PROCEEDINGS

53. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

Faculty of
Mechanical Engineering

PROSPECTS IN MECHANICAL ENGINEERING

8 - 12 September 2008

www.tu-ilmenau.de

TECHNISCHE UNIVERSITÄT
ILMENAU

Published by
Impressum

Publisher Herausgeber	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff
Editor Redaktion	Referat Marketing und Studentische Angelegenheiten Andrea Schneider Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurz, Univ.-Prof. Dr.-Ing. habil. Rainer Grünwald, Univ.-Prof. Dr.-Ing. habil. Prof. h. c. Dr. h. c. mult. Gerd Jäger, Dr.-Ing Beate Schlütter, Dipl.-Ing. Silke Stauche
Editorial Deadline Redaktionsschluss	17. August 2008
Publishing House Verlag	Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16, 98693 Ilmenau

CD-ROM-Version:

Implementation Realisierung	Technische Universität Ilmenau Christian Weigel, Helge Drumm
Production Herstellung	CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

ISBN: 978-3-938843-40-6 (CD-ROM-Version)

Online-Version:

Implementation Realisierung	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=17534

53^{rd} Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
08 – 12 September 2008

K. Weißensee / G. Linß / O. Kühn

Modelling of an Optical Coordinate Measurement Process for Uncertainty Estimation

INTRODUCTION

From various points of view measurement uncertainty is technologically and economically important. The most difficult problem in ISO-GUM-based [1] uncertainty estimation is to develop an appropriate model of the measuring process suitable for estimating of the measurement uncertainty. A model may serve to evaluate the original measuring process or to draw conclusions from its behaviour [2], [3]. The knowledge about the measuring process is represented by the model equation which expresses the interrelation between the measurand and the input quantities.

It is the aim of this paper to present a methodology based on the ISO-GUM procedure to the modelling of a measurement process prevalent in quality assurance. The suitability of the presented methodology is being evaluated for dimensional measurements on a coordinate measuring machine with visual sensors and image processing.

