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Analysis of measurement uncertainty contributions of optical sensors for the development of digital-metrological twins in coordinate metrology

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Abstract
To assess the measurement uncertainty of coordinate measuring machine (CMM) measurements, simulation techniques following e. g GUM Supplement 1, such as the Virtual Coordinate Measuring Machine (VCMM) are increasingly important. Particularly for measurement tasks in advanced manufacturing employing optical probing systems on prismatic parts and freeform geometries, measurement uncertainty evaluation by Digital-Metrological Twins (D-MTs) provide great benefits. However, mathematical-physical models are neither widely available nor economically usable, yet. We will present a strategy to systematically study the uncertainty contributions of different optical point sensors systems commonly used on CMM. Furthermore, results of the investigation of influencing parameters, such as the distance to the probed surface, the light incident angles, the point density, and the measuring speed conducted on measurement standards of different surface properties are presented. The reported results are suited to derive D-MT models for the determination of task-specific measurement uncertainty in industrial quality control for the selected sensor's measurement principles

Digital-Metrological Twins, Virtual Coordinate Measuring Machine, Optical Sensor Systems, Coordinate Metrology, Measurement Uncertainty, Advanced Manufacturing

1. Introduction

Modern production of industrial parts spans a wide variety of designs tailored to the need of specific applications, such as automotive engineering, aerospace, healthcare, or energy generation. Therefore, a variety of geometrical shapes, materials and advanced manufacturing techniques are incorporated. This paradigm shift in manufacturing poses a challenge to the quality assurance processes in production metrology and demands metrological methods for the measurements of complex workpieces comprising freeform geometries, such as blades, blisks, medical implants or aspheric moulds [1].

Coordinate measuring systems are a crucial pillar of industrial quality control. They are versatile instruments to measure three-dimensional geometries enabling users to assess the outcome of the production process of almost any part in a wide size range. Particularly, coordinate measuring machines (CMM) allow for high accuracy measurements as required for the evaluation of very tight design tolerances. While tactile measurement techniques have been used for a long time, recent advances in sensor technology and the availability of different commercial optical probing system as part of modern multi-sensor coordinate measuring machines allow for fast, contactless and holistic capturing of the outer geometries of complex parts [2]. The determination of the task-specific measurement uncertainty is crucial in all use cases, and as a consequence of increasing level of complexity of the measurement tasks, the available methods need to be expanded to provide trustworthy and reliable measurement results.

While the Guide to the expression of uncertainty in measurement [3] focusses on measurement uncertainty determination by either statistical analysis of repeated measurements (Type A) or analytical calculations (Type B), its Supplement 1 [4] describes the measurement uncertatinty evaluation by use of Monte Carlo simulations (MCS). In the past decades the latter method has gained more and more importance and is applied to tactile measurements of prismatic geometries by the so-called virtual coordinate measuring machine (VCMM) [5, 6]. The VCMM is a digital-metrological twin (D-MT) of the CMM, including the measurement device, the measurement process and the influeces of environment and workpiece [7, 8]. It can be used for metrological purposes and calibrations, since all model parameters are determined in a traceable manner, models have been validated, and fulfill the conditions of ISO 15530-4 [9].

There are only a few approaches for applying the MCS to the use of optical probe systems [10, 11], and thus, the existing models of VCMM need to be expanded to cover, e.g., the uncertatinty contribution of the probing systems and the surface-light interaction with the workpiece.

Section 2 gives an overview of commonly used optical probing systems and details the relevant uncertainty contributions. Section 3 outlines the methodology to test the influences of different parameters related to the uncertainty contributors, while section 4 provides exemplary results and the implications for a strategy to model the uncertatinty contributions to be included in MCS. Section 5 summarises the work and gives an outlook to future work.

2. Optical probing systems

While modern coordinate measuring machines can be equipped with a large variety of different optical probing systems, interferometric point sensors, line scanning sensors and chromatic confocal white-light sensors (CCS) are among the most common types. Although all of the above are currently investigated within the European Partnership on Metrology's project 23IND12 ADAM [12], this work exemplarily focusses on the characterisation of CCS. Four different CCS probing systems of two manufacturers were investigated. They were mounted on four different CMMs with different measurement volumes and different kinematic configurations.

2.1. Identification of uncertatinty contributors

Besides typical uncertatinty contributions of the geometric construction and the kinematics of the CMM, the thermal properties of the measured part and the environmental conditions, the probing process is an important contributor to the overall measurement uncertainty.

For coordinate measurements incorporating CCS, five possible uncertainty contributors (see fig. 1) tied to the optical probing system where identified:

(1) the step width S of sampled points,
(2) the measurement speed v,
(3) the surface slope angle α with respect to the incoming light,
(4) the measurement frequency f, and
(5) the vertical distance d to the measured object.

