

RESEARCH ARTICLE

OPEN ACCESS

New method for assessing the repeatability of the measuring system for roughness measurements

Carsten Engler^{*} , Anthimos Georgiadis, Dirk Lange, and Nicolas Meier 

Institute for production technology and systems (IPTS), Universitätsallee 1, 21335 Lüneburg, Germany

Received: 22 February 2024 / Accepted: 12 May 2024

Abstract. The AIAG established the MSA, 4th Edition, as an international guideline to determine if the selected measurement system is capable and can be used for the intended purpose. The MSA guideline provides a practical basis for decision-making and is applied in both scientific and industrial contexts. In addition to the MSA, the Guide to the Expression of Uncertainty in Measurement (GUM) has standardized the determination of measurement uncertainties at an international level. This paper provides a practical example of using a surface comparator to demonstrate the limitations of the MSA for roughness parameters. Additionally, it presents a new method for assessing the capability of a measuring system for roughness measurements by considering the aspects from MSA and GUM. This work considers all information, distinguishing between existing and experimentally generated data. The experimental investigations for the application of the new method were carried out using a confocal laser scanning measuring microscope. The approach presents a new practical opportunity for both science and industry.

Keywords: GUM / uncertainty / MSA / capability / roughness / new formula / new method

1 Introduction

Two main procedures are generally applied in science and industry to evaluate measurement results and measurement systems. Both guidelines examine the measured values using statistical methods. The Guide to the Expression of Uncertainty in Measurement (GUM) standardizes the determination of measurement uncertainties at an international level. This is the most frequently discussed standard in science [1]. A detailed explanation of the procedure according to GUM and the formula applied in this work is presented in Chapter 2.1. The purpose of the MSA (Measurement System Analysis) guide is to determine whether a measurement system is appropriate for a given application. The MSA Guidelines, 4th Edition (2010) provide distinctions and classifications that are outlined in Chapter 2.2. This work demonstrates that the roughness characteristic can only be evaluated to a limited extent for measuring system capability using the MSA guide. Chapter 2.3 provides a fundamental basis for subsequent considerations by discussing the topic of roughness in detail prior to this analysis. Chapter 3, ‘Results and Discussion’, presents a new method for assessing the repeatability of the measuring system in roughness measurements based on an analysis of a specific example. The aim of this procedure is

to determine whether the measuring system applied is generally capable of its intended purpose. This is achieved by combining all relevant information, conducting an experimental investigation, and analyzing it statistically. This new procedure presents a method for evaluating the measuring system for roughness characteristics in science and industry. The final chapter, ‘Conclusions’, provides a summary of the new approach and its limitations, as well as an outlook for further trials and research.

2 Materials and methods

2.1 GUM (Guide to the expression of uncertainty in measurement)

The GUM outlines the process for determining the measurement uncertainties associated with each measured value and result. It is important to note that each measured value is subject to its own unique uncertainties. The specification of measurement uncertainty for each measurement result is a requirement in various standards, including ISO 9001, ISO 10012, ISO 14253, ISO 17025, and DIN 1319. The GUM is a widely applied method for uncertainty analysis in metrology. It employs an algebraic sensitivity coefficient and a mixed approach to frequency and Bayes statistics. However, it is only applicable to linearized measurement models [1,2]. Before calculating

^{*} Corresponding author: Carsten.Engler@stud.leuphana.de

uncertainty, GUM requires that measurement results are corrected for any significant systematic effects identified and that every effort has been made to identify such effects [3].

The measured results should be presented as an interval, known as the confidence interval, rather than a single number. This is similar to a continuous random variable. By assigning a specified probability to this interval, it can be assumed that the resulting measured value falls within this range. The measurement and accuracy analysis must be carried out correctly as a prerequisite [4]. Measurement uncertainty is crucial information in metrology and manufacturing, as it affects the quality of measurements and results [5]. The GUM and its supplements provide a standard for uncertainty assessment in metrology. The measurement model, which determines the measurand as a function of its input quantities, forms the basis of this uncertainty framework [6]. The importance of considering measurement uncertainty in decision-making is increasingly recognized. This allows for an appropriate measurement effort to be determined before a task is performed. However, conformity decisions are currently made in many important application areas without a clear and harmonized basis for the allocation of risks arising from measurement uncertainty [7].

In the experimental investigation, each measured variable is determined by a measuring system on a component. Therefore, no dependent or correlated measured variables are expected. A confidence level of 95.45% is typically applied to estimate the range of values within which the true value of the measured variable can be expected without knowing the exact value. The value of the factor (k) is determined by referencing the T-Student Table for a probability of 95.45% and identifying the corresponding effective degree of freedom [8,9].

The Guide GUM distinguishes between two types of information:

- A: Statistical analysis of experimentally determined measurement data
- B: Utilization of existing information

In metrology, prior knowledge (method B) of a measured quantity is typically available, which can potentially reduce the resulting uncertainty [10]. The mathematical model is created using the influencing variables to determine the measurement uncertainty.

In reference [11], a technique for assessing calibration uncertainty in coordinate metrology is presented, taking into account thermal influences. [5] is also dedicated to the uncertainties of coordinate measuring machines. This information can be partially translated into roughness parameters and was considered in this work. Paper [12] presents a formula for evaluating standard uncertainties of coefficients in a polynomial function using Type A and B methods. However, this formula cannot be applied to roughness. The method for determining the uncertainty of hardness measurements is described in reference [1]. Reference [4] discusses the measurement uncertainty of the stiffness modulus. [13] researches on the sensitivity analysis method of coordinate measurement uncertainty

evaluation and [14] on a determination of the uncertainty of coordinate measurements. [15] researches on the uncertainty evaluation in time-dependent measurements. [16] considers uncertainty evaluation by examining the repeatability of the machine tool's positioning.