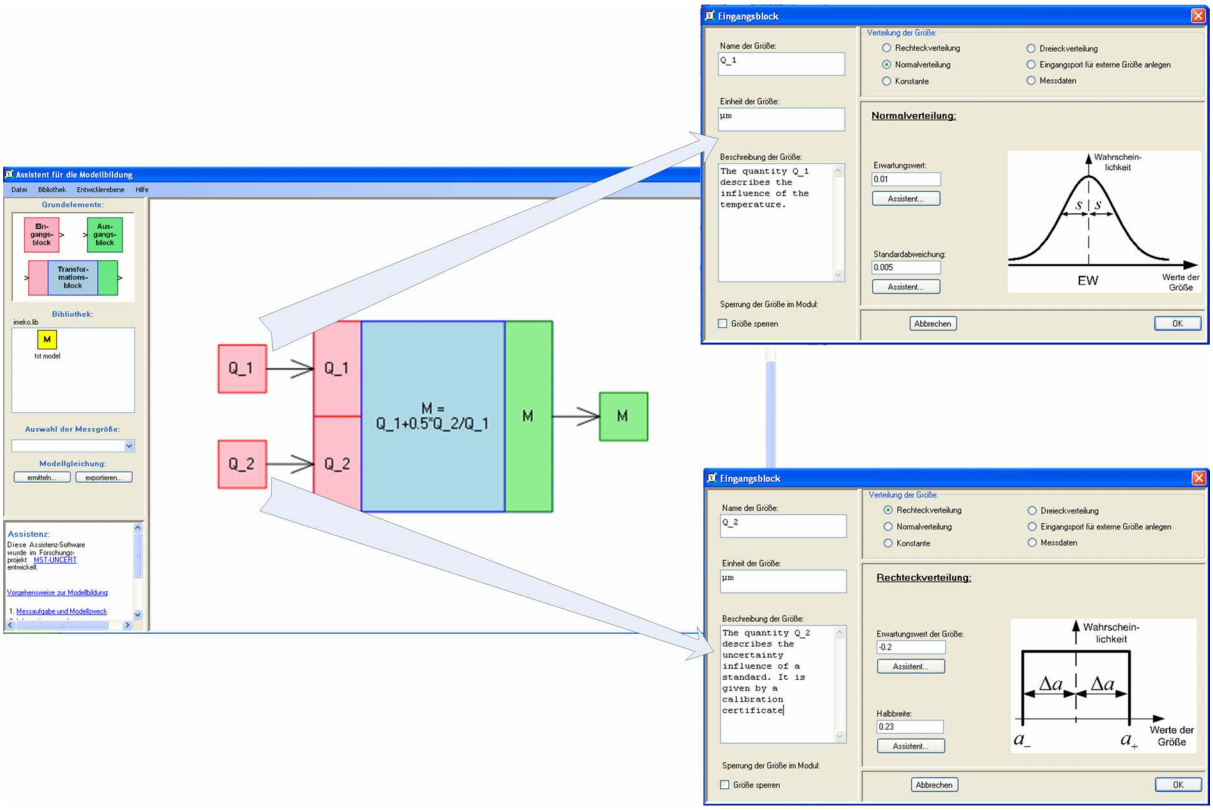
GRAPHICAL MODELLING PROCEDURE FOR UNCERTAINTY ESTIMATION

The presented modelling procedure yields to enable the construction of models for evaluating measurement uncertainty also for complex measuring systems by using a combination of different pragmatic and theoretic principles, whereas the modelling concept is based on step-by-step decomposition of the measuring chain [4], [5]. Decomposition in this context refers to the process of breaking a complex problem down into easily-understood and achievable parts. Its advantages are the structuring and the reducing of complexity of the measuring process. For the purpose of uncertainty evaluation the step-by-step decomposition is used to create an appropriate model of the measuring process. For uncertainty evaluation based on ISO-GUM [1], knowledge about the measurement process and the quantities and parameters that may influence the measurement result is needed. The knowledge about the influence quantities is represented by appropriate probability density functions (PDF) whereas the knowledge about the measurement process is expressed by the so-called model equation [6]. It poses a big challenge to set up the whole functional principle of complex measuring systems. But for the limited purpose of measurement uncertainty evaluation the effort on system analysing and modelling will considerably be reduced if a systematic structured procedure is applied. For the purpose of the mathematical expression of the relationship between the measurand, the indication and the relevant influence quantities, the cause-and-effect approach has been proved to be very useful [2].

According to this approach and the decomposition principle the investigated system is divided into its basic functional components and their interconnections are defined. All components are represented in a graphical model ordered along the cause-and-effect relationship [6]. The measuring chain constitutes the path of the measurement signal from cause to effect. The graphical model gives a clear impression of all system components even for complex measurement systems. It facilitates the understanding of the cause-and-effect relations and it allows for assigning influence quantities and uncertainty contributions to their causing components. The main objective is primarily not a functional description of the measurement system but a representation of the system structure related to the evaluation of measurement uncertainty [6]. After arranging and connecting all system components in a block diagram, there is a need for describing the functional behaviour and parameters of each component. Equations are contained in transformation blocks with an arbitrary number of input and output quantities.

Within the cooperative research project MST-UNCERT the application software “Model Assistant” was developed. The software intends a stepwise user-guide for graphical modelling. The graphical visualisation and connection of basic modelling elements is realised (Fig. 1). Quantities of the model are being characterised conforming to the ISO-GUM [1]. Components of a model called modules can be saved and reused. It is possible to export models as XML-file and to use them in other programs for uncertainty calculation. On the basis of these models the uncertainty calculation can be realised according to ISO-GUM [1] or by means of “Monte-Carlo Simulation” [7, 8].

In this paper the trail version of the novel application software “Model Assistant” is used for the exemplary modelling of an optical coordinate measurement process and for the applicability test of the presented modelling method for such measurement processes.



Assistenz:
Diese Assistenz-Software wurde im Forschungs-projekt MST-UNCERT entwickelt.

Vorgehensweise zur Modellbildung:

1. Messaufgabe und Modellzweck

Name der Größe: Q_1
Einheit der Größe: µm
Beschreibung der Größe: The quantity Q_1 describes the influence of the temperature.
● Normalverteilung
Erwartungswert: 0.01
Standardabweichung: 0.005
☐ Größe sperren

Name der Größe: Q_2
Einheit der Größe: µm
Beschreibung der Größe: The quantity Q_2 describes the uncertainty influence of a standard. It is given by a calibration certificate
● Rechteckverteilung
Erwartungswert der Größe: -0.2
Halbbreite: 0.23
☐ Größe sperren

Fig. 1 “Model Assistant” with a simple model consisting of two uncertainty contributions Q_1 and Q_2. For characterisation of the input quantities Q_1 and Q_2 separate dialogue windows are used.