The identified parameters are typically selected and modified depending on the measured feature and can (in many cases) be defined by the user/operator of the CMM using the manufacturer's software. It should be noted, that although all optical probing systems of the CCS type share the same measurement principle, the specific build constrains the specifications for each model individually.

2.2. Parameter selection

The goal of the investigation was to retrieve information about possible uncertainty contributions depending on sensor parameters either constraint by the measurement task or set by the software/the operator of the CMM. To determine the range of values for each parameter, the rated operating conditions provided by the sensor manufacturer were considered. In case no specifications were available, the range of possible settings has been tested experimentally by repeated measurement using different parameters. Consequently, for the latter, the limits were set by the lowest and highest parameter values that still allowed capturing of coordinates by the standard operating software provided by the CMM manufacturer.

3. Test strategy

Using the information gathered about the limits of the available sensors, a common test procedure was derived. The goal of the procedure was to conduct the same investigation for each of the different sensors on different CMMs, laying groundwork for comparison and interpretation of commonalities to enable future modelling.

Once the ranges for all contributors of each of the studied CCS probing systems had been retrieved, parameters for the tests were fixed. Therefore, five levels , labeled *low* (L), *medium low* (ML), *medium* (M), *medium high* (MH), and *high* (H), were chosen and calculated for each of the parameters.

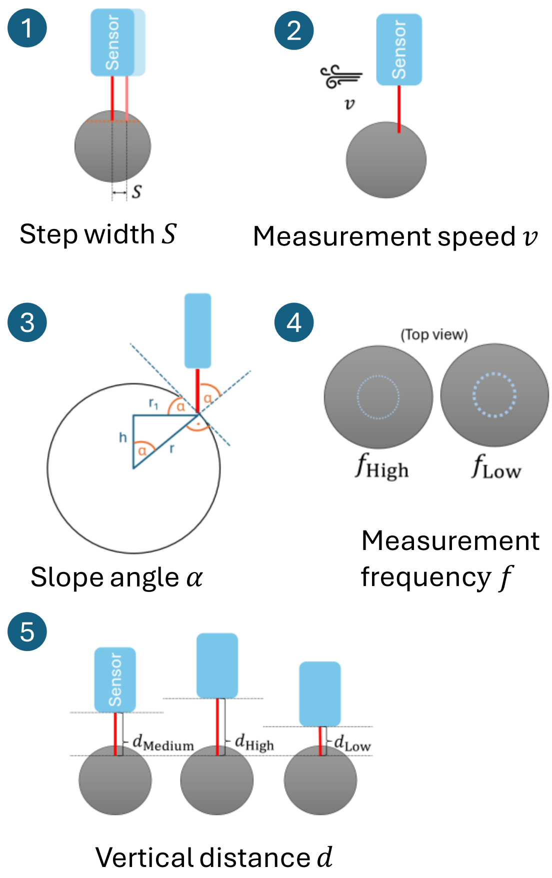

Figure 1. Five measurement uncertainty contributors were identified for investigation.

The selected values were distributed at the fractions of 0.1, 0.3, 0.5, 0.7, and 0.9 of the range specified or determined in experimental studies. For the example of a surface slope angle specified between $\alpha = 0°$ and $\alpha = 40°$ the values for all five levels can be found in table 1. A similar calculation was carried out for each contributor yielding a full set of parameters for the investigation of each CCS.

Table 1 Selected levels for the test of the uncertainty contribution by the slope angle α for a specified range of $\alpha = 0°$ to $\alpha = 40°$.

Level	**Slope angle α**
Low (L)	4°
Medium low (ML)	12°
Medium (M)	20°
Medium high (MH)	28°
High (H)	36°

Using the determined levels, five measurement runs were performed for each of the contributors. In these runs, the other four parameters were kept constant at their medium level, while each level of the tested parameter was set, thus neglecting correlations between the parameters as a first step. Within each of the measurement runs, ten repeated measurements with identical settings were performed.

The selected test strategy was chosen to be generically applicable to other sensors than the CCS as well. It resulted in five sets of five parameter variations each, with five of them being identical, so a total of 21 combination of parameter levels were tested in the study of each CCS probing system available.

In order to separate the general beahviour of the investigated CCS systems from the contribution of the surface properties of the measured part, all measurements were conducted on four calibrated reference spheres (cf. fig. 2). They were made of ceramics and metal, respectively, and covered a wide range of surface roughness levels.

It should be noted that for the comparability and interpretability of any results obtainted during the measurements, it is of utmost importance to minimise any additional measurement deviations resulting from the probe qualification process and the determination of the workpiece coordinate system (WCS). Thus great care was taken, that the procedures used for these purposes were aligned.

