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Modeling of coordinate measurement uncertainty using an expert system with machine learning elements

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Abstract
The estimation of coordinate measurement uncertainty is a fundamental and necessary task when assessing product conformity with specifications using coordinate metrology. Existing methods for uncertainty estimation in industrial environments are widely regarded as complex and time-consuming. This paper presents a novel tool currently under development at the Laboratory of Coordinate Metrology at Cracow University of Technology, aimed at rapid estimation of coordinate measurement uncertainty based on prior knowledge of the measurement task—without the need for conducting a real measurement.
For the first time, the conventional sequence of uncertainty estimation is reversed. Instead of estimating uncertainty during or after measurement, this approach enables users to predict measurement uncertainty beforehand. This capability is particularly valuable in scenarios where traditional uncertainty estimation is infeasible—for example, due to limited access to measuring machines or when the object exists only in the design phase.
Predicting uncertainty during the measurement task design phase shortens procurement processes for coordinate measuring machines (CMMs), supports simulation of measurement strategies for hard-to-access parts, facilitates efficient production line design, and enables optimal selection of measurement equipment for specific applications.
The paper includes metrological investigations carried out with modern multisensor CMMs, statistical analyses, and programming efforts focused on developing an expert system-based application enhanced with machine learning techniques. A key component of the application is a valuable computational module that utilizes information on the quality of fit of measurement tasks. The study also includes method testing, validation, and verification. The study concludes with a set of findings and outlines future research directions aimed at improving product safety. By making uncertainty estimation more accessible and applicable in practice, the presented method can help reduce the risk of incorrect conformity declarations.

Uncertainty estimation, Coordinate Measuring Machine (CMM), expert system, machine learning, multisensor system

1. Introduction

Uncertainty estimation is a key issue in assessing product conformity with specifications; however, the methods currently used in industrial practice are widely regarded as time-consuming and complex. As a result, machine operators may incorrectly adopt the machine's Maximum Permissible Error (MPE) as the measurement uncertainty, which may lead to unsafe decisions and erroneous conformity assessments. Consequently, the development of fast and simple methods for measurement uncertainty estimation has become a significant challenge. In practice, laboratories mainly use standardized methods for uncertainty estimation. The most commonly used approach is the comparative method described in ISO 15530-3:2011 [1], which is based on repeated measurements of a calibrated standard similar in size and shape to the measured object, or the multi-position method [2], which involves measuring the object in different locations and orientations. Although these methods provide a high level of accuracy, they are time-consuming and require complex measurement procedures as well as a wide range of reference standards.

Trends driven by Industry 4.0 and 5.0 have led to growing interest in simulation-based methods [3]. Numerous studies have focused on the development of virtual machines [4,5], which significantly accelerate the process of measurement accuracy assessment. A widely adopted approach is the Monte Carlo simulation method [6,7], which enables uncertainty estimation through statistical analysis of simulation results.

However, existing approaches are mainly focused on simulating errors in the machine space, whereas the concept presented in this paper adopts a more parametric approach, based on information about the measurement task and dedicated databases. This paper presents the concept of a new tool for fast and simple estimation of coordinate measurement uncertainty. The work is discussed with particular emphasis on the data acquisition stage, and includes results from both an exemplary measurement and the developed model, followed by a summary and an outline of future development directions for the proposed tool.

2. Methods and equipment

The key component of the developed tool is a model based on machine learning methods and archival data, which enables the prediction of measurement uncertainty for measurement tasks prior to performing the actual measurement. The process of data collection for training the model is an important and time-consuming stage of the work (Fig. 1). The data must be acquired in accordance with the standards of an accredited laboratory and following good metrological practice. Data are obtained from multi-sensor coordinate machines, such as the Zeiss O-Inspect or the Romer Absolute Arm 7320RI. Measurements are performed under varying conditions of the measurement task, by changing individual elements of the task, e.g., the object, the measured feature, the method of uncertainty estimation, or the standard (input data – **x**), so that the influence of each component on the measurement uncertainty (output data – **y**) can be examined. The databases are supplemented with data from archival tests, with reduced weighting applied to account for potential discrepancies arising over time, even when ostensibly identical measurement strategies were used.