For application of the model equation, all input quantities have to be described by a PDF which specifies the expectation value and its range of uncertainty. Evaluation of statistic information (ISO-GUM-Type A) is possible for experimental data x_i. The mean value q (1) and the standard deviation s (2) of a series of direct observations deliver the parameters of the probability distribution.

$$q = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (1),$$

$$s = \frac{1}{n-1}\sum_{i=1}^{n}(x_i^{\,2} - q) \quad (2)$$

Evaluation of non statistic information (ISO-GUM-Type B) is based on experience and estimated values. A distribution function, e.g. Gaussian or rectangular distribution, and its parameters have to be specified.

The selection of a calculation method for uncertainty evaluation complies with the mathematical properties of the model equation. For linear model equations, the Gaussian uncertainty propagation can be applied [1].

Nonlinear model equations need the application of the Monte-Carlo-Method [8]. In that case all input quantities are represented by random numbers according to their probability distribution. The following calculation by the model equation provides the probability distribution of the measurand which allows for calculation of the expectation value and the associated measurement uncertainty. For the evaluation of measurement uncertainty it is necessary to convert the resulting mathematical model to the measurand. The cause-and-effect model has to be established in a way that it can mathematically be converted into the model equation [6]. Figure 2 visualises the stepwise standard-ISO-GUM procedure.

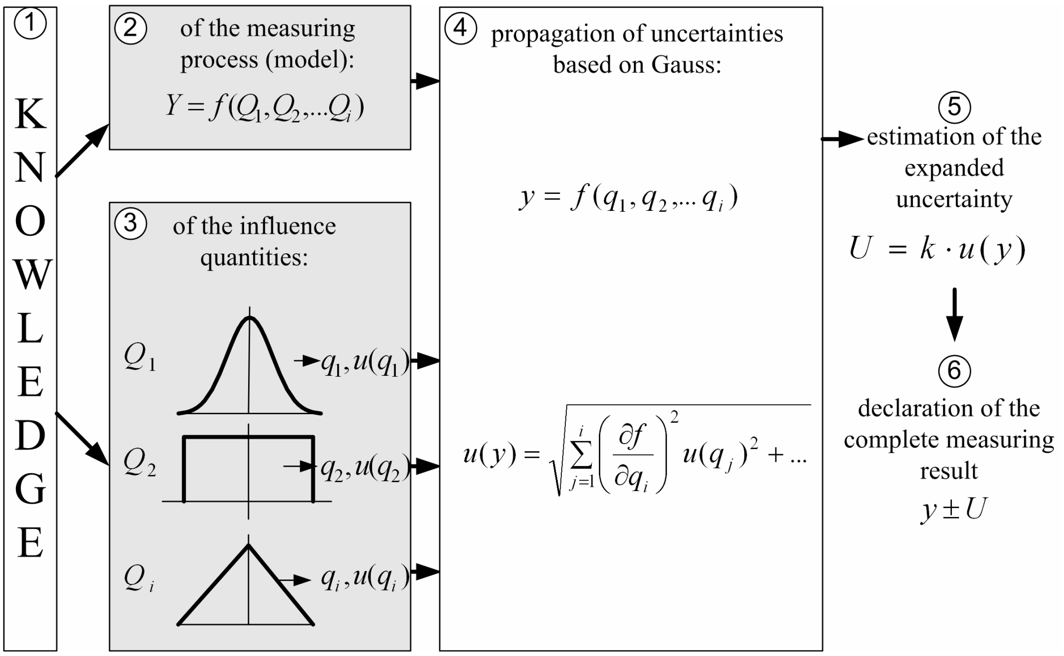


Fig. 2 Illustration of the concept of the ISO-GUM procedure [1]. Symbols: Y - measurand; $Q_1, \ldots Q_i$ - input/influence quantities; $y = E[Y]$ - expectation/best estimate of the PDF for the measurand; $u(y)$ - standard uncertainty associated with $y = E[Y]$; $q_1, \ldots q_i$ - expectations of the PDFs for the input quantities; $u(q_1), \ldots u(q_i)$ - standard uncertainties associated with $q_1, \ldots q_i$, k - coverage factor; U - expanded measurement uncertainty [2].

EXEMPLIFICATION OF THE MODELLING PROCEDURE

The considered measurement task for this example is a dimensional measurement on the optical coordinate measuring machine ZKM 250. The measurand was the radius of a 2D-calibration standard with given expanded measurement uncertainty. For visualisation of the cause-effect relationship the Ishikawa diagram, a capable tool for the graphical arrangement of uncertainty causes, is used (Fig. 3).

