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VIRTUAL CMM MODEL ADAPTED FOR USAGE IN INDUSTRIAL CONDITIONS

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Abstract–Due to the rigorous requirements for implementation of the virtual models of CMMs they are usually used in the renowned calibration laboratories. This paper presents the novel methodology of implementing the virtual CMM model that is capable of correct uncertainty determination for measurements done in less stable industrial conditions. The verification results were also presented under varying ambient conditions. They prove the correctness of proposed methodology.

Keywords: virtual machine, CMM, uncertainty determination

1. INTRODUCTION

The virtual models of Coordinate Measuring Machines are getting more popular nowadays. Their main limitation is the necessity of providing the stable conditions in the machine's proximity. Also difficult and relatively long experiments that has to be performed before virtual machine implementation may limit the range of its applications. This is why virtual CMM models are usually used in calibration laboratories in which fulfilling of mentioned requirements is not that problematic as in case of the laboratories met in industrial conditions.

The stability regarding the ambient conditions is especially important regarding the temperature. The typical virtual CMM models, like those presented in [1-3] are based on determination of certain error sources that occur in coordinate measurements. Their variability is checked in different places of the machine working volume and basing on this knowledge, their impact on measurement result may be simulated multiple time. Some of the major error components are dependent on the temperature value. This relation can be seen the most, in case of all errors connected with the machine kinematics. It does not matter if the model of machines kinematic errors is based on the typical 21 geometrical errors components [4,5] or if it uses the residual kinematic error distributions [6]. In all cases determined errors strongly depends on thermal changes [5,7]. In the result, the influence of temperature should be thoroughly examined what is connected with a big amount of time spent on experiments. Additionally, because of various solutions used in CMMs, these experiments may differ for different machines. This is why the authors of virtual CMM models usually assumes that the machine should work in the room in which the temperature oscillates about the reference value 20 °C. And the maximum permissible differences from this value, set by the originators of each virtual CMM, usually exclude the possibility of using this virtual model on CMMs working in rooms with standard thermal variations met in industrial metrological laboratories.

The second important reason for using the virtual machines only in the renowned metrological laboratories is the complicated process of gathering the data regarding the distributions of errors that influence the measurement result. It would be hard to perform the long-lasting experiments, needed for implementation of the virtual CMM, on the machines that are used almost 100 % of plant working time and that are crucial point of production quality assurance system. This is why, the time spent on performing the experiments that are integral part of virtual CMM implementation should be reduced to the necessary minimum.

Given the above facts, the authors have decided to develop the virtual CMM that will be able to faithfully model the measurements performed in changing ambient conditions and to develop the methodology of its implementation that can be used on CMMs working in industries, without causing the long breaks in machine's everyday duties. Developed virtual CMM was then implemented in chosen machine using new methodology and tested in order to prove the proper functioning of the model. The results of this stages of work were also presented in this paper.

2. GENERAL ASSUMPTIONS OF DEVELOPED VIRTUAL CMM

Presented Virtual CMM is based on the model presented in [3]. It uses measurements of spherical standard for determination of probe head errors and LaserTracer system combined with multilateration method for determination of residual kinematic errors distribution.

In order to model the thermal instability of machine's measuring volume, the distributions of residual errors were determined for different temperature ranges. The results showed that there is a significant difference in the machine residual kinematic errors distributions obtained for different temperatures. This is why the authors decided to use temperature monitoring system that will check the temperature in the measuring volume of the machine. Depending on recorded temperatures, the proper distribution of residual errors is recalled. Basing on performed experiments, the authors decided that the residual errors distributions should be determined for temperatures 20 ± 0,2 °C, 18,6 ± 0,2 °C and 21,4 ± 0,2 °C. Resulting distributions would be then recalled and used in ranges (18;19,3), (19,3;20,7) and (20,7;22). In this way, the thermal changes of the machine are taken into account during the uncertainty determination.

In order to make the model more suitable for industrial usage also the experimental procedure performed during implementation of virtual CMM had to be modified. The functioning of the virtual CMM modules is based on experimental determination of certain errors in the number of reference points. The bigger is their number, the representation of real measuring conditions is more faithful. But also the time needed for determination of error values is longer. As mentioned in the introduction, too long time needed for experiments during implementation on the machine in industrial conditions is a very important drawback. From industrial point of view, the smallest possible number of reference points should be used. This was the reason for performing the optimization of number of reference points both for module responsible for simulating CMM kinematic residual errors and the module responsible for simulating the probe head errors.

