Knowledge-based uncertainty estimation of dimensional measurements using visual sensors

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Abstract. The aim of this paper is to present an approach to the uncertainty estimation of dimensional measurements on coordinate measuring machines preferably by means of visual sensors. The primary ambition of this paper is to contribute to the automatable and therewith reproducible and comparable measurement uncertainty estimation in coordinate measurement technique using visual sensors. The novel approach uses quality information about the measurement for predicting the uncertainty associated with the measurement. Foundations are laid for indicating the complete measuring result, consisting of the best estimate and the expanded measurement uncertainty, under practice-relevant measuring conditions. In this regard, individual characteristics of the unit under test are advisable considered, because essentially image information is used for evaluating the measurement uncertainty.

1. Introduction

The fact, that the measurement result contains uncertainty, is as old as the measuring itself. The metrological experience demonstrates, that measuring processes never can be controlled perfectly and that measuring conditions are never exactly known and to be remained stable. Due to the incomplete knowledge about the measuring process it is impossible to assign the true value to the measuring quantity. Arising from the definition, measurement uncertainty is a quantitative measure for the quality of a measurement result [1]. The confidence in comparability of measurement results is of great importance in national trade and international exchange of goods. The comparability of measurement results is expedient only if the measurement uncertainty is compared too and if the measurement uncertainty is determined under a uniform procedure [2].

Dimensional Measurements form a fundamental subarea in production measurement technology. They are essential elements of the quality assurance [3]. In the majority of cases measurements on technological components can be realised only contactless. The numerosness of inspection features per component requires small measuring times suitable for the appliance in production measurement technology. Due to the contactless operation mode, the large operating distance, the concomitant large measuring range and the short measuring time the measurement of lowest dimensional inspection features is advantageously realisable using optical measuring principles preferably by means of visual sensors.
2. Uncertainty estimation of image-based measurements

2.1. Suitability of the GUM procedure for image-based measurements

The Guide to the Expression of Uncertainty in Measurement (GUM) [4] establishes general rules for evaluating and expressing uncertainty in measurement. Using this rules the approaches suggested in [5] and [6] enable the evaluation of measurement uncertainty also for complex measuring systems. This requires a model of the measuring process, whereas the modeling concept is based on the idea of the measuring chain. The measurand and other influence quantities are considered according to the ISO-GUM [4] as causative signals.

It was found out that for dimensional measurements based on image processing the cause-effect concept of the ISO-GUM procedure is realisable in practice only with great effort [7]. On the one hand dimensional measurements are always associated with fitting algorithms for appropriate geometry elements. These iterative algorithms effect that the standard-ISO-GUM procedure is not applicable, because it is not possible to set up a closed model equation. A possible solution of this problem is to use the Monte-Carlo method, recommended and explained in detail in the first supplement to the ISO-GUM [8], [9]. On the other hand it is of particular importance that the digital image of the unit under test is the foundation of any dimensional image-based measurement. But the causes for effects on images are very multifarious and interdependent.

It is not possible to find the correct cause only on the basis of the particular image. And it is not possible to analyse the measurement result, for example the radius of a circle, only on the basis of parameter settings and other influences on the image-based measuring process. Following this, the principle of the ISO-GUM, that analyses and describes influence quantities as causes of measurement errors in form of PDF and yields to a PDF for the measurand, associated to the model equation, is not suitable for image-based measurements.

2.2. Suitability of ISO/TS 15530-3:2004 for image-based measurements

Another methodology for determining the uncertainty of dimensional measurements, given by ISO/TS 15530-3:2004, is based on substitution measurements. It provides an experimental technique for simplifying the uncertainty evaluation of coordinate measuring machine (CMM) measurements, whose approach leads to measurements being carried out in the same way as actual measurements, but using calibrated workpieces of similar dimension and geometry instead of the unknown workpieces to be measured [10]. The procedure requires repeated measurements for uncertainty estimation, connected with a large time investment. The major difficulty is to find an adequate calibrated workpiece meeting the demands for using the methodology of [10] for example:

- Similarity to dimension and design
- Similarity to surface texture
- Similarity to material property
- Similarity to inspection features

The acquisition of such a workpiece is extensive and only profitable for high volume measurements.

3. Novel approach for the uncertainty estimation of image-based measurements

3.1. Specific characteristic of image-based measurements

A new method of measurement uncertainty estimation of dimensional measurements on a CCM using visual sensors and image processing has been developed. It is based on knowledge about the quality of the image, especially the part or detail of the image, which contributes to the detection of coordinate points as a measure for the dimension of the unit under test. For this purpose it is of particular importance that the digital image of the unit under test is the prerequisite of any dimensional measurement. Surface structures with intensity junctions or contour lines of workpieces play a decisive role for the measurement themselves. They are the general basis for edge detection in the
image. According to this the effect, the digital image of the unit under test, is exclusively considered, in the image-based measurement technique. Image parameters like contrast, transitions or intensity could be utilized for evaluating the quality of edge detection. In the following these image-based quantities are called quality parameters QP. Such image quantities with a high quality, i.e. high contrast or small transition, are correlated with a low uncertainty of resulting coordinate points. The idea is to estimate the uncertainty using the real quality of representative image quantities and to use the knowledge of the effect which is caused by them.