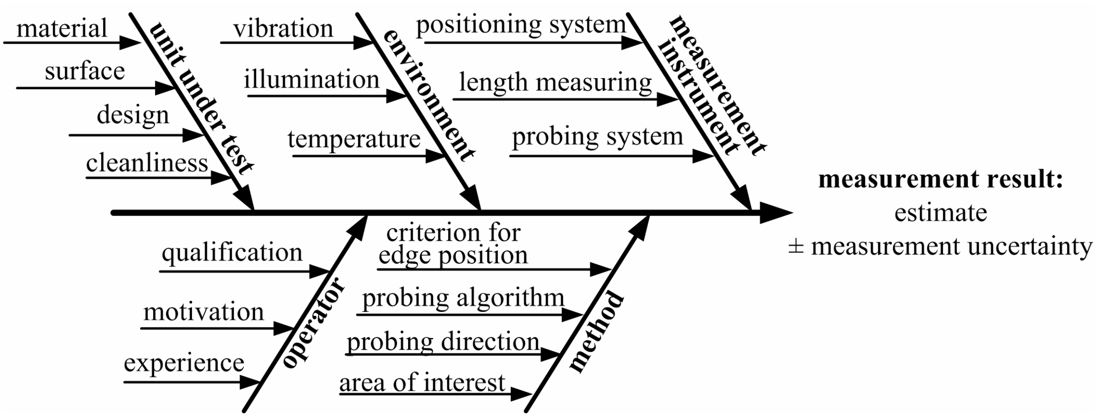


Fig. 3 Ishikawa diagram with influences on the measurement result for dimensional measurements on coordinate measuring machines with visual sensors.

The exemplification of the presented procedure demands using the decomposition method for evaluating measurement uncertainty. The first decomposition step (black-box) is based on repeated measurements that directly deliver values of the measurand. The deviation of these values represents effects of all influence quantities of the measuring process. In repeated measurements a standard deviation of $s=u_c=0.02\ \mu\mathrm{m}$ for optimal measuring conditions and parameter settings was calculated. Under unfavourable measuring conditions and parameter settings for example in case of measurements realised by non-experts a standard deviation of $s=u_c=0.15\ \mu\mathrm{m}$ was achieved.

In the second step the measuring process is decomposed into three clearly delimitabled and self-contained components: The coordinate measuring machine (CMM), the probing system and the unit under test (UUT). Within the third step the probing system is decomposed further in optical system and image processing (Fig. 4).

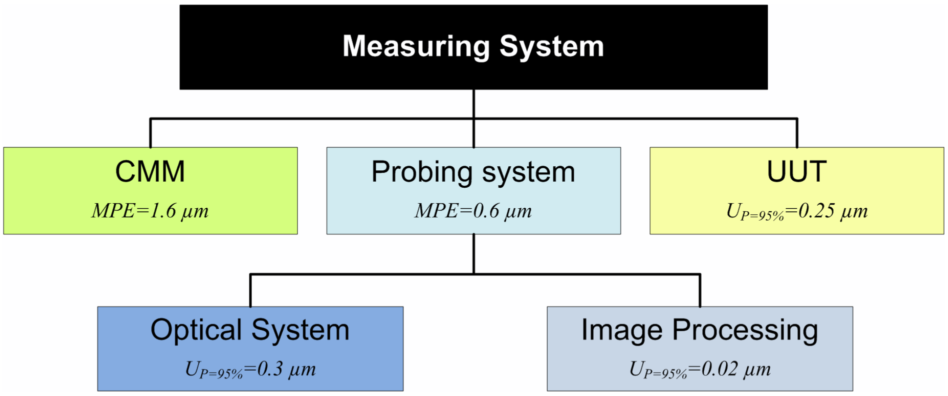
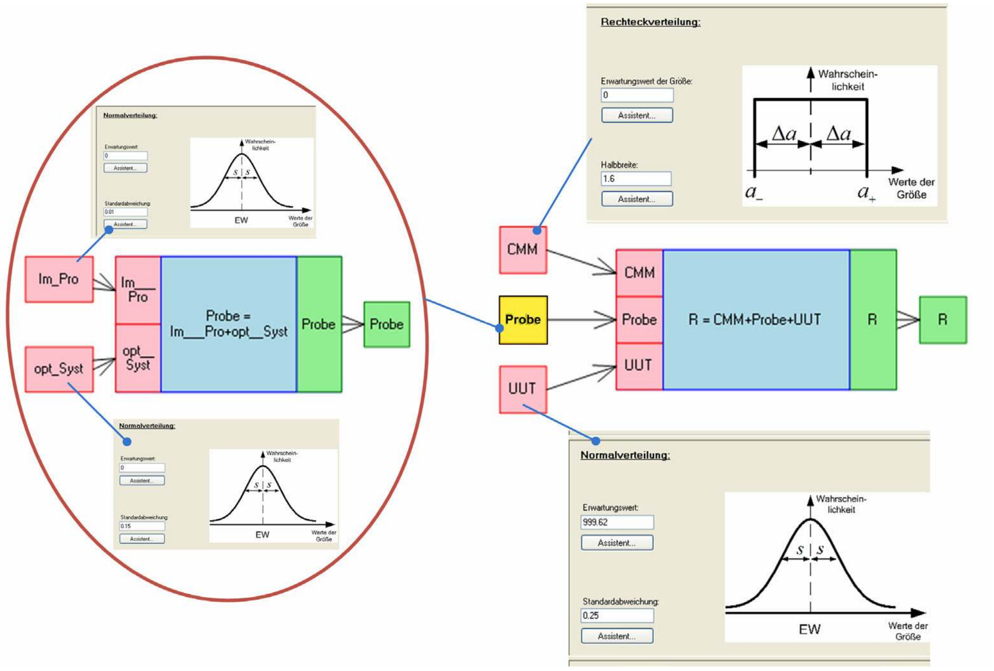


