Optimization of kinematic errors model used in virtual CMM systems

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Abstract. The kinematic errors are one of the main contributors of coordinate measurement total error and should be taken into consideration during preparation of virtual CMM (VCMM) models. Modules responsible for simulation of kinematic errors that were used so far required long-lasting experiments to be performed before implementation of VCMM. It was one of the biggest limitations regarding its usage. The optimization method for kinematic error model was proposed in this paper. Its usage resulted in reduction of duration of implementation experiments more than 4 times.

1. Introduction

The development of manufacturing technology and increased requirements on the accuracy of products, delineates new challenges for coordinate metrology. Measuring systems used nowadays are getting more accurate and the measurement duration is still decreasing [1]. However, fast and precise estimation of measurement uncertainty (which may be treated as a quantitative measure of its accuracy) is still problematic.

The most promising methods that are currently used for uncertainty estimation are simulative methods which are usually based on utilization of virtual models of measuring systems. They do not require performing multiple repetitions nor the broad base of material standards what cause that their usage is several dozen cheaper than usage of different methods (like multiple measurement strategy [2,3] or method using calibrated workpiece [4]).

The simulative methods are based on constructing the simulative model of measurement performed in considered system. The model should include all of the error sources that are known and possible to predict, and use the information about the possible error values in each place of measuring volume of the system. Using this information, the mathematical model of ideal measuring system is enhanced by the model of errors. The enhanced model is then used to simulate the performed measuring tasks multiple times and the results of simulation are the basis for calculating the uncertainties corresponding to each task.

Virtual CMM prepared for CMM should consist of at least two parts: a module simulating the errors of CMM kinematic system and a probe head errors module. Virtual models of CMMs are often improved by adding different sources like environmental influences or influences of measured object [5-7]. Both for the kinematic system of CMM and the probe head, the error models are based on a previous determination of the errors’ variability in the modelled area. It is clear that there is no
possibility to experimentally determine errors in the whole area of the machine. It is therefore necessary to choose some reference points within the machine volume, in which errors would be determined experimentally, and then to use them as a base for interpolation of the error values between them. What instantly comes into mind is that the larger number of points gives better representation of reality, but increases the measurement time, while smaller number of points may reduce the time and costs of experiments that have to be performed before construction of each module but may lead to weaker mapping of the errors. In the second situation, also the interpolation of errors may give wrong results as the local changes of errors may not be identified properly (or at all). On the other hand, too long time needed for implementation experiments is the serious drawback regarding the implementation of VCMM in some cases, especially in the industrial conditions where any CMM downtime is a financial loss. Therefore, it is needed to perform each time the model optimization so the experimental procedure can be as fast as possible without loss of accuracy.

The method of optimization of probe head errors module was already presented in [8]. Different methodology had to be developed for optimization of module responsible for simulation of kinematic errors. It is presented in this paper on the example of module based on identification and simulation of kinematic system residual errors (described in [9,10]). However, the general approach presented here should also be useful regarding any other modules of kinematic errors simulation.

2. Optimization of kinematic errors model

The model presented in [9,10] was built on 52 reference points. The experiments aimed on identification of kinematic residual errors were based on measurements using LaserTracer system and consisted of repeated approaching to the considered points from different directions. In place of the stylus the "cat eye" retroreflector was mounted. Position of the retroreflector was tracked in the dynamic mode by LaserTracer installed in the measuring volume of the machine. After a sequence of approaches at the point machine reached the next one and the cycle was repeated. Whole measurement sequence was repeated four times, each in different position of LT, in order to determine the coordinates of points using multilateration method [9]. Described experiments took 8 hours. That amount of time is too big regarding the usage of these model in industrial conditions for which it was designed. This is why the authors decided to perform the optimization of this module. As an optimization criterion the minimum number of reference points that provides faithful simulation of measurement uncertainty can be taken. "Faithful simulation" means here that the results obtained using simulative model based on optimized residual error module are comparable to results provided with use of other uncertainty estimation methods like the multiple measurement strategy and the method using calibrated workpieces. To check if the level of comparability is enough the validation method which is based on the concept of statistical consistency control was developed and described in details in [11].

In order to get the uncertainty of measurement it is necessary to use the whole, functional model of VCMM. So the module responsible for simulation of kinematic residual errors was connected with module responsible for simulating probe head errors based on 46 reference points and presented in [8,9]. The probe head module was the same (it was based on the same input data) for all of the measurements presented in this paper.

The procedure of optimization was based on performing 5 steps each time the number of reference points was reduced to \( n \):

1. Determination of residual errors in \( n \) reference points.
2. Generating of new input matrices for module responsible for simulation of kinematic residual errors. These matrices contain data regarding the nominal coordinates of reference points and values of residual errors obtained for them.
3. The validation measurements. During all of the measurements the coordinates of measured points and approach vectors for them were recorded. These data is then used as an input for the VCMM simulations.
4. Uncertainty simulations using VCMM.
5. Data analysis aiming in determination of validation result.

Four stages of optimization were performed. They were done for kinematic residual errors modules based on: 52, 36, 16 and 9 reference points. The schematic diagram of presented optimization method is given in Fig. 1. The results of performed experiments were presented in section 3 (results were presented for modules based on: 36, 16 and 9 reference points as correct functioning of module based on 52 points was proved in [9]).

