neurones) processing supplied data in a concurrent manner and a fact that a network, unlike conventional computer programs, can learn instead of being programmed and is capable of creating new connections. For a neural network to work properly and give good results for the anticipated measuring errors of a CMM for a given measuring task, it has to be properly prepared. Firstly a kind of a network ought to be selected. Normally it should be a non-linear, multilayer type network, i.e. possessing an input, hidden and output layer. Care must be taken when deciding a number of neurones in each layer. Too small a number will prevent a network from an accurate and effective learning the way of solving a problem, if the number of neurones is too big it will result in a ”memory” type of a network operation, i.e. a network, having many neurones available will memorise and duplicate a problem instead of solving it. An optimal number of neurones in each layer will force a network to ”think” which is required.

The next stage is creating a relevant learning set generating specified input signals. This set should clearly and precisely define data and parameters which are to be analysed by a network. Also, a test set must be created which will allow a network to verify results of performed analysis and to monitor progress in learning. In case of a CMM, a learning set will contain results of a CMM calibration, e.g. with a ball plate ”Scanned” measuring volume of a machine in this way will enable to elaborate a grid of errors with relevant values in nodes. As a testing set dimensions of a ball plate treated as actual values can be taken. The way neural networks have been used for modelling CMMs is shown in fig.1.

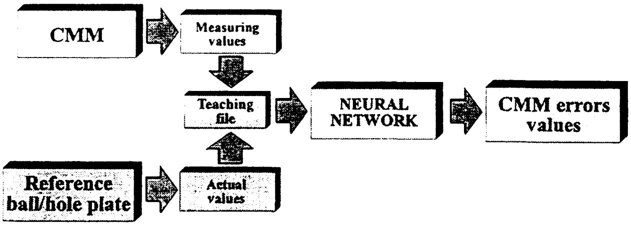

Figure1: Application of neural networks for modelling of CMMs.

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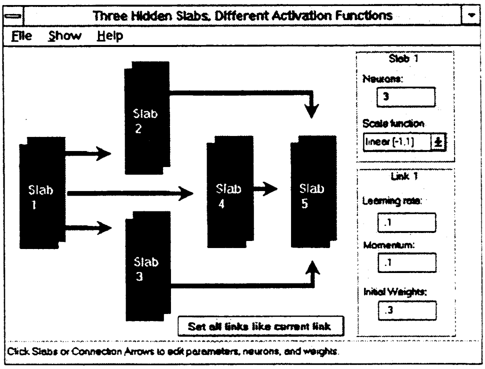
For computer simulation of a neural network a program 'NeuroShell2 for Windows' was used [6]. The best results were obtained when using a backward error propagation and different activating functions, as presented in fig. 2.
Symbols:
- Slab 1 - input layer (for input data) containing 3 neurones with a linear activation function,
- Slab 2 - first hidden layer (selected structure consisted of 3 such layers) containing 3 neurones, activation function is a Gauss function,
- Slab 3 - second hidden layer containing 3 neurones, activation function is a tanh function,
- Slab 4 - third hidden layer containing 3 neurones, activation function is a Gauss function,
- Slab 5 - represents an output layer (providing results) containing 3 neurones, activation function is a logistics function.

The above presented network features the following initiating parameters:
- learning rate -0.1 ,
- momentum -0.1 ,
- initial weights -0.3.



Three Hidden Slabs, Different Activation Functions

Slab 1
Neurons: 3
Scale function: linear [-1,1]

Link 1
Learning rate: .1
Momentum: .1
Initial Weights: .3

Click Slabs or Connection Arrows to edit parameters, neurons, and weights.

Figure:2 Architecture of a selected neural network

The teaching file contains both input data and expected output data. It was created directly within NeuroShell2 using results of measurements performed in measuring space of a CMM. For measuring points identification ball or hole-plates are used. They are positioned within a measuring space of a CMM so that metrological definition of a given CMM can be carried out. A so-called "teacher guided" method for teaching a network was applied. It means that a learning network tries to resolve a problem by minimising the sum of the squares errors comparing expected output data (teacher) with actual output generated as an output when learning. In this case it was assumed that the effect of learning (taking advantage of ten patterns, i.e. nominal points co-ordinates and corresponding measurement errors) will be considered satisfactory when the network is capable of distinguishing values with an accuracy of at least ten times higher than that of the expected values based on teaching file.

The next step was to generate a file neuro.def which contained definitions of learned neural network. To realise a task of generating coordinates measurements, basing on input nominal coordinates of the points, a NeuroCMM program was created [7] . Testing of the developed concept of applying neural networks for modelling CMM errors was accompanied by using Megakal-software from PTB Braunschweig, which implements a concept of VCMM in analytical form. During the test the same measuring points were selected (nominal points) and generated errors compared in these points for a given CMM. Tests proved the two methods give similar results.

In conclusion, the developed method and built neural network seems to be very promising but requires further experimental verification for different kinds of CMM construction.