Fig. 4 Decomposition steps of the radius measurement with 2D-CMM and visual sensor system combined with image processing.

These components are characterised according to ISO-GUM-Type B based on given information on calibration certificates. The calibration certificate of the CMM gives a maximal permissible error (MPE) of $1.6\ \mu\mathrm{m}$ for 2D-measurements. A rectangular PDF with half-width=$1.6\ \mu\mathrm{m}$=MPE is used to characterise the influence contribution of the CMM. On the calibration certificate of the UUT, the 2D-calibration standard, the expanded measurement uncertainty is given with $U_{P=95\%} = 0.25\ \mu\mathrm{m}$. A normal or Gaussian PDF with standard deviation $s = u = U_{\mathrm{P}=95\%}/2 = 0.125\ \mu\mathrm{m}$ is used to describe the error of the UUT. The manufacturer of the optical probing system specifies MPE=$0.6\ \mu\mathrm{m}$ for 2D-measurements. This component is characterised as rectangular PDF too. In the third decomposition step it is divided into the uncertainty contributions of the optical system and image processing. For the optical system the expanded uncertainty is given with $U_{P=95\%} = 0.30\ \mu\mathrm{m}$. A normal or Gaussian PDF with standard deviation $s = u = U_{\mathrm{P}=95\%}/2 = 0.15\ \mu\mathrm{m}$ is used to describe the error of the optical system. The influence of the image processing according to the described measuring task was estimated by experiments using type-A evaluation of measurement uncertainty [1]. Also a normal PDF with standard deviation $s = u = U_{\mathrm{P}=95\%}/2 = 0.01\ \mu\mathrm{m}$ is used to characterise this influence quantity. For graphical illustration the “Model Assistant” is used (Fig. 5).



Erwartungswert: 0
Standardabweichung: 0.01

Erwartungswert: 0
Standardabweichung: 0.15

Erwartungswert der Größe: 0
Halbbreite: 1.6

Erwartungswert: 999.62
Standardabweichung: 0.25

Fig. 5 Model in the third decomposition step with the component probing system (Probe) as submodel using the “Model Assistant”.