The module which simulates probe head errors is based on the measurement of spherical standard. Due to multiple measurement (in order to gather statistically representative sample)of standard at specified points, which constitutes a grid of reference points, it is possible to assign a probability density function that represents the probe head error in relation to two angles of stylus deflection. The mean radial error in each point can be interpreted as a representation of systematic error, when the standard deviation associated to it can be treated as a random error. These parameters for each point of reference grid are the input data of the module. The initial measurements involved measurement of 289 points distributed evenly over the surface of the upper hemisphere of the standard. They defined the verifying data set for the models based on a smaller number of points. Four models have been developed: first model included 163 reference points, the second model was based on 82 reference points, the third model consisted of 46 reference points, the last model was based on the 25 reference points. For these models the values of probe head errors were obtained by simulation. The comparison of results for points laying on the equator of the standard sphere was presented in Tab. 1 and Fig.1. The error values simulated using considered models were compared with empirically gathered data set (289 pts). The error value was considered to be simulated correctly if it differs from the corresponding value obtained through the measurements, not more than ± 3 * standard deviations assigned to the considered point. Results of simulations showed that the first three models reflects the actual functioning of the probing system in a satisfactory manner. The model based on 25 reference points gave the worst results (17% of points do not fulfil assumed criteria) so authors decided to use the 46 pts model. The time required for the data acquisition for this model is about 1/2 hour.

Table 1. Comparison of probe head errors depending on stylus deflection angles (α,β) determined experimentally (289 pts) and by simulation for models based on different number of reference points (163 pts, 82 pts, 46 pts, 25 pts). Values of probe head errors given in mm.

α	β	289 pts	163 pts	82 pts	46 pts	25 pts
0°	0°	0.0011	0.0014	0.0011	0.0011	0,0020
15°	0°	0.0007	0.0012	0.0006	0.0005	0,0009
30°	0°	0.0010	0.0005	0.0000	-0.0000	-0,0002
45°	0°	-0.0004	-0.0001	-0.0003	-0.0004	-0,0013
60°	0°	0.0002	-0.0003	-0.0001	-0.0004	-0,0009
75°	0°	0.0000	-0.0003	-0.0000	-0.0005	-0,0005
90°	0°	0.0003	-0.0001	0.0004	-0.0000	0,0000
105°	0°	0.0003	0.0004	0.0010	0.0006	0,0002
120°	0°	0.0007	0.0014	0.0017	0.0012	0,0005
135°	0°	-0.0001	-0.0002	0.0006	0.0005	0,0007
150°	0°	0.0000	-0.0005	0.0004	0.0003	0,0007
165°	0°	0.0006	-0.0001	0.0006	0.0001	0,0007
180°	0°	0.0005	0.0006	0.0011	0.0005	0,0008
195°	0°	0.0006	0.0010	0.0012	0.0007	0,0008
210°	0°	0.0011	0.0011	0.0009	0.0006	0,0008
225°	0°	0.0006	0.0009	0.0004	0.0003	0,0009
240°	0°	0.0000	0.0002	-0.0000	0.0000	0,0001
255°	0°	0.0006	0.0002	-0.0005	-0.0003	-0,0007
270°	0°	-0.0007	-0.0004	-0.0009	-0.0006	-0,0015
285°	0°	-0.0007	-0.0005	-0.0010	-0.0006	-0,0011
300°	0°	0.0007	0.0006	-0.0001	0.0000	-0,0006
315°	0°	0.0006	0.0005	0.0007	0.0006	-0,0001
330°	0°	0.0007	0.0007	0.0010	0.0009	0,0006
345°	0°	0.0010	0.0010	0.0011	0.0010	0,0013