5 Application of a virtual machine for assessment and anticipating of accuracy of a measurement task

A process of planning measurements and developing a measurement program tends to be based on CAD files. They allow, without using a CMM, to select probe pins, simulate a measurement run choosing a collision-free paths, define clearance points and build a whole measuring program selecting an optimal strategy of measurements. Linking a CAD-based system of measurement planning, metrological software of CMMs and problems of "on-line" measurement accuracy assessment will make it possible to integrate a CMM with a quality assurance system. A key problem is integrating a virtual machine into a CMM software. Analysing this issue in a strategy of applying a CMM in a quality assurance system suggests another issue, of which the significance was emphasised at the beginning. It is a problem of technical possibilities of anticipating measurement accuracy without a need to actually perform a measurement. The algorithm is shown in fig. 3. It is based on a measurement task simulation, the following being taken into account:

* workpiece design in the form of a CAD file,
* manufacturing tolerances
* CMM error field identification
* simulation of form errors variation within a tolerance zone
* superposition of CMM error field and shape deviations of a workpiece.

Analysis performed in this way allows us to:

- anticipate measurement accuracy for a single feature measurement and then for the whole workpiece,
- assess measurement capabilities and consequently assess manufacturing capabilities,
- take informed decisions when accepting a production order, basing it on available machines,
- considerably reduce time needed to prepare a production process by simulating measurements and assessing obtainable accuracy without manufacturing prototypes,
- plan an optimal utilisation of a CMM through calculating measurement time and selecting a frequency of inspection for a given set of measured features.

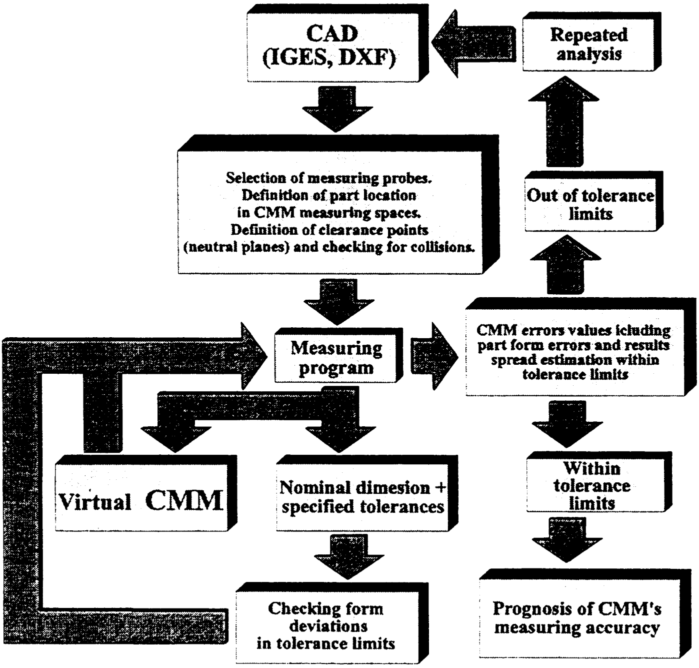


Figure3: Forecasting accuracy of measurements performed by CMMs as an element of strategy of quality assurance system integration.

6 Summary

Cracow University of Technology has conducted research into accuracy of Coordinate Measuring Machines (CMM) for many years. Many practical solutions of a problem of total CMM error have been developed based on various kinds of master standards. both in planar and spatial forms. Assessing accuracy involves above all evaluating of basic kinematic errors of a machine

(21 components) and of a measuring head. Currently researches are made concerning a virtual CMM for the purpose of assessing and correction of accuracy of real machines. A specially prepared software (SymCMM) is used for a CMM kinematic errors analysis, for assessment of probing heads and for assessing how workpiece form errors affect accuracy of measurements. In addition to this, software obtained from Phiskalisch Technisch Bundesanstalt in Braunschweig is also taken advantage of (Kalkom, Megakal, Tkal)[5]. It uses ball or hole plates (calibrated with a laser interferometer) to analyse CMM's errors and identify their source. This software makes it possible to simulate a measurement process and estimation of actual errors for a given CMM and a measurement task (measurement of a circle, plane, cone, sphere, distance, angle). Alternatively, in order to solve the above described problems a neural network can be applied to analyse and anticipate accuracy of measurements. During measurements made with a virtual machine a properly taught neural network will analyse a measured element taking its position in a measuring volume into consideration in order to anticipate the errors and maximum accuracy with which a given measuring task can be performed.

Benefits arising from the above described application of neural networks for anticipating accuracy of CMM makes it possible to more properly design production process, manufacture a part correctly, establish its position in a measuring volume of a CMM, generate a suitable measuring program for a given part and to measure a part itself. A properly built and taught neural network is capable of continual improvement through learning, Thus, a CMM accuracy could be continually analysed and assessed. Errors of measurements could be evaluated and anticipated with regard to a measurement strategy.

Knowing a measurement accuracy at a design stage (CAD) will contribute to reducing cost and time involved in passing from design to manufacturing. It requires a close link and strict co-operation between CAD, CAM and CAQ systems.

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