The study indicates that there is much discussion and research regarding the consideration of uncertainty in accordance with the international GUM standard. This work contributes to the investigation of roughness values by considering their uncertainty. The study also demonstrates the benefits of this approach. An estimate of the value range is determined in which the true value of the measured variable is expected with a certain confidence level. However, it becomes clear that this approach has limitations. Having knowledge of the expected value range is valuable information, but it does not provide a complete assessment of whether the measuring system is suitable for its intended purpose. Determining uncertainty through mathematical formulas requires extensive knowledge of mathematics and physics.

The formula applied to evaluate roughness parameters in this work is:

$$y = \hat{y} \pm U. \quad (1)$$

[17].

$$U = k \cdot u_c. \quad (2)$$

[17].

$$u_c = \sqrt{u_{SYS}^2 + u_{CAL}^2 + u_{BI}^2 + u_{PRO}^2}. \quad (3)$$

[17].

y Measurement result.

$\hat{y}$ Display value for the measurement results.

U associated expanded measurement uncertainty.

k Expansion factor for a certain degree of confidence.

u_c Combined standard uncertainty.

u_{SYS} Temperature-induced systematic measurement uncertainty.

u_{CAL} Uncertainty occurred due to the limited accuracy of the standard calibration.

u_{BI} Uncertainty due to uncorrected systematic measurement errors, bias uncertainty.

u_{PRO} Uncertainty due to scattering in repeat measurements (Measuring method/measuring process).

$$u_{SYS} = (T - 20^\circ\text{C}) \cdot \alpha \cdot l. \quad (4)$$

[17].

T Measured average temperature.

α Linear thermal expansion coefficient specific to the material.

l Measured dimension

$$u_{CAL} = \frac{U_{CAL}}{k_p}; \text{ from calibration certificate.} \quad (5)$$

Table 1. Distinctions and classifications of MSA guideline.

Procedure	Description
1	Bias: systematic measurement deviation and repeatability of the measurement system
2	GRR: Repeatability and comparative accuracy of the measuring process with operator influence
3	GRR: Repeatability and comparative accuracy of the measuring process without operator influence
4	Linearity: Study on the linearity of the measuring system
5	Stability: continuous monitoring of measurement stability
6	Attributive: Attributive measurement system analysis

[17]

$$u_{BI} = x_{BI} = |x - x_{Ref}|. \quad (6)$$

[18]

$$u_{PRO} = \sqrt{\frac{1}{n-1} * \sum_{i=1}^n (x_i - \bar{x})^2}; \text{ mit } \bar{x} = \frac{1}{n} * \sum_{i=1}^n x_i. \quad (7)$$

[17]

2.2 MSA (measurement system analysis)

To carry out industrial process monitoring and product inspection, it is essential to use appropriate measurement systems. Thus, it is necessary to conduct measurement system analyses in advance to ensure good performance for the required task. However, indiscriminate application of statistical methods and overestimated acceptance criteria in the analysis of measurement systems should be avoided [19]. The AIAG's MSA guide, in addition to VDA Volume 5, has become widely accepted in the industry worldwide. As of the writing of this paper, the 4th edition from 2010 is available. The purpose of this guideline is to determine whether a measuring system is appropriate for its intended application. Table 1 displays the distinctions and classifications outlined in the MSA guidelines.

This work focuses on procedure 1. A measurement system can be collectively defined as the hardware, software, and tooling of the gauge instrument, along with the standards or reference parts, procedures, personnel, and measurement environment, as well as the statistical assumptions, hypotheses, and data analysis. Measurement systems analysis (MSA) aims to estimate the accuracy and precision of measured, tested, and inspected characteristics of manufactured products. It ensures that the inherent variabilities of all elements of a measurement system are understood and controlled, alongside the variability of the product manufacturing process, which is controlled within set limits [20]. The analyst must determine whether the measurement results can be accepted with confidence or rejected as incorrect. Additionally, it is crucial to assess the suitability of the analysis method for the intended use [21].

The approach in this paper aligns with the MSA guidance, with acceptance set at 95.45% confidence [20]. It is recommended to use a standards with a reference value and a calibration certificate to determine the systematic measurement deviation. If it is not possible to use a calibrated standard to measure the characteristic, the MSA guide permits the use of production parts as masters. There are no standards available for roughness parameters that come with a calibration certificate. VDI 3400 prescribes the use of a surface comparator for roughness parameters.

The MSA employs a hypothesis test, specifically the Student t-test, to determine whether the bias is acceptable. This is in line with the objective approach of the analysis.

H_0 : bias = 0

H_1 : bias $\neq$ 0.

The null hypothesis is accepted if

$$|\bar{x} - x_{Ref}| \leq t_{f;1-\frac{\alpha}{2}} * \frac{s}{\sqrt{n}}. \quad (8)$$

[18].

$t_{f;1-\frac{\alpha}{2}}$ is the two-sided quantile of the T -distribution for $f = n-1$ degrees of freedom and confidence level $1-\alpha$.

The value for $t_{f;1-\frac{\alpha}{2}}$ can be obtained from tables for the T -distribution or calculated using the Excel function 'T.INV'. The MSA guide presents the following formula for determining capability:

$$c_p = \frac{T}{6s_p}. \quad (9)$$

[18].