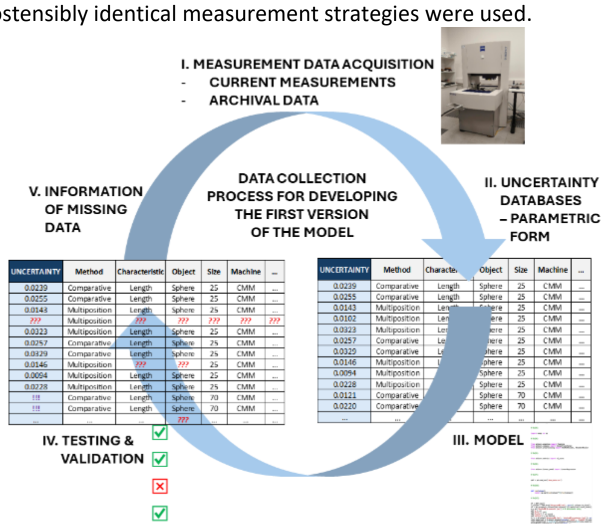

Figure 1. Data acquisition process scheme

The application code was developed in Python. The Pandas library was used for data loading, processing, and analysis, while regression models were implemented using the Scikit-Learn library. Regression for the current dataset provides satisfactory results; however, in cases where a decrease in prediction quality is observed, modifications to the model are allowed. Records corresponding to the same measurement tasks are considered collectively during model building and training. When different uncertainty values occur under identical measurement conditions, their root mean square is taken as the representative value. This approach helps to minimize the impact of random deviations and increases the reliability of the predicted uncertainty.

3. Results

As an example of the acquired data, the results of ring measurements performed on the ZEISS O-Inspect multisensor measuring system are presented. The Maximum Permissible Error MPE(E0) = 0.0019 + 0.004 · L/1000 mm for tactile and 0.0022 + 0.004 · L/1000 mm for optical measurements.

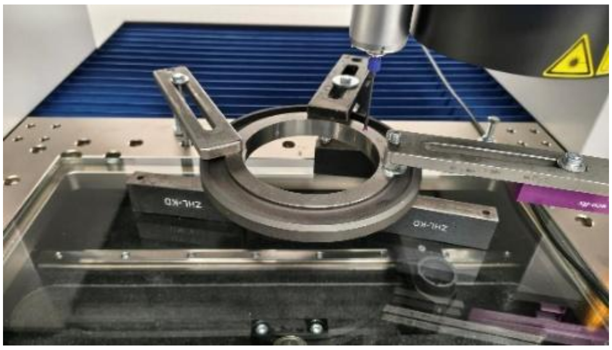
Figure 2. Ring measurement on the Zeiss O-Inspect system

Table 1 Corrected calibration results with expanded uncertainty U for ring measurement, mm

Tactile	Diameter_Circle			Diameter _Cylinder
	_Bottom	_Middle	_Top	
Result	99.99689	99.99710	99.99706	99.99699
U	0.00028	0.00121	0.00371	0.00092
Optical	Diameter_CIR_OPT_8		Diameter_CIR_OPT_3x8	
Result	99.99769		99.99757	
U	0.00030		0.00037	

Uncertainty prediction is performed using linear regression. The data are transformed according to the following scheme: categorical data are encoded using one-hot encoding, while for columns with numerical data, additional columns containing nonlinear transformations of the original features are added to capture potential nonlinear relationships. Based on the first data sample, a coefficient of determination R^2 of 0.92154 was obtained, which is considered a high-quality fit in practice. This allows the project to proceed with the inclusion of additional rows representing various data combinations, the addition of columns with new parameters, and further work on model refinement.

4. Summary

The initial version of the developed tool has been successfully validated, as described in [8]; however, a full evaluation of the model will be conducted after the database is expanded with additional measurement records. Model testing will include an assessment of the recommendation rankings from both practical and technical perspectives. The system will then be enhanced with expert-based recommendations regarding task similarities – this is crucial for predicting uncertainty for tasks lacking training data. Users will be informed when recommendations are based on partially mismatched tasks, with several scenarios planned, including the option to calculate a weighted average from the best results. A key challenge is not only developing a model with high predictive performance but also ensuring its proper adaptation to market realities and the actual needs of potential users, for example in terms of minimizing measurement uncertainty or supporting the selection of optimal measurement conditions and strategies.

Acknowledgements

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References

[1] ISO 15530-3:2011 GPS CMM Use of calibrated workpieces or measurement standards
[2] ISO/TS 15530-2 (draft) GPS CMM Use of multiple workpiece orientations and calibrated simple standards
[3] Gąska A, Sładek J and Gąska P 2020 In: Proceedings of 5th International Conference on the Industry 4.0 Wang L, Majstorovic V, Mourtzis D, Carpanzano E, Moroni G and Galantucci L (eds) Springer, Cham, 92–104
[4] Rost K Wendt K and Härtig F 2016 *Precis. Eng.* **44** 220-230
[5] Stojadinovic S M, Majstorovic V M, Durakbasa N M and Stanic D 2022 *Meas.: Sens.* **22** 100372
[6] Xia H, Ding Y, Chen W, Zhang J, Li H, Zhao H and Song R 2026 *Meas.* **258A** 119031
[7] Garg N, Yadav S and Aswal D K 2019 *Mapan - J. Metrol. Soc. I.* **34** 299–304
[8] Owczarek D 2017 Uncertainty Model in Optical Coordinate Measurement, *Monograph Cracow University of Technology*