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VIRTUAL EXPERIMENTS FOR UNCERTAINTY EVALUATION OF MEASUREMENTS PERFORMED USING COORDINATE MEASURING MACHINES

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Abstract: This paper presents the uncertainty evaluation method for measurements performed on coordinate measuring machines that is based on use of virtual experiments. Assumptions and implementation of the method is presented on the example of measurements of calibrated cylindrical square standard. The results with associated uncertainty values obtained using virtual experiments are compared to results of other uncertainty determination methods based on use of calibrated workpieces or simulations. It is proved that method based on virtual experiments is capable of producing metrologically correct values of measurement uncertainties. Advantages of this approach are also discussed.

Key words: virtual experiments, CMM, uncertainty, simulations

1. INTRODUCTION

In the era of digital transformation and increasing automation in industry, measurement science, or metrology, is undergoing significant evolution. Traditional measurement methods are being increasingly supported or replaced by advanced simulation techniques, such as virtual experiments (VEs) and digital twins (DTs) [1]. These technologies enable the modeling and analysis of complex measurement systems without the need for costly and time-consuming physical experiments, offering new opportunities for uncertainty evaluation in measurement processes.

Measurement uncertainty plays a fundamental role in metrology as it provides essential information on the reliability and comparability of measurement results. The Guide to the Expression of Uncertainty in Measurement (GUM) [2] establishes standardized procedures for evaluating and expressing measurement uncertainty. However, when dealing with complex or nonlinear measurement systems, such as coordinate measuring machines (CMMs), traditional methods may not always yield accurate or

practical results [3]. In such cases, virtual experiments present an effective alternative.

A virtual experiment involves the use of computational models to replicate the behavior of physical measurement systems, including the impact of various error sources. Schematic diagram of VE functioning is presented in Fig. 1. Through careful modeling and Monte Carlo simulations, VEs allow for the propagation of measurement uncertainties in a way that reflects the actual behavior of the system under study [3]. This approach is particularly advantageous when physical experiments are impractical due to economic, time, or safety constraints, or when the number of necessary repetitions to achieve statistical significance is prohibitively high [4].

Coordinate measuring machines (CMMs) are widely used in industrial metrology for the precise measurement of geometrical features of manufactured parts. Accurate determination of measurement uncertainty for CMMs is critical for quality control, process validation, and compliance with standards. The complexity of CMM systems, combined with numerous potential sources of systematic and random errors, makes uncertainty evaluation particularly challenging. Traditional methods, such as the Law of Propagation of Uncertainty (LPU) or the

use of calibrated artefacts, may not fully capture the nonlinearities or the combined effects of multiple error sources present in real-world applications [3].

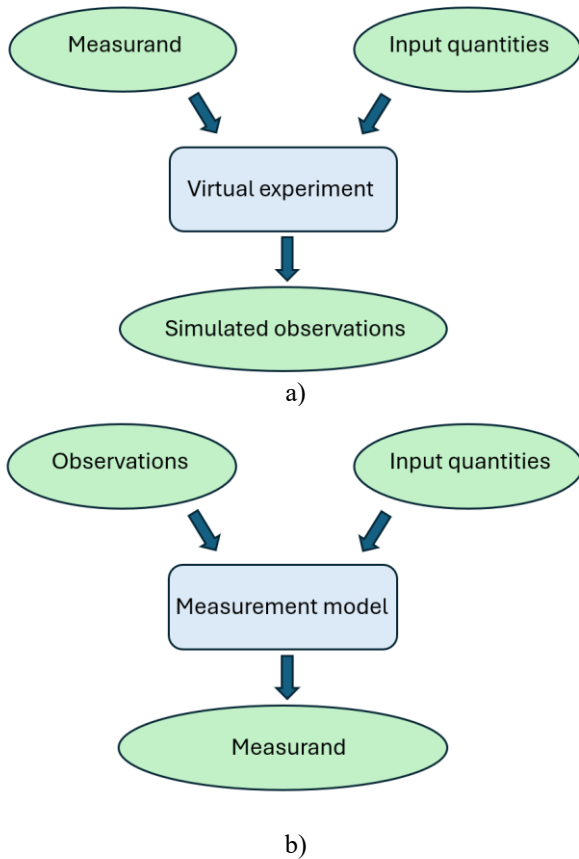


Fig. 1. Schematic diagram of virtual experiment functioning and its relation to the approach described in Guide to the Expression of Uncertainty in Measurement: a) generic virtual experiment that produces simulated observations given known values of measurand and input Quantities, b) generic GUM measurement model which relates the measurand with observations and input quantities [5].