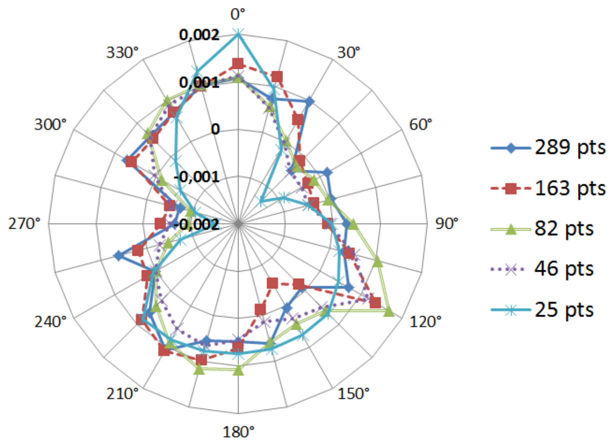

Fig. 1. Comparison of probe head errors (in mm) depending on stylus deflection angles (α,β) determined experimentally (289 pts) and by simulation for models based on different number of reference points (163 pts, 82 pts, 46 pts, 25 pts).

The optimization of reference points number was performed also for the model responsible for simulation of residual kinematic errors. Initially, the number of reference points was set as 52 [3]. Then the number of reference points was reduced to 36, 16 and finally 9. Correctness of the model was checked each time using comparison of

Table 2. Comparison of results obtained by the Virtual CMM using 9, 16 and 36 reference points for modeling the residual kinematic errors. Results (x) and uncertainties (U(x)) are given in mm.

Feature	Substitution method		Multiple measurement method		Virtual CMM 36 points		Virtual CMM 16 points		Virtual CMM 9 points	
	x	U(x)	x	U(x)	x	U(x)	x	U(x)	x	U(x)
Plane-plane distance	99,9635	0,0009	99,9632	0,0015	99,9668	0,0036	99,9659	0,0038	99,9662	0,0039
External diameter	35,0177	0,0011	35,0179	0,0015	35,0186	0,0032	35,0184	0,0034	35,0187	0,0032
Internal diameter	24,9818	0,0011	24,9818	0,0012	24,9835	0,0033	24,9838	0,0034	24,9841	0,0037
Flatness	0,0043	0,0010	0,0042	0,0012	0,0048	0,0012	0,0047	0,0013	0,0045	0,0015
Cylindricity	0,0066	0,0014	0,0056	0,0018	0,0045	0,0016	0,0049	0,0019	0,0050	0,0018

uncertainties given by the virtual machine which uses defined number of reference points with the uncertainties given by the multiple measurement method or the substitution method. The measurements was done according to methodology presented in section 5. The only difference was that during measurements presented here, the temperature in machine's surroundings was in the range of 20±0,2 °C. The results of performed measurements are given in Tab. 2. They proved correct functioning of all models and this is why for further works the model based on 9 points was used. The time required for data acquisition in this case was about 2 hours.

3. METHODOLOGY OF VIRTUAL CMM IMPLEMENTATION

The general procedure of implementation of a virtual machine consists of four steps: determination of the kinematic residual errors distribution, determination of the probe head errors, software installation, and the virtual machine validation. The first stage begins with determination of the amount and distribution of points which define the reference grid. Their number depends on the size of the machine's measuring volume and its accuracy. The points distribution should be regular in order to cover equally the whole measuring volume of the machine (or the part of it, defined by the user of the machine). Usually, the minimum number of points described in section 2 is used, and if the correct working of the machine is proved during verification measurements the model based on this number of points is used by the virtual CMM. After determining the structure of the grid, the measurement with the LaserTracer ought to be proceeded. The machine with fixed retroreflector approaches 14 times to each node of the grid, every time from other direction. The entire sequence is repeated four times for different LaserTracer position. As a result of measurement, the standard deviations of reproduction of point coordinates x, y, z are obtained. They are the input data for the module which is responsible for kinematic residual errors simulation. The procedure must be repeated for all considered temperatures.

Second part involves multiple measurements of spherical standard. The number of reference points depends on user decision, however default points amount (46 points) is recommended. The standard used in this stage has to meet several requirements. It's form deviation should be less than 0.2 * P_{FTU} defined according to [8], and sphere diameter should be less than 30 mm (so the influence of machine kinematics on the measurement results can be regarded as insignificant). Standard should be mounted in such position in machine volume so that the sum of residual errors, determined in previous step, for all sampling points would be the smallest.