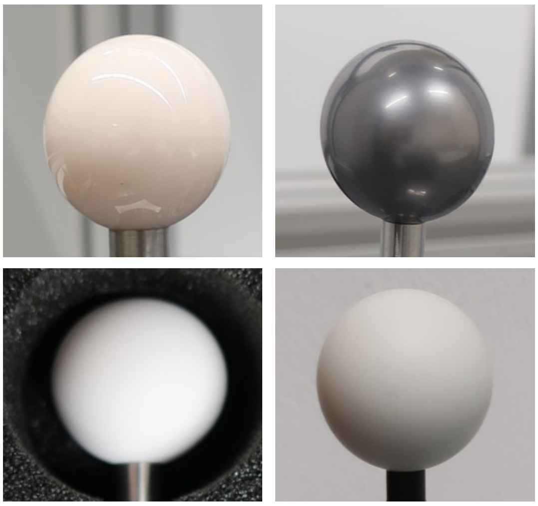

Figure 2. Four different reference spheres were used to test the dependency of parameters on workpiece properties, such as roughness, material, and colour.

4. Results

4.1. Measurement results

By analysis of measurements following the test strategy described in section 3 and using the reference spheres depicted in fig. 2, some commonalities and trends can be extracted.

From the measurement of circle paths on the surface of the reference spheres, the respective deviation to the spheres' calibrated radii were computed.

In a first step, a comparison to tactile measurements of a reference sphere with a polished surface has been carried out. For this purpose, measurement data has been gathered in single point measurement mode and scanning measurement mode for both of the sensor types, i.e., tactile and optical sensors, respectively. An example of the observation can be seen in fig. 3.

The results show both, an offset of the measured radius with respect to the calibrated radius, as well in comparison of the optical measurements to the tactile measurements. In contrast, no signifiact discrepancy between single point measurements and scanning measurements could be observed for any of the two sensors. However, a characteristic directional behaviour of the optical sensor is present for the single point mesasurements and the scanning measurements alike. The curve depicted in fig. 3 is representative for this particular sensor, but may differ in shape amplitude, as well as position of peaks and dips for different sensors.

In addition to the comparison of tactile and optical measurements, the systematic variation of the parameters provides valuable information on the trends in the measurement behaviour of the CCS probing systems.

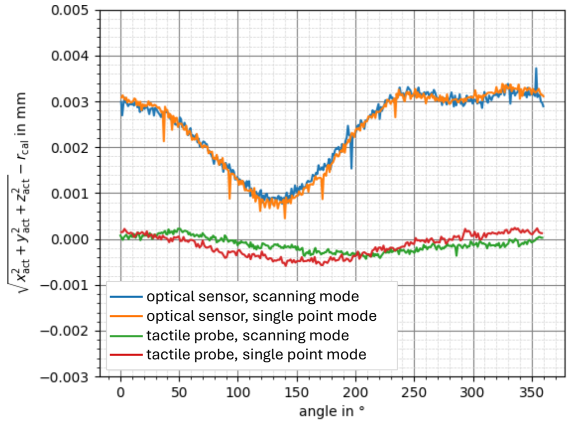

Figure 3. The comparison of the results from tactile and optical measurements show a characteristic directional devitation of the measurement of the optical sensor as well as an overall offset with respect to the calibrated radius.

An example of the results for the parameter *measurement velocity* that has been evaluated for one of the CCS probing systems using all four reference spheres, is displayed in fig. 4.

In this case, for each of the measurements using the same reference sphere (i.e., the same panel of fig. 4) it is clearly visible that the velocity dependence is very weak, if not negligible. Furthermore, an increase in scattering of the deviations can be observed with rising surface roughness of the measured objects (top to bottom panels in fig. 4). Both findings are plausible, while particularly the latter can be expected as a results of local surface variation with respect to the spot sizes of the CCS probing systems, which are typically a few micrometers in diameter.

While some of the parameter variations show clear trends or indicate that they do not influence the measurement results, for other influences this is not the immeditate case. These need more detailed investigations to create a solid base for modelling of the sensor behaviour.

In general, neither an influence of the selected step width nor of the measurement frequency could be observed in the study. For some of the CCS, a variation of the measurement speed showed slight shifts in the characteristic deviation curve of the respective sensor, while maintaining the overall shape of the curve. The attribution of this finding to the sensor or the CMM kinematics is further scrutinized in future work. A clear dependency of the observed radial deviations was visible for the vertical distance of the sensor to the probed surface and the local surface slope angle.