In recent years, the application of virtual experiments for CMM uncertainty evaluation has gained increasing attention. By simulating the entire measurement process, including machine geometry, sensor behavior, environmental influences, and object-specific features, virtual experiments provide a comprehensive means of estimating measurement uncertainty. Such simulations not only allow for the assessment of standard uncertainties but can also incorporate complex error distributions and biases in data analysis methods [3].

Example of uses of virtual experiments in relation to measurements performed on CMMs

include simulation of measurement processes, evaluation of measurement uncertainties and optimization of inspection strategies without the need for using physical machines. In [6,7] virtual CMMs were used to offer vivid graphical representations and powerful simulations of CMM operations. They allowed users to plan inspection strategies, perform virtual measurements, and evaluate measurement uncertainties using Monte Carlo methods. They also provided rapid feedback on measurement uncertainty, enabling users to optimize inspection plans before actual measurements. In [8] Virtual Coordinate Measuring Machines were implemented as software tools designed to estimate uncertainties in tridimensional measurements. They were essential for making decisions related to product quality.

Publications [9,10] presented application of Monte Carlo methods in virtual experiments to evaluate measurement uncertainties. These methods comply with international guidelines [11,12] and can handle complex, non-linear models. Monte Carlo simulations are applied to virtual CMMs to estimate uncertainties in measurements, such as those involving optical components and aspheric surfaces [10].

Virtual experiments were also applied for other types of coordinate measuring systems like Articulated Arm CMMs. In [13] and [14] virtual models for articulated arm CMMs were developed to simulate and correct probe head errors. Other example of device towards which virtual experiments were used are five-axis CMMs. Virtual models for these systems incorporate error analysis and multistage correction to improve measurement accuracy. These models were presented and their use validated in [15, 16].

Virtual models of CMMs were also used to interface with physical CMM controllers, allowing measurement programs generated in the virtual environment to be executed on physical machines. It is important for example in measurements of micro- and nano- parts, where due to small dimensions of measured workpiece it is not easy to program the measurement sequence on the machine [17].

Main challenges identified in literature towards virtual experiments for CMM measurements include need for accurate

calibration and validation of virtual models, which is essential for ensuring measurement traceability and reliability. This involves addressing systematic and random deviations and validating the models against real measurement data [18, 19]. Another important challenge is continuous development and refinement of virtual experiments models for state-of-the-art measuring systems, such as laser tracking systems and optical sensors used on CMMs [20,21].

This paper presents a novel uncertainty evaluation method based on virtual experiments applied to measurements performed using coordinate measuring machines. The method is demonstrated through the example of measurements of a calibrated cylindrical square standard. The results obtained using the proposed VE-based approach are verified by comparing to other uncertainty evaluation methods, including those based on physical calibrated artefacts and conventional simulations. The study demonstrates that the VE-based method can provide metrologically valid uncertainty values while offering several practical advantages, including reduced cost, improved flexibility, and enhanced insight into measurement processes. Additionally, the benefits and limitations of the virtual experiment approach are critically discussed.

2. METHODS AND MEASUREMENTS

The cylindrical square that was presented in Fig. 2 was chosen as a measured workpiece in order to present functioning of Virtual Experiment described in subsection 2.1 of this paper.