T Tolerance (USL (upper specification limit) – LSL (lower specification limit)).

c_p Capability (process).

s_p Standard deviation (process).

This specification of process capability includes all factors that influence the entire manufacturing process. The measuring system's capability index is assigned 20% of the total process tolerance, resulting in its capability:

$$c_g = \frac{0.2T}{6s_g}. \quad (10)$$

resp [22].

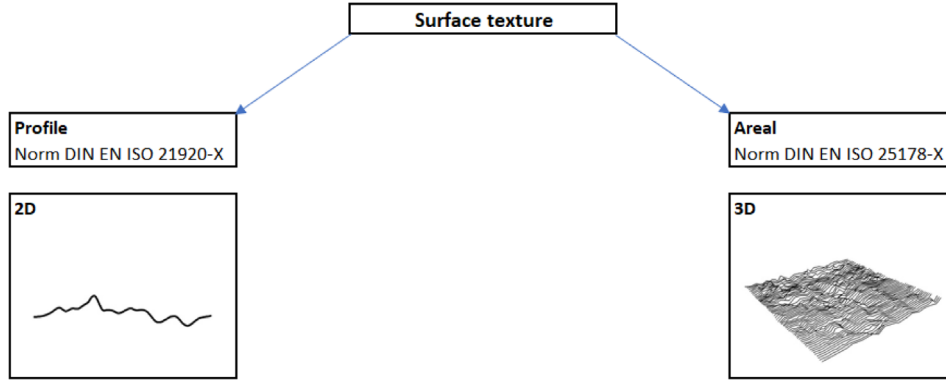


Fig. 1. Description of surface texture in standards (own research out of [26,27]).

$$c_{gk} = \frac{0.1T - |Bi|}{3s_g}. \quad (11)$$

[22].

c_g Capability (gage).

c_{gk} Critical gage capability (The position of the measured values is taken into account).

s_p Standard deviation (gage).

The measuring system requirements necessitate capability parameters for $c_g \geq 1.33$ and $c_{gk} \geq 1.33$.

The benefit of this approach is to offer a foundation for the operator to determine if the measuring equipment utilized is appropriate for the intended application. The MSA guideline is widely approved in industry and science, as it provides a basis for decision-making. [21] is using these statistical tools for practical examples like “an active ingredient in pharmaceutical drugs, a heavy metal in fishery products, and a drug in seizures”. [19] critical reflects the target capability index value of the MSA procedure. In reference [20], a new approach is proposed for adjusting acceptance criteria in bias studies by considering the degree of overlap between the confidence interval of the bias fit data and the uncertainty bars of the reference standards. A bias of independently based gain and offset error is researched in [23]. A gage capability according to MSA procedure is considered and evaluated for a scanning system on a CNC machine in [24]. MSA as a conformity assessment is used in [7]. The main benefit of this approach is that it offers the operator a standardized procedure to determine if the measuring system is appropriate for the intended use.

However, this method also has limitations. It is a strictly prescribed procedure that requires in-depth statistical knowledge. Conducting the experimental tests is complex and requires trained operators. These methods do not allow for a statement to be made about the interval in which the true value can be expected with a certain probability of error. MSA methods have been scientifically examined in many areas of measurement technology for various characteristics. The use of an MSA method for roughness parameters is a novel approach. This approach makes a significant contribution to the field. However, it is important to note that this general, practice-oriented MSA approach may not be applicable to all features.

2.3 Roughness characterization

Various surface parameters can be analyzed to determine surface quality or properties. Geometric parameters, including waviness, roughness, and profile parameters, are defined by [25]. The two standards displayed in Figure 1 provide a description of the surface finish of components. This information is necessary for better understanding [26].

The choice of profile roughness or area parameters depends on the type of surface property characterization [26]. This work examines the profile parameters Rz and Ra at the customer’s request. In [28], a comparison is made between the profile and areal surface parameters. The roughness profile, also known as the R-profile, is applied to evaluate the R-characteristics [29,30]. Parameters for the extensive surface finish are characterized in [29,31]. [30,32] defines the length of the measuring section for the evaluation according to roughness parameters.

As a general rule, the parameters of the roughness profile are calculated based on five individual measuring sections. This relationship is illustrated in Figure 2.

According to [25], a measured distance l_n is recorded and evaluated. The standard DIN EN ISO 21920-2 uses the term evaluation length l_e to determine Rz based on the single measuring distance and Ra based on the evaluation length. The length l_e in the direction of the x-axis is used to determine the geometric structures. Figure 2 illustrates the procedure through image recording. According to [34], an evaluation length of 4 mm is advised for Rz, while an evaluation length of 5 mm is advised for Ra values. Tables 1 and 2 of [32] recommend a single measuring distance of 0.8 mm and a measuring distance of 4 mm for both Ra and Rz characteristic values.