![Schematic diagram of presented optimization method.](image)

**Figure 1.** Schematic diagram of presented optimization method.

### 3. Results of performed experiments

All described experiments were done on Zeiss WMM 850S machine equipped with PH10 probe head and TP20 STD module. The results of chosen features and relations measured on multi-feature check using different methods and different numbers of reference points (in case of VCMM method) were presented in Tab. 1.

| Feature               | Substitution method | Multiple measurement method | Virtual CMM 36 points | Virtual CMM 16 points | Virtual CMM 9 points |
|-----------------------|---------------------|----------------------------|-----------------------|-----------------------|----------------------|
| Point-to-point distance | x = 199.6289, U(x) = 0.0001 | x = 199.6286, U(x) = 0.0004 | x = 199.6291, U(x) = 0.0011 | x = 199.6292, U(x) = 0.0010 | x = 199.6294, U(x) = 0.0013 |
| Diameter of cylinder   | x = 12.0158, U(x) = 0.0001 | x = 12.0158, U(x) = 0.0002 | x = 12.0159, U(x) = 0.0007 | x = 12.0158, U(x) = 0.0007 | x = 12.0160, U(x) = 0.0008 |
| Parallelism deviation  | x = 0.0040, U(x) = 0.0002 | x = 0.0040, U(x) = 0.0001 | x = 0.0042, U(x) = 0.0001 | x = 0.0042, U(x) = 0.0002 | x = 0.0040, U(x) = 0.0001 |
| Squareness deviation   | x = 0.0072, U(x) = 0.0004 | x = 0.0070, U(x) = 0.0002 | x = 0.0064, U(x) = 0.0004 | x = 0.0063, U(x) = 0.0005 | x = 0.0061, U(x) = 0.0006 |

All stages of optimization gave positive result during validation. Number of reference points was not reduced below 9 because authors decided that smaller number of points would be ineffective, especially for CMMs with bigger measuring volume. Thus, 9 was taken as an optimal number of reference points for module simulating residual kinematic errors.
4. Conclusions
The optimization that was performed led to significant reduction of time spent for implementation experiments needed for gathering the input data for residual errors module. From 8 hours needed in case of 52 reference points to approx. 3.5 hours in case of 9 points. So the reduction was bigger than 2 times. The time of implementation experiments was reduced even about 5 times when the module based on 9 reference points were compared with the kinematic errors module used in classical VCMM, which need determination of residual kinematic errors using hole plate standard. Process of their determination in different points in the volume of considered CMM takes about 16 hours.

Additionally, results presented in [12] show that the kinematic errors model based on 9 points is functioning properly also for ambient conditions that differs from reference conditions. Faithful representation of real residual errors values was proved for temperatures ranging from 18 to 22 °C.

Thanks to performed optimization it was possible to solve the problem of too long time needed for implementation of VCMM. The total time of implementation measurements equals now to approx. 5 hours. That short time does not discourage CMM users from industrial conditions to implement a virtual model on their equipment and presented VCMM was already implemented in one of automotive companies near Cracow [12].

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References
[1] Kunzmann H, Pfeifer T, Schmitt R, Schwenke H and Weckenmann A 2005 Productive Metrology - Adding Value to Manufacture CIRP Ann. Manuf. Technol. 54 155-68
[2] Osawa S, Busch K, Franke M and Schwenke H 2005 Multiple orientation technique for the calibration of cylindrical workpieces on CMMs Prec. Eng. 29 56-64
[3] Sato O, Osawa S, Kondo Y, Komori M and Takatsuji T 2010 Calibration and uncertainty evaluation of single pitch deviation by multiple-measurement technique Prec. Eng. 34 156-63
[4] Weckenmann A and Lorz J 2005 Monitoring coordinate measuring machines by calibrated parts J. Phys. Conf. Series 13 190-3
[5] Sladek J 2016 Coordinate Metrology Accuracy of Systems and Measurements (Berlin: Springer)
[6] Wilhelm R G, Hocken R and Schwenke H 2001 Task Specific Uncertainty in Coordinate Measurement CIRP Ann. Manuf. Technol. 50 553-63
[7] Aggogeri F, Barbato G, Modesto Barini E, Genta G and Levi R 2011 Measurement uncertainty assessment of Coordinate Measuring Machines by simulation and planned experimentation CIRP J. Manuf. Sci. Technol. 4 51-6
[8] Gąska A, Harmatys W, Gąska P, Gruza M, Mathia T and Sladek J 2015 Optimization of probe head errors model used in Virtual CMM systems, Proc. 11th International Conference on Laser Metrology and Machine Performance (LAMDAMAP) (Huddersfield, UK, 17-18 March 2015) ed L Blunt, H N Hansen pp 177-86
[9] Sladek J and Gąska A 2012 Evaluation of coordinate measurement uncertainty with use of virtual model machine based on Monte Carlo method Meas. 45 1564-75
[10] Gąska A, Krawczyk M, Kupiec R, Ostrowska K, Gąska P and Sladek J 2014 Modeling of the residual kinematic errors of Coordinate Measuring Machines using LaserTracer system, Int. J. Adv. Manuf. Technol. 73 497-507
[11] Gromczak K, Gąska A, Ostrowska K, Sladek J, Harmatys W, Gąska P, Gruza M and Kowalski M 2016 Validation model for coordinate measuring methods based on the concept of statistical consistency control Prec. Eng. 45 414-22
[12] Gąska A, Harmatys W, Gąska P, Gruza M, Gromczak K and Ostrowska K 2017 Virtual CMM-based model for uncertainty estimation of coordinate measurements performed in industrial conditions Meas. 98 361-71