In the third stage, data obtained in previous steps, together with the virtual machine software are uploaded into machine user computer. Also the program add-on for user defined metrological software is installed to establish connection between the software and virtual machine.

In the last step, virtual machine functioning should be verified by comparing the uncertainties determined with usage of virtual machine with one of the popular methods of uncertainty estimation (multiple measurement method or substitution method). This stage is described in more details in the section 5.

4. IMPLEMENTATION ON CHOSEN CMM

The methodology presented in section 3 was used on the CMM located in premises of Laboratory of Coordinate Metrology at Cracow University of Technology. The bridge CMM with measuring volume of 1000:1200:500 mm equipped with touch-trigger probe was used. The minimum number of reference points was used in case of both virtual CMM modules. As the range of temperature variability in the machine room was assumed as 18-22 °C, the residual kinematic errors were determined in three different temperatures 18,6 ± 0,2 °C, 20 ± 0,2 °C and 21,4 ± 0,2 °C (Fig. 2a). Also the additional temperature monitoring system was implemented at the machine in order to check the actual temperature and to switch the residual kinematic errors distributions when necessary.

Probe head errors were determined using spherical standard with nominal diameter 24,9902 mm (Fig. 2b) located in the place in measuring volume of the machine where the residual kinematic errors have the smallest values.

a) b)

Fig. 2. a) Determination of distributions of residual kinematic errors; b) measurements of sphere standard aiming in determination of probe head errors.

The MODUS metrological software was used at the modeled machine. The add-on that allow to implement the virtual CMM algorithms was developed using DMIS language and installed at the machine's computer. The uncertainty evaluation is done using user-friendly prompts (Fig. 3).

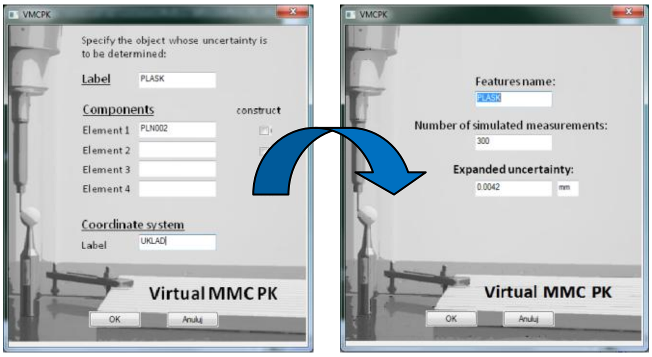

Fig. 3. Prompts in add-on implemented in MODUS software used to initialize the uncertainty evaluation.

After installation of the virtual CMM at considered coordinate machine the verification tests were performed. They were described in section 5.

5. VERIFICATION TESTS

Validation process of the virtual machine functioning involved measurements of selected geometrical features of multi-feature-check standard, which is used for task specified uncertainty estimation. In order to verify the correctness of virtual machine functioning the following features was measured: distance between two planes, cylindricity and diameter of standard body, plane flatness and angle between two planes. The Koba Step, ring standard and gauge block was used as reference objects, according to guidelines of calibrated workpiece method. Measurements was performed in variable temperatures in order to check if the Virtual CMM model is resistant for the unstable conditions.

Measurement uncertainty for all mentioned tasks was estimated analytically using acclaimed methods: the calibrated workpiece method (substitution method) and multiple measurement method, which are both based on multiple measurement of the tested object and the standard, in different positions in the measuring volume of CMM. Measurement uncertainty was also determined using virtual machine. The validation criterion was chosen according to [9-11] and was checked for comparisons of uncertainties between Virtual CMM-substitution method and Virtual CMM-multiple measurement strategy. The criterion is based on the idea of statistical consistency. It requires performing following procedure:

1. Calculate the weighted mean *y*:

$$y = \frac{x_1/u^2(x_1) + \cdots + x_N \,/\, u^2(x_N)}{1/u^2(x_1) + \cdots + 1/u^2(x_N)} \qquad (1)$$

where: x_i - measurement result obtained using considered method, $u(x_i)$ - standard uncertainty corresponding to the x_i result, *N*- number of compared methods.