2.4 Confocal laser microscopy, the applied measurement device

The initial stage before any measurement is to choose a potentially appropriate measuring device and measuring system. Confocal laser measuring microscopes are commonly used for surface and roughness measurements in science and industry. [35] presents three measurement devices for surface evaluation: optical microscopy, optical profilometry, and x-ray computed tomography. Reference

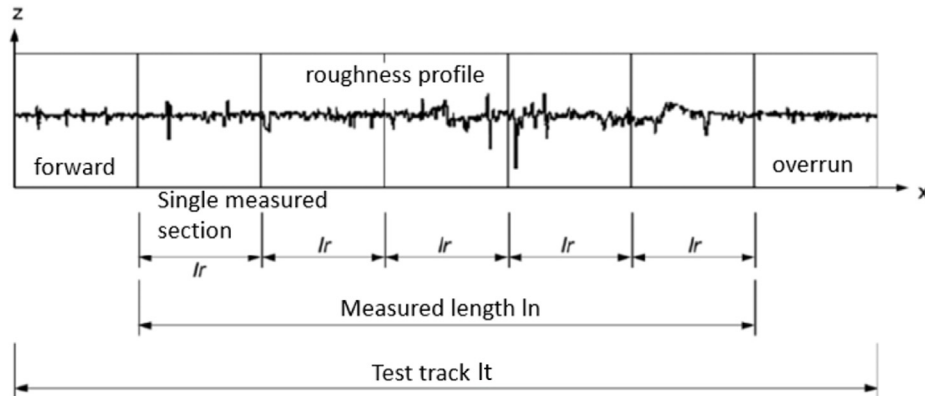


Fig. 2. Definitions of roughness profile [33].

Table 2. Representative surface roughness parameters [30,31].

Parameter	Designation
Spc	Arithmetic mean value of peak curvature
Sa	Mean arithmetic height of the scale-limited surface area
RSm	Mean spacing of the profile elements
Ra	Arithmetic mean value of the height
Sdr	Developed transition area ratio of a scale-limited surface
Str	Aspect ratio of the surface texture
Sz	Maximum height of the scale-limited surface
Rz	Maximum height

[36] introduces a confocal sensor for precise measurement with the goal of characterizing surface topography and minimizing uncertainty. A laser based sensor was examined in [37] for the analysis of a typical additive manufacture surface texture. [38] measured the surface topography of different workpieces with a confocal and an interferometric sensor, with benefits for the confocal mode in resolution for the x- and y-axis, more suitable for C45 steel and a better visualization of surface features. In [39] the roughness evaluation for a surface bending-fatigued fracture surface topography was performed with a confocal surface topography measurement technique and a focus variation microscope. Metal powder bed fusion surfaces, particularly those produced through additive manufacturing, pose measurement challenges due to their complex topographies. To solve these measurement challenges, a scanning confocal microscope was examined [40]. As mentioned in [41], digital filtering is a crucial aspect. The measurement manufacturer set the filtering in this work. In [42] an illumination microscopy was used for surface measurement.

The confocal laser scanning microscope was selected for this work due to its main advantages:

- High precise measurements with 65536 gray scales.
- Automated adjustment of the scanning area.
- Microscope was easy to handle, also experienced by the customer.
- Fast focus adjustment with automated focus recognition.

Table 2 constitutes the parameters that can be imaged with the applied focal laser scanning microscope.

2.5 Surface comparator, the applied gage

To conduct an MSA study, there are specific standards for geometric characteristics, such as gauge blocks or test pins. Each standard has a corresponding calibration certificate that adheres to the relevant standards. For instance, gauge blocks follow the DIN EN ISO 3650 standard. The MSA 1 method utilizes the values listed on the calibration certificate for calculations. It is important to note that reference standards or gauge blocks, which typically come with a calibration certificate, are not available for roughness features. The Association of German Engineers (VDI) recommends using a surface comparator, also known as a reference sample. The standard describes the production of comparative surfaces on workpieces through electro erosive machining. The surface quality of the machined workpiece is determined by the shape and depth of the discharge craters. These are divided into classes according to this standard and can be applied to record common roughness measurements [43]. Figure 3 displays the surface comparator used in this work. [44] provides a classification of milling surface roughness.

The surface comparator's classes are categorized according to Table 3.



Fig. 3. Surface comparator [own research].

Table 3. Specification of roughness values on the surface comparator [43].

Class K	12	15	18	21	24	27	30	33	36	39	42	45
Ra [μm]	0.4	0.56	0.8	1.12	1.6	2.24	3.15	4.5	6.3	9.0	12.5	18.0
Rz max [μm]	1.6	2.3	3.2	4.5	6.3	9.0	12.5	18.0	25.0	35.0	49.0	70

Conducting an MSA 1 study with a surface comparator according to standard VDI 3400 is a novel approach in both science and industry.

2.6 Conducting the experimental investigation

For the execution of the experiments it was aligned with the customer to perform three MSA 1 studies for the classes 12, 27 and 33. These studies aimed to investigate the representative surface qualities of the customer's products. Ten images were taken of each class. After each image, the surface comparator was removed from the slide and placed back on it. The temperature in the measuring room was monitored using nine calibrated temperature and humidity sensors. This work adheres to the recommendation of standard VDI/VDE 2627 Sheet 1. It is determined a nominal temperature of 20°C [45]. Figure 4 displays the temperature curve of a representative sensor during the measurements. The temperature and humidity were recorded every 6 min.

For temperature-dependent calculations, a mean temperature of 20.3°C is utilized. As stated in [46], the reference standard was acclimatized in the measuring room for at least 24 h prior to the measurements. The examination took into account the recommendations of standards 21920 and 4288. The confocal laser scanning microscope settings were reviewed and established in consultation with the manufacturer. A 50x magnification was chosen for the surface comparator.