Exemplary the influence of the unit under test can impact the quality of a digital image in different ways. Images of units under test, for instance made of transparent materials like plastics, normally have a low contrast and look like out of focus. But also units under test with ideal edges just right for image measurements can cause incorrect measuring results, for example in the case of unfavourable measuring conditions and parameter settings or inexperienced operators (figure 1).

Figure 1. Image examples: a) ideal unit under test, 2D-calibration standard made of glass and coated with chrome, measured under optimal parameter settings, b) transparent casting made of plastics, measured under optimal parameter settings, c) 2D-calibration standard made of glass and coated with chrome, measured under unfavourable parameter settings (too high illumination intensity) [7].

3.2. Application of a knowledge-based method for uncertainty estimation
Due to the high complexity and the incomplete information about image measurements, knowledge-based technique will be used for uncertainty estimation. This is based on rules which infer new knowledge using existing knowledge and a defined logical inference relation. In this regard determining the inference relation is the major difficulty because of the incompleteness of existing information and the fuzziness of the knowledge base [11], [12]. The inference relation is realising the deduction of general functions from special observations to yield further assumptions, especially an estimate for uncertainty. It should be experimentally examined.

Transferred to the problem of this paper, existing knowledge is extracted from preliminary analyses. The digital image of the measuring scene thereby acts as a passive knowledge memory. Referring to inspection features, relevant quality parameters QP are evaluated within the knowledge acquisition component (figure 2). On the basis of the inference relation in the knowledge processing component the measurement uncertainty of an individual analysis is estimated.

Figure 2. Schematic illustration of a knowledge-based system [11] adapted to the uncertainty estimation of image based measurements.
3.3. Procedure for determining the measurement uncertainty of image-based measured coordinates

The novel knowledge-based approach is divided in preliminary analyses, which are corresponding to
the knowledge acquisition, and an individual analyse of the current image, which is in accordance with
an actual (online) measurement (figure 4). The measurement uncertainty of the individual analyses is
determined inferring from information of preliminary analyses saved in the database.

The basic idea of the approach determined in this paper is based on analysing the signal trace along
search lines. Quality parameters QP are used for evaluating the uncertainty of detected edge points.
During the measurement a set of QP is determined by the processing- and controller unit of the
measuring instrument. Examples of QP are transitions, contrast, intensities and standard deviation of
grey values within special ranges of the image signal trace. The criterion of edge detection used in
measurement has essential influence on the values of determined coordinates and therefore on the
feature-based measurement uncertainty. For the definition of QP the algorithm of edge detection and
thetwether the operations used for analysing the signal trace are of extreme importance (figure 3).
Quality parameters suitable for the procedure should be significantly correlated with the standard
deviation of repeated measurements. The level of significance is based on experience in the context of
preliminary analyses. By way of example, table 1 shows the significant QP for a special kind of
measuring task. All these significant QP are used within the inference relation.

Due to the fact that the inference relation is valid only for a special kind of measuring task,
previously the definition of a measuring type is necessary. A measuring type X is defined by the
assignment of during the measurement used measuring equipment/hardware-configuration (e.g. type
of sensor, reproduction scale of the objective, illumination type, setting of measuring parameters) and
the used software-configuration (e.g. edge detecting criteria, fitting algorithm). At first within
preliminary analyses measuring instrument settings according to a measuring type and a set of
significant QP are determined and for further access filed in the database (figure 4). Estimating the
measurement uncertainty is reliably realisable only if preliminary analyses of the same measuring type
are used as knowledge base. Within preliminary analyses for each measuring type repeated reference
measurements are operated.

Table 1. Example of significant QP for a special measurement type with correlation coefficients to
experimental determined standard deviations.

| QP                                      | Correlation coefficient |
|-----------------------------------------|-------------------------|
| lower frequency centroid $SP_1$        | 0.47                    |
| centroid difference $\Delta SP$         | -0.44                   |
| lowest grey value in the subpixel area $GW_{SP,min}$ | 0.47 |
| contrast in the subpixel area $K_{SP}$ | -0.52                   |
| median contrast $K_m$                   | -0.64                   |
| median intensity $I_m$                  | 0.56                    |
| difference to a step function $\Delta step$ | 0.41 |
| standardised medium $s_{standard}$      | 0.42                    |
| standard deviation $s_{standard}$       | -0.63                   |
| slope of a regression line in the subpixel area $A$ | 0.91 |
| propagated noise of the measurement system $N_P$ |                         |

Figure 3. Illustration of QP derived from the signal trace
According to this, a set of significant QP and the standard deviation $\sigma$ associated with measuring type $X$ are determined and filed in the database. In this connection, the standard deviation is used as the best estimate for the standard uncertainty [13]. Individually measured values and quality parameters QP are determined in conjunction with the carrying out of subsequent individual analysis for the predefined measuring type $X$. Calculating the measurement uncertainty of the individual analysis is based on the inference relation and the individual QP. The inference relation delivers an uncertainty estimate for the actual detected coordinate in dependence of the measuring type-based significant set of QP. In this way the novel approach yields to estimates for $x$- and $y$-components of coordinate uncertainties in image-based measurements.