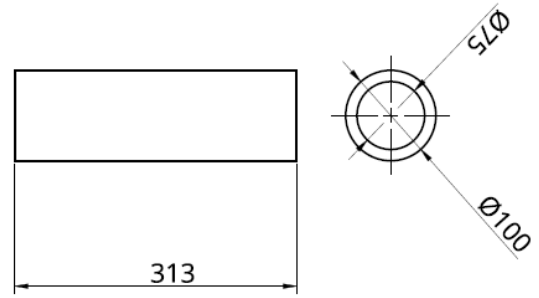


Fig. 2. Cylindrical square selected for measurements and simulations

Except from simulations run in the scope of Virtual Experiment scenario the cylindrical square was also measured on Leitz Infinity 12.10.7 (Fig. 3) coordinate measuring machine using assumptions of multiple measurement strategy described in (more details on measurement sequence are given in subsection 2.3) [22]. Measurement data recorded during the first measurement run were used for providing input data for Virtual CMM model that were described in subsection 2.2 of this paper.



Fig. 3. Measurements of cylindrical square performed using Leitz Infinity 12.10.7 coordinate measuring machine according to guidelines of [22]

2.1 CMM Virtual Experiment explanation

As a virtual representation of measurement of the cylindrical square standard we assumed following model. The cylindrical square is measured in 3 intersections that are parallel to

front plane of the standard (32 measuring points were used in each intersection, which gives 96 measuring points in total). Additionally, after measurement of whole cylindrical square, in one chosen intersection (the middle one), three circles built on different angles of arc (180, 90 and 30 degrees) were measured each time using 32 measuring points. Measured coordinates on all circles mentioned above are modelled as (1):

$$X_i = \begin{bmatrix} r_i \cos\left(\frac{2\pi}{N}i\right) + x_0 \\ r_i \sin\left(\frac{2\pi}{N}i\right) + y_0 \end{bmatrix}, \text{ for } 1 \leq i \leq N \quad (1)$$

where (x_0, y_0) are the coordinates of the centre of the underlying ideal circle, N is the total number of measured coordinates, and r_i is the radius for point i that depends on the lobes present in the circle, modelled using (2):

$$r_t = r + \frac{P}{2} \cos\left(N_L \frac{2\pi}{N}i + \phi_L\right) \quad (2)$$

with r the radius of the circle, P the peak-to-valley value or non-circularity of the lobed circle, N_L the number of lobes in the circle and ϕ_L the angle defining the rotation offset of the lobes. The combined data of all measured coordinates is represented by X , which is an $N \times 2$ matrix in which each row represents the x - and y -coordinates of a single measurement point as described in (1).

The error sources considered in this research include the squareness between the x -axis and y -axis - specifically, the deviation of the angle between these axes from the ideal 90° . Additionally, scale errors along both the x -axis and y -axis are taken into account, each modeled by a single scaling factor.

The term squareness refers to the effect of non-orthogonality between the axes in a Coordinate Measuring Machine (CMM). While the x -axis and y -axis are ideally perpendicular, in practice they always deviate from this ideal alignment. The impact on the measured coordinates X^m can be described by (3):

$$X^m = X \begin{bmatrix} 1 & s_{xy} \\ 0 & 1 \end{bmatrix} \quad (3)$$

The parameter s_{xy} represents the angular deviation between the x -axis and y -axis from the

perfect 90° , calculated as 90° minus the actual measured angle between them. Since s_{xy} is typically very small, only first-order effects are considered in this model. Accordingly, the tangent of s_{xy} is approximated by s_{xy} itself, and the cosine of s_{xy} is approximated by 1, with s_{xy} expressed in radians.

The scale error refers to the discrepancy that arises when a displacement along an axis is not measured accurately. For example, if the CMM moves 1.0 mm along the x -axis but the recorded displacement is only 0.9 mm, a scale error is present. Such errors can occur along both the x - and y -axes. Given the scale errors of the x -axis (s_x) and y -axis (s_y), the impact on the measured coordinates X^m is given by (4):

$$X^m = X \begin{bmatrix} 1 + s_x & 0 \\ 0 & 1 + s_y \end{bmatrix} \quad (4)$$

Finally, random noise present in the measured data is taken into account, arising from unpredictable effects. This noise is assumed to be independent and identically distributed, following a normal distribution with a mean of zero and a known standard deviation, denoted by σ .