SUITABILITY OF THE PRESENTED PROCEDURE FOR IMAGE MEASUREMENTS

The presented approach enables the evaluation of measuring uncertainty also for complex measuring systems by using a combination of different pragmatic and theoretic principles, whereas the modelling concept is based on the idea of the measuring chain. The measurand and other influence quantities are considered as causative signals.
Exemplary, it was shown how influence quantities are built in the model and characterised. Relating to the measurement task it was ascertained, that under special conditions, the empirical combined standard uncertainty can go below the given MPE values of several quantities. For a complex measuring system like the described optical CMM decomposition yields to higher uncertainties because of worst-case estimations and unknown correlations between the influence quantities.
It was found out that for dimensional measurements based on image processing the cause-effect concept of the ISO-GUM procedure (Fig. 2) is not expedient. On the one hand dimensional measurements are associated ever with fitting algorithms for appropriate geometry elements. These iterative algorithms are the reason for non-applying the standard-ISO-GUM procedure because it is not possible to set up a closed model equation. Hence, it is also not possible to calculate adequate sensitivity coefficients. The solution of this problem is to use the Monte-Carlo method, recommended and explained in detail in the first supplement to the ISO-GUM [7, 8].
On the other hand 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 play a decisive role for the measurement themselves. They are the general basis for edge detection. According to this, in the image based measurement technique exclusive the effect, the digital image of the unit under test, is considered. For evaluating the quality of edge detection image parameters like contrast, slope or intensity could be utilised. On the basis of these parameters it is not possible to infer the causes of an outstanding good or bad measuring image. 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 (Fig. 6).

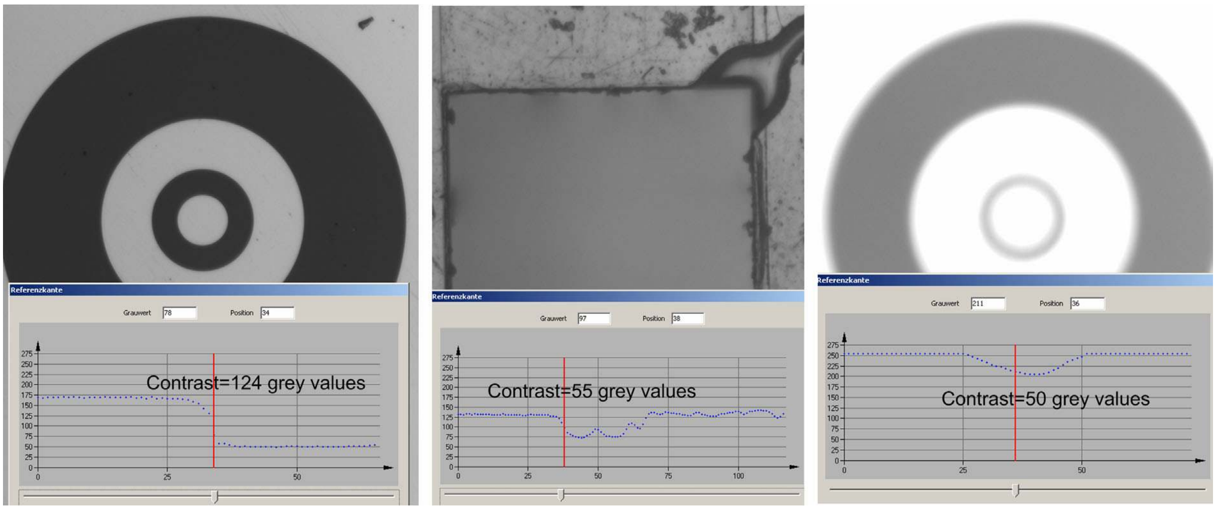


Fig. 6 Image examples (5-times magnified, impinging light): a) ideal UUT, 2D-calibration standard made of glass coated with chrome, measured under optimal parameter settings, b) transparent casting made of plastics, measured under optimal parameter settings, c) 2D-calibration standard made of glass coated with chrome, measured under unfavourable parameter settings (too high illumination intensity).

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. Also it is not possible to analyse the measuring result for example the radius of a circle only on the basis of parameter settings and other influences on the image measuring process. From this it follows that the principle of the ISO-GUM, that analyses and characterises influence quantities as causes of measurement errors in form of PDFs and yields associated to the model equation to a PDF for the measurand, is not suitable for image measurements.

Alternative an approach is developed that exclusively evaluates the quality of dimensional image measurements on the basis of image parameters like contrast, noise and intensity. For measurement uncertainty estimation of dimensional measurements on a coordinate measuring machine with visual sensors and image processing an inductive inference method will be developed exclusively based on image parameters.

Conclusion

Consequently, in the first part of the paper a stringent systematic plan of procedures is demonstrated with the ambition to evaluate the measurement uncertainty of a dimensional measurement on an optical coordinate measuring machine. Fundamentally, this procedure is based on the actual state of the art in modelling for uncertainty estimation [3], [4]. It was reasoned that the cause-effect concept of the ISO-GUM procedure is not appropriate to uncertainty estimations of dimensional measurements with image measuring technique. Therefore, prospective research activities at the department of quality assurance at TU Ilmenau will deal with an inductive inference approach to evaluate the measurement uncertainty of image based dimensional measurements.

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