3.4. Exemplification of the novel method
Detecting coordinate points on different units under test, the novel method on estimating associated uncertainties will be tested. Typical units under test with defined microstructures are etalons. It is assumed that the edge detection on these structure transitions delivers low uncertainty.

The mean standard uncertainty of detected coordinate points along a circle on an etalon is approximately $0.12 \, \mu m$, estimated by the novel knowledge-based method. By comparison, the mean standard uncertainty of detected coordinate points along a circle on an industrial conductor plate yields to approximately $0.20 \, \mu m$. Furthermore, as shown in the diagram (figure 5) the estimated uncertainty (mean of $u_x$ and $u_y$) of coordinate points on the micro etalon is considerably more homogeneous and lower than on the conductor plate.
4. Propagation of coordinate uncertainties to the measurement uncertainty of dimensional inspection features

Usually, dimensional measurements are based on point clouds. Using fitting algorithms the quantities of the inspection features are calculated. In the same way the uncertainties of all included coordinates can be propagated to inspection feature quantities using the Monte-Carlo-Method (MCM) [9].

For using MCM, the quantity to propagate has to be described by a probability density function (PDF). According to the central limit theorem the determined coordinate uncertainties can be taken for granted as normal distributed, because within the knowledge-based estimating a multitude of quantities is combined. This fact corresponds to the covering of random variables. Based on experiments the assumption of normal distributed coordinates was validated. Using statistical tests the distribution type of image-based measured coordinate values was examined. The histograms of x- and y values of a repeated coordinate measurement yield to approximately normal distributed frequencies (figure 6). Based on hypothesis tests on normal distribution, especially the tests of Kolmogorov-Smirnov/Lilliefors and D’Agostino, the hypothesis of normal distribution was confirmed.

![Figure 5. Comparison of the standard measurement uncertainty associated to detected coordinate points on two different units under test.](image)

![Figure 6. Graphical representation of the frequency distributions for x- and y-coordinates of a 1000 times repeated image-based measurement.](image)
In figure 7 the measurement of a straight-line on a micro-structured unit under test is demonstrated. Figure 7 a) shows the edge detection with five search lines. In figure 7 b) the uncertainty of each determined coordinate is illustrated. Regarding this, for the x- and y-component of each detected point uncertainties are estimated using the knowledge-based approach. According to experimental examination results the coordinate uncertainty is characterised by a two-dimensional normal PDF. The values of x- and y-uncertainties of each coordinate can vary, corresponding to the set of QP calculated on the basis of the search line signal trace. Using the MCM [9] coordinate uncertainties are propagated based on fitting algorithm. In figure 7 c) the fitted straight-line is illustrated, described by a linear function with uncertain parameters. If, for example, the inspection feature is the distance between two parallel lines, than the uncertain line parameters could be subsequently propagated. Thereby, the multitude of coordinate uncertainties is reduced to only one uncertainty value for the distance.

5. Conclusion
Within the first part of the paper it was exemplified that existing procedures to the evaluation of measurement uncertainty using the cause-effect principle are not efficiently applicable to image-based measurements.

The methodology presented here is based on the essentially utilisation of image information for the estimation of measurement uncertainty. Fundamentally, the novel knowledge-based approach is built on an explicit database, which consists of measurement results of preliminary analyses and regularities for a set of quality parameters QP. Based on QP of an individual measurement and the knowledge-based data the uncertainty of an edge detection is estimated using an inference relation.

According to this, the novel knowledge-based approach lays the foundation for indicating the complete measuring result consisting of the best estimate and the expanded measurement uncertainty for practice-oriented image-based measurements.

The knowledge-based uncertainty estimation method is executing on-line to the measurement. Hence, immediately after the measurement it quantitatively replies to the question: How good is the quantity value reflected by the measurement result? The measurement uncertainty, estimated using the new knowledge-based approach, enables the users to evaluate the reliability of the measurement result and to compare the results of different measurements of the same measurand, without supplemental experiments.

It could be shown, that the new method gives estimates of uncertainty which are practicable and adapted to the real image quality. The results presented in this paper can be applied in any kind of dimensional image-based measurements using visual sensors.

Prospective research activities will deal with the extension of the knowledge-database on the basis of further preliminary analysis for different measuring types. In this way the application area of the novel uncertainty estimation method will be enlarged.
Furthermore, the reliability of the estimations should be tested by comparisons with conventionally evaluated measurement uncertainties. If the deviations of the knowledge-based procedure were in an acceptable range, the automatable method could be used in the industrial measurement technique. There it would lead to the reduction of measurement times and in connection with this to the reduction of measuring cost.

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