In conclusion, the measured coordinates X^m are modelled as follows (5):

$$X^m = g(Y, Z | N, N_L, \phi_L, \sigma) = X \begin{bmatrix} 1 & s_{xy} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 + s_x & 0 \\ 0 & 1 + s_y \end{bmatrix} + E \quad (5)$$

where Y is the vector of measurands (r, P, x_0, y_0) , Z is the vector of error sources (s_{xy}, s_x, s_y) , X are the true coordinates given by an $N \times 2$ matrix of which each row is defined by (1), and E describes the random measurement noise given by an $N \times 2$ matrix of which each element is independent and identically distributed and drawn from a normal distribution with mean 0 and standard deviation σ [3].

Equation (5) is utilized for generating the $N_{MC} = 1\,000$ samples of measurement data and determining the corresponding measurement uncertainties using “propagation of distributions: virtual experiment with correction” method described in [3].

2.2 Virtual CMM model

As a second method that was used for uncertainty determination of the cylindrical square measurements, the virtual CMM model composed of module responsible for CMM kinematic residual errors simulation and module for probe head errors simulation described in [23,24] was taken.

Distributions of residual kinematic errors for CMM and distributions of probe head errors for devices used in these experiments were determined before running measurements described in this paper (using LaserTracer system and spherical standard).

Input data for simulation using this virtual CMM were x , y , z - coordinates of all points recorded during first run of measurements done on Leitz Infinity CMM according to multiple measurement strategy (input for kinematic residual errors module) and $[i, j, k]$ approach vectors to all of these points (as input for probe head errors module, where i, j, k are direction cosines defining the approach direction).

2.3 Multiple measurement strategy

Measurements performed according to guidelines of [22] included 12 repetitions of measurement procedure described at the beginning of section 2 in two different positions of the cylindrical square in the measuring volume of the machine. In the first position axis of the cylindrical square was parallel to x -axis of CMM's coordinate system, while in the second one it was parallel to y -axis of CMM's coordinate system. It gave in total 24 measurement repetitions. In all of them external diameter and cylindricity deviation of cylindrical square were determined and diameters and roundness deviations were determined for all 3 circles measured in the middle intersection of the standard. All measurements were performed using the same probe tip (ball diameter equal to 5 mm, length equal to 80 mm), pointing in Z - direction (probe head errors model used by virtual CMM was determined for probe head working with the same probe tip).

3. RESULTS

Results of performed measurements and simulations are presented in Tables 1-3.

Table 1

Values of features/relations along with the corresponding expanded uncertainty values (coverage factor $k=2$) simulated using Virtual Experiments

Feature/ relation	Value / mm	Uncertainty of measurement / mm
Cylinder diameter	100.2459	0,0018
Cylindricity deviation	0.0064	0,0033
Circle 180deg diameter	100.2451	0,0020
Circle 180deg roundness deviation	0.0039	0,0035
Circle 90deg diameter	100.2452	0,0020
Circle 90deg roundness deviation	0.0041	0,0034
Circle 30deg diameter	100.2165	0,0021
Circle 30deg roundness deviation	0.0036	0,0035

Table 2

Values of features/relations along with the corresponding expanded uncertainty values (coverage factor $k=2$) simulated using Virtual CMM model

Feature/ relation	Value / mm	Uncertainty of measurement / mm
Cylinder diameter	100.2441	0,0003
Cylindricity deviation	0.0032	0,0005
Circle 180deg diameter	100.2438	0,0003
Circle 180deg roundness deviation	0.0007	0,0004
Circle 90deg diameter	100.2445	0,0004
Circle 90deg roundness deviation	0.0009	0,0003
Circle 30deg diameter	100.2155	0,0004
Circle 30deg roundness deviation	0.0004	0,0002

Table 3

Values of features/relations along with the corresponding expanded uncertainty values (coverage factor $k=2$) measured according to guidelines of [21] (multiple measurement strategy)

Feature/ relation	Value / mm	Uncertainty of measurement / mm
Cylinder diameter	100.2445	0,0005
Cylindricity deviation	0.0030	0,0007
Circle 180deg diameter	100.2442	0,0004
Circle 180deg roundness deviation	0.0008	0,0006
Circle 90deg diameter	100.2442	0,0005
Circle 90deg roundness deviation	0.0009	0,0006
Circle 30deg diameter	100.2157	0,0006
Circle 30deg roundness deviation	0.0005	0,0008

Figures 4-6 show comparison of measurement results for chosen features/relations determined during measurements or simulations using all three considered methods.