3 Results and discussion

Due to the manufacturer's recommended settings, it was possible to achieve individual measuring distances of $>0.28\text{ mm}$. Each image generated 21 sensing distances, as shown in Figure 5. This results in a measuring distance l_n or an evaluation length l_e of more than 5.8 mm ($21 \times 0.28\text{ mm}$). However, confocal microscopes have limitations and require compromises. The higher the

resolution and magnification, the smaller the resulting image. Standard DIN EN ISO 4288 requires a single measuring distance of 0.8 mm (l_r) and a measuring distance of 5 mm , which is not feasible at high magnification. To address this issue, the software can merge multiple small images into a larger one, but this results in longer processing times. The above parameter settings represent a compromise that was discussed with the measuring device manufacturer and approved by the customer. Figure 5 displays the measurement strategy resulting from the mentioned compromise. A surface topographic image of each class of the surface comparator was obtained. In this area, 21 sensing distances were defined. Each blue line represents a profile distance l_t . All 21 scanning distances define the measuring distance l_n or the evaluation length l_e .

Figure 6 shows the dimensions of the recorded topographic area, with recorded heights represented by the adjacent color palette.

Figure 6 displays the limitations of the image at a 50x magnification in both the x and y directions. The distances in the x direction and y direction are 0.28 mm and 0.21 mm , respectively, which do not meet the length requirements of the DIN EN ISO 4288 standard.

Figure 7 shows the roughness profile of a scanning path, resulting in a single measuring path (l_r). The two yellow lines represent the forward and overrun. This figure is an example of class 12.

Tables 4 and 5 constitute the measurement results of the roughness values of the surface comparator for the three different classes.

Chapter 2.2 outlines the four necessary steps for the MSA 1 study:

Student t test bias.

Determination and assessment C_g .

Determination and assessment C_{gk} .

The tolerances for $T_{Rz} = 12$ and $T_{Ra} = 3$ were obtained from the customer's production. Table 6 below displays the results of the MSA 1 study, calculated using the formulas from chapter 2.2:

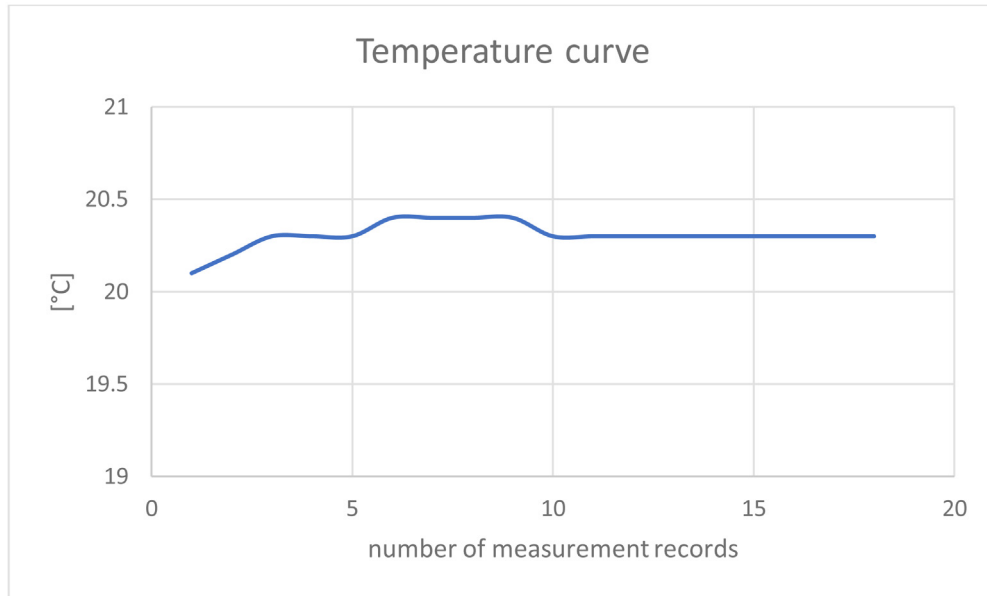


Fig. 4. Temperature curve of a representative sensor [own research].

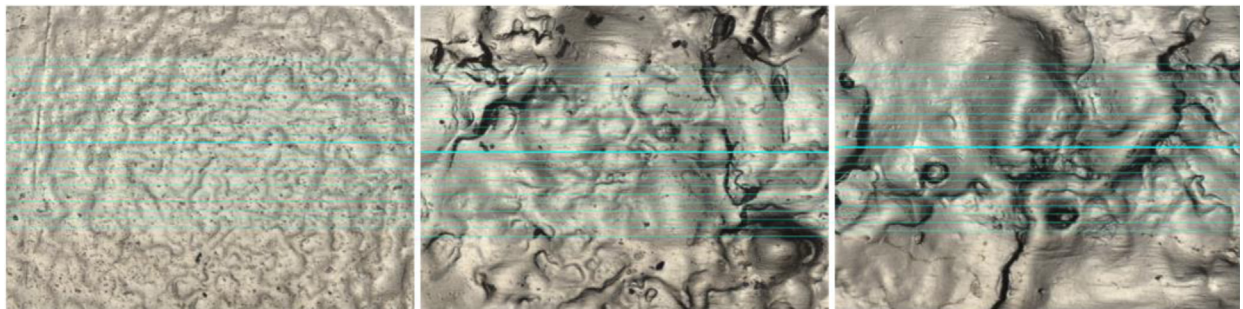


Fig. 5. Topographic image of each class of the surface comparator with 21 sensing distances [own research].