4.2. Implications for modelling

For the modelling of uncertainty contributions it is of great importance that the behaviour of the sensor can either be described by a model equation or by an empirical look-up table characterising the influence on the measured 3D coordinates. In case a model equation can be set up, this is favorable.

Since the metrological conditions of the measurement system may change depending on the measurement settings and strategy, parameters of the model equations have to be determined to enable reliable results. Thus, they have to be described by statistical properties of the realistic parameters, such as their mean value and their probability distribution function.

To enable a wide-spread usability of the D-MT models for the analysis of measurement uncertatinty, traceability to the international system of units (SI) has to be established and users of D-MTs including the models have to be assisted by suitable strategies to derive parameters and their distribution functions. This can be achieved by measurement plans and evaluation routines tailored to the CCS probing system that are carried out on calibrated measurement standards.

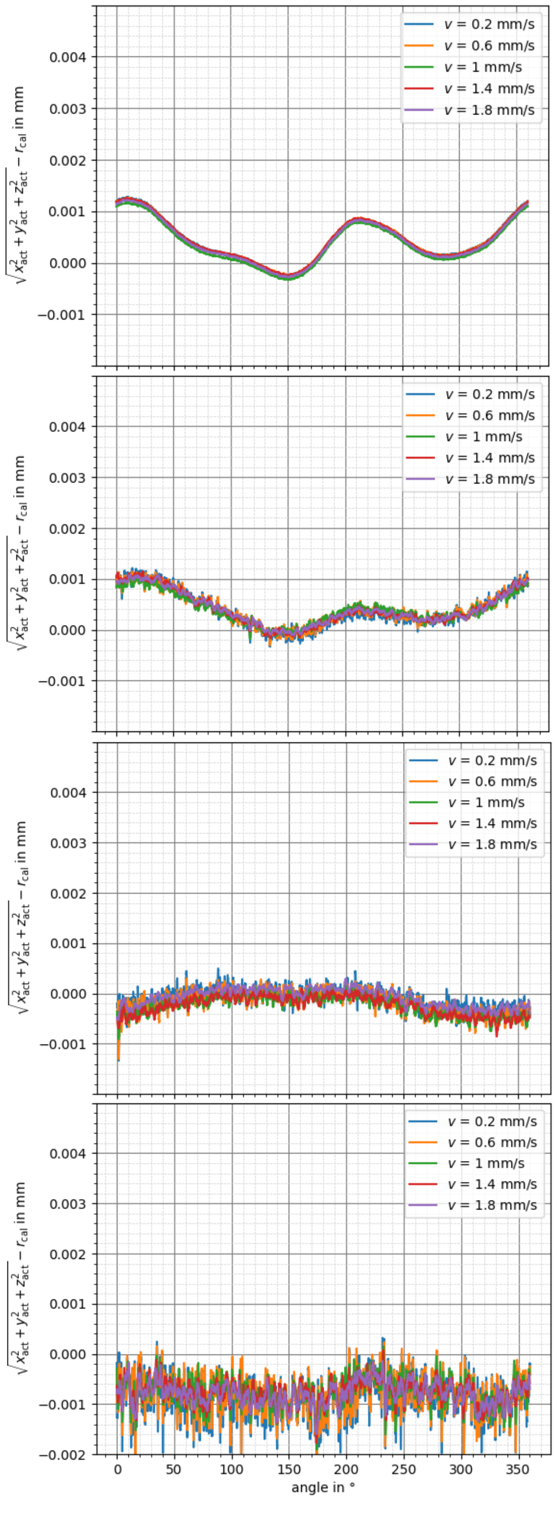

Figure 4. Four different reference spheres have been measurend with settings of five different levels of each parameter. The example of the velocity dependence shows a characteristic deviation behaviour for each object and a clear increase in scatted with increasing surface roughness from top to bottom.

5. Conclusions

In this work, a method has been presented to assess parameters contributing to the measurement uncertatiny of coordinate measurements using chromatic confocal sensors on CMM (cf. section 3). The parameters have been tested within the specified or evaluated limits of their respective parameter range enabling judgements on their respective importance and providing evidence for strategies to derive models to include in D-MTs (see section 3).

While for some parameters, no influence of their variation on the outcomes of the measurements could be observed, in particular, a clear dependency of the observed radial deviations was visible for the vertical distance of the sensor to the probed surface and the local surface slope angle. As presented in section 4, in general, increased scatter of coordinate measurements was present with increased surface roughness of the workpiece. Since not all of the tested parameters showed a clear trend that could be described by a model equation, further investigations will focus on these. Furthermore, it should be noted, that the possible correlations between different uncertainty contributors have to be investigated in future work

The identified influences will be modelled based on the experimental results and are expected to be included in D-MTs such as the VCMM.

Acknowledgments

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