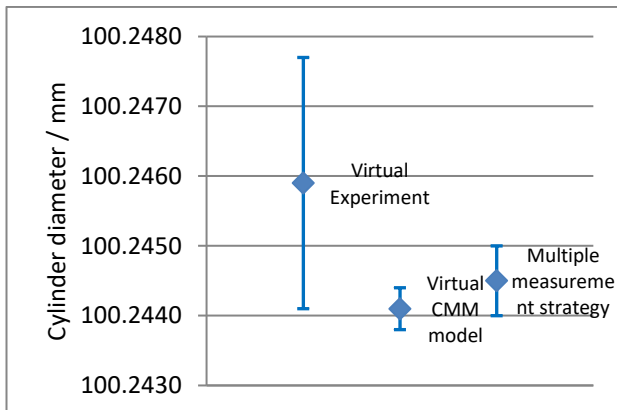


Fig. 4. Comparison of measurement/simulation results for measurement/simulation of cylinder diameter performed using all three considered methods.

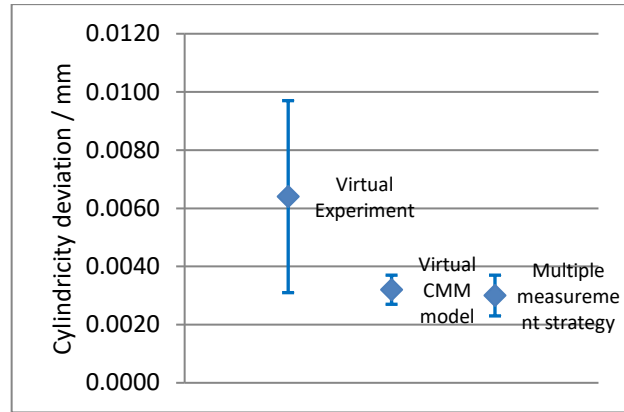


Fig. 5. Comparison of measurement/simulation results for measurement/simulation of cylindricity deviation performed using all three considered methods

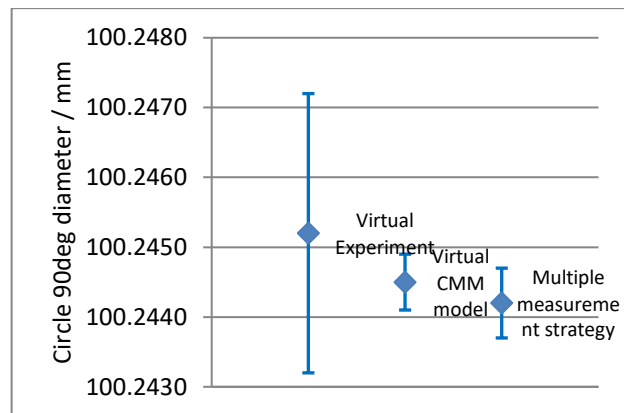


Fig. 6. Comparison of measurement/simulation results for measurement/simulation of circle 90deg diameter performed using all three considered methods

Additionally, statistical consistency of all three methods were checked for each of 8 measuring tasks included in Tables 1-3, using methodology presented in [25]. It was proven for all measuring tasks.

4. DISCUSSION AND CONCLUSIONS

This study presented the application of Virtual Experiments (VEs) for uncertainty evaluation in measurements performed using Coordinate Measuring Machines (CMMs), with a focus on a calibrated cylindrical square standard. The results obtained through the VE-based method were compared against both a Virtual CMM model and physical measurements conducted according to ISO 15530 guidelines employing the multiple measurement strategy. The comparative analysis provided valuable insights into the accuracy, efficiency, and practical applicability of the VE approach.