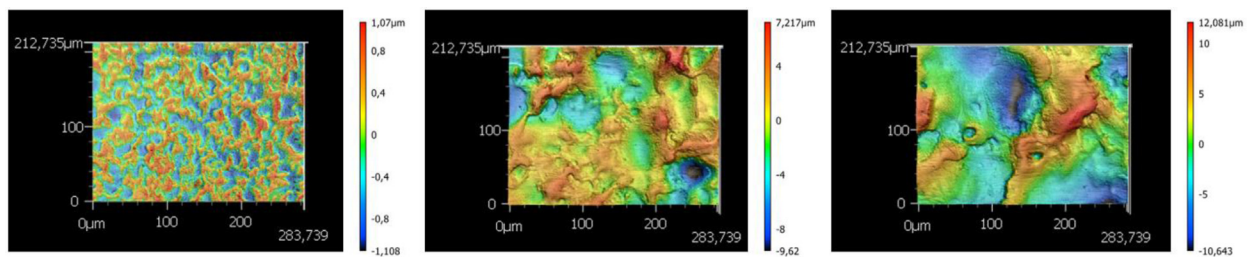


Fig. 6. Recorded heights represented with adjacent color palette [own research].

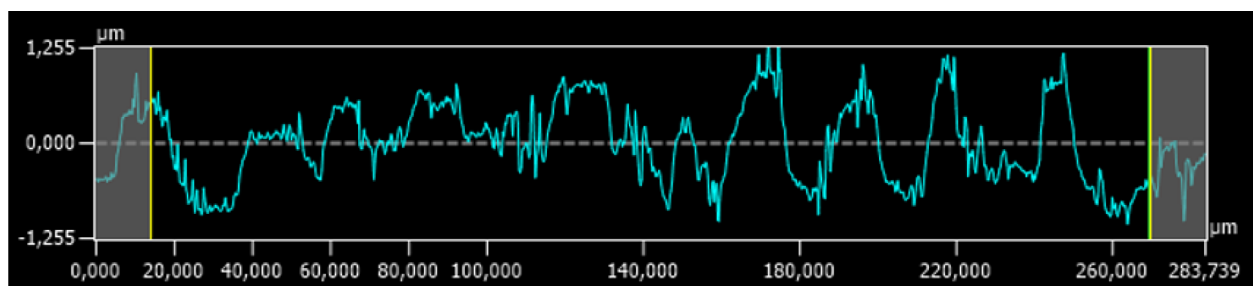


Fig. 7. Roughness profile of a scanning path with forward and overrun [own research].

Table 4. Measurement results for Rz characteristic.

Measured value	Rz value in [μm] for class 12	Rz value in [μm] for class 27	Rz value in [μm] for class 33
1	2.370	10.055	20.262
2	2.134	11.761	19.233
3	2.477	11.212	21.162
4	1.884	10.369	18.101
5	2.153	10.019	21.800
6	1.847	10.073	21.502
7	2.214	9.930	18.250
8	2.022	10.351	20.981
9	2.224	12.888	18.707
10	2.420	13.909	18.868
Mean value	2.174	11.057	19.887
Standard deviation	0.214	1.386	1.413
Reference value	1.600	9.000	18.000

Table 5. Measurement results for Ra characteristic.

Measured value	Ra value in [μm] for class 12	Ra value in [μm] for class 27	Ra value in [μm] for class 33
1	0.387	2.378	4.277
2	0.326	2.706	4.149
3	0.408	2.141	3.737
4	0.304	2.156	3.983
5	0.335	2.247	4.932
6	0.291	1.853	4.710
7	0.349	1.966	4.337
8	0.320	1.820	4.629
9	0.363	2.484	4.166
10	0.331	2.649	3.824
Mean value	0.342	2.240	4.274
Standard deviation	0.036	0.313	0.388
Reference value	0.4	2.240	4.500

Table 6. Results of the conducted MSA 1 study for Rz characteristic [own research].

MSA 1 result / Class K	Bias [μm]	t -test	C_g	C_{gk}
12	0.574	0.153	1.869	0.975
27	2.057	0.991	0.289	-0.206
33	1.887	1.011	0.283	-0.445

The t -test column value is smaller than the bias for all three classes. According to the formula from chapter 2.2, the null hypothesis must be rejected. All ability values, except for the C_g value for class 12, are not achieved. The tolerance of 12 for class 12, which has a reference value of 1.6, is incorrectly selected and should be rejected.

Tables 6 and 7 present comparable results. In summary, the measuring system may not be used for the three roughness classes for Rz in accordance with the MSA 1

study. Alternatively, the general formulas of the MSA type may only be suitable to a limited extent for determining measuring system capabilities for roughness parameters Ra and Rz. After presenting these results to the AIAG “Quality Initiatives department”, they recommended referencing the British document ASME B46.1-2019, since the MSA guideline does not provide a procedure for this. This document will be considered when creating a new method.

Table 7. Results of the conducted MSA 1 study for Ra characteristic [own research].

MSA 1 result / Class K	Bias [μm]	<i>t</i> -test	C_g	C_{gk}
12	0.058	0.026	2.778	2.241
27	0	0.224	0.319	0.319
33	0.226	0.278	0.258	0.064

Table 8. Information applied for the new formula.

Information/ number	Available	Generated by experiment
1	Surface comparator (reference value)	Combined uncertainty (chapter 2.1)
2	British standard “ASME B46.1-2019”	Mean value of the measurement series
3	Temperature logging	Standard deviation of the measurement series
4		Bias
5		<i>T</i> -test for bias

3.1 Creation and description of the new method

The aim of the new method, as defined with feedback from the AIAG, is to provide the user with a procedure to determine whether the measuring system being used is capable of measuring the roughness parameters Rz and Ra for the intended purpose.