2. Determine standard deviation $u(y)$ corresponding to the *y* quantity:

$$\frac{1}{u^2(y)} = \frac{1}{u^2(x_1)} + \cdots + \frac{1}{u^2(x_N)} \qquad (2)$$

3. Use chi-squared statistical test in order to perform the general consistency check for results obtained using different methods, where χ^2_{obs} is the value of chi-squared test:

$$\chi^2_{\text{obs}} = \frac{(x_1 - y)^2}{u^2(x_1)} + \cdots + \frac{(x_N - y)^2}{u^2(x_N)} \qquad (3)$$

The consistency check fails when (4) is satisfied:

$$\Pr\{\chi^2(\nu) > \chi^2_{\text{obs}}\} < 0.05 \qquad (4)$$

Table 3. Results of performed verifications. Results (x) and uncertainties (U(x)) are given in mm, temperatures in °C. Features: A - Plane-plane distance, B - External diameter, C - Internal diameter, D - Flatness, E - Cylindricity.

Temp.	Feat.	Calibrated Object		Multiple measurement		Virtual CMM	
		x	U(x)	x	U(x)	x	U(x)
18,2 - 18,8	A	99,9626	0,0006	99,9621	0,0023	99,9655	0,0041
	B	35,0165	0,0009	35,0161	0,0017	35,0177	0,0028
	C	24,9811	0,0009	24,9812	0,0016	24,9821	0,0035
	D	0,0041	0,0009	0,0040	0,0010	0,0047	0,0012
	E	0,0081	0,0017	0,0075	0,0023	0,0070	0,0018
20,3 - 21,0	A	99,9638	0,0009	99,9635	0,0013	99,9663	0,0036
	B	35,0179	0,0012	35,0181	0,0016	35,0187	0,0033
	C	24,9821	0,0010	24,9819	0,0011	24,9844	0,0038
	D	0,0044	0,0011	0,0042	0,0013	0,0047	0,0014
	E	0,0066	0,0013	0,0057	0,0017	0,0051	0,0020
21,3 - 21,9	A	99,9647	0,0007	99,9649	0,0019	99,9673	0,0037
	B	35,0191	0,0010	35,0189	0,0016	35,0199	0,0032
	C	24,9827	0,0010	24,9828	0,0014	24,9809	0,0036
	D	0,0043	0,0010	0,0041	0,0012	0,0049	0,0017
	E	0,0074	0,0015	0,0071	0,0019	0,0065	0,0022

where: Pr{} - probability of an event, v - number of degrees of freedom calculated as $v = N$-1.

The results of performed verifications are presented in Tab. 3. Described criteria was met for all comparisons so the Virtual CMM model can be regarded as functioning properly.

6. CONCLUSIONS

The authors have made an attempt to solve some problems regarding the implementation of virtual machine models in industrial conditions. Two main problems were discussed and the solution to them was given. These problems are the unsuitability of existing Virtual CMM models for industrial usage due to the necessity of using it in stable ambient conditions and the long time of experiments aiming in practical implementation of virtual models.

Presented model of Virtual CMM, that uses the findings of this paper, was firstly checked in Laboratory of Coordinate Metrology, in the room that was suited for reproducing the conditions that can be met in industrial conditions. The tests went correctly and the model is currently being implemented for the first time in industrial conditions. The first results from this implementation show that the virtual model of the machine is working properly for the evaluation of uncertainties of standard measuring tasks like distances between two elements, angles between two elements, radius/diameter measurements, position measurements, straightness, flatness, roundness, cylindricity deviations.

The necessity of adding the separate function written in considered programming language (in case of Modus software it is DMIS language combined with Python) for determination of uncertainty of each measuring task, should be regarded as the major drawback of this method. Another problem is that the simulation of measurement becomes very complicated when solving of the measuring task needs construction of elements using measured features. Then, a kind of the measurement decomposition has to take place and the measured features has to be simulated *n*-times firstly, secondly, the construction based on simulated features has to be repeated *n*-times and in the last step, the evaluation of chosen relation or feature has to be done also *n*-times.

The Virtual CMM is now still tested in company from automotive industry located near Krakow. It is under constant development and new functionalities are added to it. The new implementations of this model in Polish companies are being prepared and the model is being adapted for usage in combination with metrological programs different than Modus.

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