The findings confirm that virtual experiments are capable of delivering metrologically valid uncertainty estimates that are consistent with those obtained from both advanced simulation models and traditional physical measurement methods. For key geometric features such as cylinder diameter, cylindricity deviation, and roundness deviations, the VE-based uncertainties were generally a bit higher than those derived from the Virtual CMM and physical measurements. This is an expected outcome, as the simplified VE model incorporates broader assumptions (it does not include data about all 21 geometrical errors components but uses chosen ones, it also does not assign probe head errors to each probing direction but uses one parameter to characterize maximum possible error) compared to the Virtual CMM model, which explicitly simulates kinematic residuals and probe head errors. The slightly higher uncertainty values provided by VEs may thus make them more useful in cases where high confidence is required without risking underestimation of uncertainty.

One of the key advantages of the VE approach lies in its cost-effectiveness and flexibility. Unlike physical measurement campaigns, which require machine availability, trained personnel, and material resources, VEs can be performed rapidly and iteratively, enabling optimization of measurement strategies in a purely digital environment. Moreover, the ability to model specific error sources, such as squareness errors and scale deviations, provides valuable insight into how these factors influence measurement outcomes. This enhances the understanding of uncertainty contributors and supports more informed decision-making in quality control and manufacturing process validation.

The comparison also highlighted the strengths of the Virtual CMM model, which, due to its detailed representation of machine-specific errors, yielded the lowest uncertainty values. This suggests that when precise uncertainty quantification is critical, and when machine-specific input data is available, Virtual CMMs remain the main choice. Nonetheless, their implementation requires more sophisticated modeling efforts, long-lasting implementation

procedures, and domain expertise, which may not always be feasible in industrial contexts with limited resources.

Furthermore, the comparison with the ISO 15530-based physical measurements demonstrated statistical consistency across all methods, providing strong validation for the VE approach. This consistency is crucial, as it indicates that even though the VE method operates in a simplified digital domain, it can reliably reflect the outcomes of real-world measurements within acceptable uncertainty bounds.

Despite these positive findings, several challenges and limitations were identified. Accurate calibration and validation of virtual models remain essential to ensure traceability and reliability, especially as measurement tasks become more complex or as new sensor technologies, such as optical systems, are introduced. The ongoing development of more sophisticated VE models, possibly incorporating machine learning or adaptive algorithms, represents a promising direction for future research.

As a further steps for development of presented Virtual Experiment-based method authors want to prepare models for different types of measurement tasks, as the one presented here may only be used in case of measurements of rotary workpieces. Additionally, measurements of 3d workpieces is currently possible by simulating different intersections of the workpiece and then merging simulated data. This is why, as another direction for further development, creation of fully 3d measurement models may be considered. As mentioned above, a bias was observed for results simulated using virtual experiments, especially in cases when form deviations are considered. As a next step of works on presented model, the purpose of its existence will be investigated and measurement models will be corrected for that bias.

In conclusion, the study demonstrates that virtual experiments offer a robust, flexible, and economically advantageous method for uncertainty evaluation in CMM-based measurements. While they do not yet fully replace physical measurements or detailed virtual CMM models for high-precision

applications, VEs provide a practical tool for preliminary uncertainty assessment and measurement strategy planning. Continued development and validation of virtual metrology tools will further enhance their role within the evolving landscape of digital manufacturing and Industry 4.0.

5. FUNDING

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EXPERIMENTE VIRTUALE PENTRU EVALUAREA INCERTITUDINII MĂSURĂTORILOR EFECTUATE CU MAȘINI DE MĂSURARE ÎN COORDONATE

Această lucrare prezintă metoda de evaluare a incertitudinii pentru măsurătorile efectuate pe mașini de măsurat în coordonate, bazată pe utilizarea experimentelor virtuale. Ipotezele și implementarea metodei sunt prezentate pe baza unui exemplu de măsurători ale unui etalon cilindric pătrat calibrat. Rezultatele, împreună cu valorile de incertitudine asociate, obținute prin utilizarea experimentelor virtuale, sunt comparate cu rezultatele altor metode de determinare a incertitudinii bazate pe utilizarea pieselor de prelucrat calibrate sau a simulărilor. Se demonstrează că metoda bazată pe experimente virtuale este capabilă să producă valori metrologice corecte ale incertitudinilor de măsurare. De asemenea, sunt discutate avantajele acestei abordări.

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