The objectives of the new approach can be summarized as follows:

- New method, new formula for roughness parameters Rz and Ra.
- Utilization of all accessible information
- Creation of new information through experimental investigation
- When selecting an index or capability parameter, it is recommended to use a value that is familiar and known to the user.

The new index is referred to as ‘ c_{rk} ’, where ‘ c ’ stands for ‘capability’ in the MSA guide and ‘ r ’ stands for ‘roughness’ in the new method. A c_{rk} value of ≥ 1.33 is considered capable, and ‘ k ’ is a critical value analogous to [22], taking into account the position of the distribution shape. Table 8 below presents the information used to create the new method in a concise format.

The formula is created using eight pieces of information. It is the sum of three weighted factors that consider all eight pieces of information.

$$c_{rk} = \sum f(x_1) + f(x_2) + f(x_3). \quad (12)$$

3.1.1 Step 1: Processing information on the measurement method

The Function $f(x_1)$ generates a value based on the information provided in the international standard ASME B46.1-2019, which pertains to surface texture, including surface roughness, waviness, and lay [47]. As of June 2020,

this standard was valid. A revision of this standard is expected in 2025. It takes into account various production processes, including abrading, casting, coating, cutting, etching, plastic deformation, sintering, wear, and erosion [47]. This standard categorizes measuring equipment suitable for measuring surface finishes, as shown in Figure 8.

According to this standard, confocal microscopy is a suitable method for measuring surface properties. If this standard is applied, further investigations could be omitted at this point. However, the aim of this work is to use all available information to determine whether the measuring system is suitable for its intended purpose. The argument for this work is that the confocal microscopy method is suitable in principle for its intended use. This work examines whether the measuring equipment manufacturer has accurately implemented the method in its measuring system. The fact that the method is already known and suitable in principle will be included in the new method with a weighting factor. Thus applies:

$$f(x_1) = \text{“Result from the table Information on the measurement method”}$$

This work applies the following to the analyzed optical confocal laser measuring microscope:

$$f(x_1) = 0.5.$$

3.1.2 Step 2: Determination of bias and *t*-test evaluation

The process for this step is identical to that of the MSA process. If the null hypothesis is rejected, the MSA guideline recommends identifying and eliminating the cause. The new process also follows this recommendation. However, unlike the MSA guideline, this information is included in the formula as a weighted factor to ensure that all information

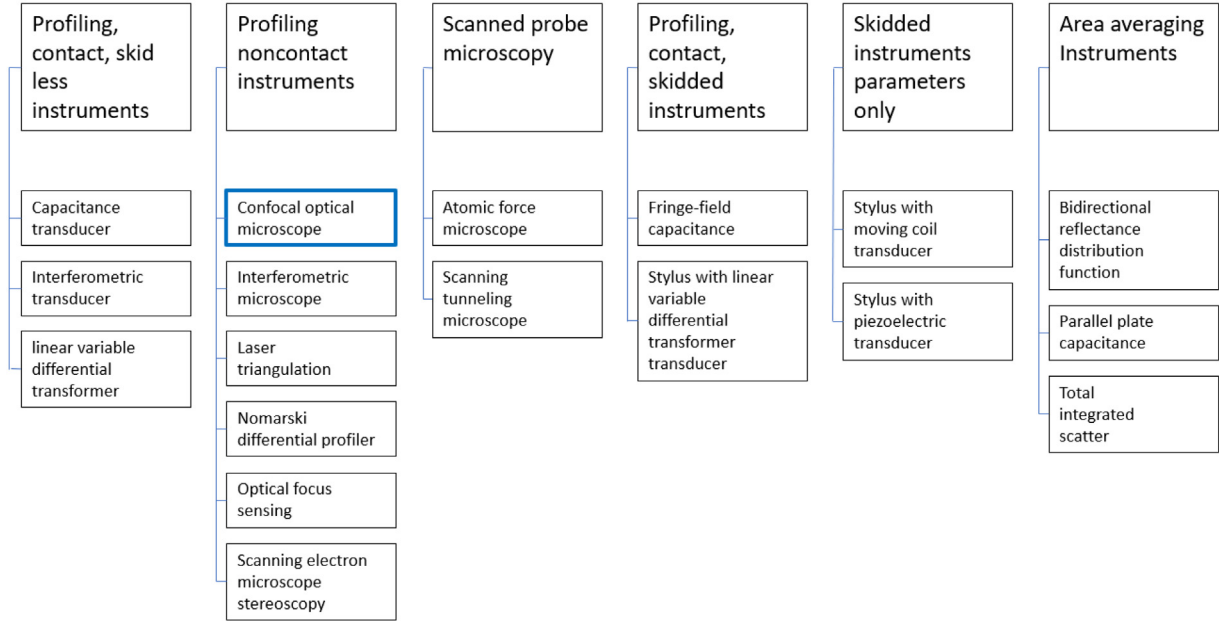


Fig. 8. Measuring equipment suitable for measuring surface finishes according standard ASME B46.1-2019 [47].

Table 9. Information on the measurement method for $f(x_1)$.

The measurement method is included in Figure 8	Result for c_1 - bzw. c_{rk} -
Yes	0.5
No	0

Table 10. Information for bias and t -test for Rz characteristic $f(x_2)$.

Result / Class K	Bias [μm]	t -test value	t -test result	Result for c_{rk} -
12	0.574	0.153	Failed	0
27	2.057	0.991	Failed	0
33	1.887	1.011	Failed	0

is considered in the new formula and index value. The presence of the null hypothesis is crucial information that will be incorporated into the new formula with a weighting factor. The null hypothesis is considered ‘accepted’ when it has a value of 0.5, while a value of 0 is assigned to the null hypothesis when it is ‘rejected’, see Table 10.

The guidelines outlined below are applicable to all three categories in this work:

$f(x_2)$ = Results from the table Information for Bias and the t -test”

$$f(x_2) = 0$$

The results for Ra, Table 11 differ from the results for Rz, Table 10.

Table 11. Information for bias and t -test for Ra characteristic $f(x_2)$.

Result / Class K	Bias [μm]	t -test value	t -test result	Result for c_{rk}
12	0.058	0.026	Failed	0
27	0	0.224	Passed	0.5
33	0.226	0.278	Passed	0.5

Table 12. Uncertainty results for Rz $f(x_3)$.

Result / Class K	u_{BI} [μm]	u_{PRO} [μm]	u_c [μm]	U [μm]
12	0.574	0.214	0.613	1.225
27	2.057	1.386	1.921	3.842
33	1.887	1.413	1.997	3.993

3.1.3 Step 3: Determination and evaluation of the standard deviation

In this step, evaluate the standard deviation will be evaluated by dividing it into the ratio to the tolerance, resulting in the capability index, as outlined in the MSA guide. Additionally, it will be considered and evaluated the standard deviation in combination with the result from GUM [9]. To do this, it will be determined the uncertainty in accordance with Section 2.1. As there is no calibration certificate for a reference standard, the following applies:

$$U = k \cdot u_c. \quad (13)$$

Table 13. Uncertainty results for Ra $f(x_3)$.

Result / Class K	u_{BI} [μm]	u_{PRO} [μm]	u_c [μm]	U [μm]
12	0.058	0.026	0.064	0.127
27	0	0.224	0.224	0.448
33	0.226	0.278	0.358	0.717

Table 14. Result d_1 and d_2 for Rz characteristic $f(x_3)$.

Result / Class K	Max value [μm]	Min value [μm]	d1	d2
12	2.477	1.847	18.215	2.907
27	13.909	9.930	-1.985	2.228
33	21.800	18.101	-1.269	1.492

[17].

A factor of 2 is used for k to cover a confidence interval of 95.45%, according to [4,13].

$$u_c = \sqrt{u_{SYS}^2 + u_{BI}^2 + u_{PRO}^2}. \quad (14)$$

With

$$\begin{aligned} u_{SYS} &= (T - 20^\circ\text{C}) * \alpha * l \\ &= (20.3 - 20) * 0.0000117 * 1,6\mu\text{m}. \end{aligned} \quad (15)$$

[17]

l from Table 3.

 α 11,7 *10⁻⁶ * K⁻¹ out of [43]

Due to its size, u_{SYS} has a negligible share of the total uncertainty and can therefore be disregarded.

$$u_{BI} = \Delta x_{BI} = |\bar{x} - x_{Ref}|. \quad (16)$$

[18]

$$u_{PRO} = \sqrt{\frac{1}{n-1} * \sum_{i=1}^n (x_i - \bar{x})^2}. \quad (17)$$

[17]

Function $f(x_3)$ calculates the uncertainties for Rz and Ra. Tables 12 and 13 summarize the uncertainties and results for Rz and Ra, respectively as function $f(x_3)$.

$f(x_3)$ = “Results and interpretation of roughness uncertainty calculation according to GUM”.

All eight pieces of information can be analyzed and summarized in three simple tables. The table below evaluates the position of the distribution shape and the distance between the maximum and minimum values of the measurement series. This procedure is similar to the MSA process for determining the C_{gk} value [18]. In this work,

however, the method according to GUM [9] is taken into account in the determination. A statistically possible scenario is considered in order to be able to estimate the respective tolerance limits.

To determine the distance d, the following guidelines apply:

$$d_1 = \frac{USL - (\max\text{Wert} + U)}{s}. \quad (18)$$

$$d_2 = \frac{(\min\text{Wert} - U) - LSL}{s}. \quad (19)$$

The results can be summarized in the following simplified tables:

The evaluation should not consider Class 12 since a tolerance of 12 μm with a nominal dimension of 1.6 μm is too large.

The evaluation should not consider Class 12 since a tolerance of 3 μm with a nominal dimension of 0.4 μm is too large.

The results for d_1 and d_2 from Tables 15 and 16 are used as whole numbers without rounding in the following table.

According to [18], the scatter of a normal curve is represented by 99.73%, which is equivalent to $\pm 3s$. This paper evaluates the measurement system. In addition to the measuring system, there are many other factors that influence the total scatter. Therefore, [22] allows only 20% of the tolerance range for a capable measuring system. In this new method, roughness is given more consideration than in [18]. The formula takes into account a distance of 1s to the tolerance limit with a capability index of 0.33. It is important to note that the reference standards, as per [43], were manufactured using defined parameters in the electrical discharge machining process. Therefore, any manufacturing variations are also reflected in the new capability index.

3.1.4 Step 4: Overall result determination c_{rk}

The overall result for Rz is determined by considering only the smallest values in the respective table:

$$c_{rk} = \sum f(x_1) + f(x_2) + f(x_3) = 0.5 + 0 + 0 = 0.5.$$

The capability index c_{rk} of 0.5 is inadequate for the specific application, as it falls short of the required value of 1.33. The new formula and corresponding tables demonstrate why this measuring system is unsuitable for this case, particularly since it is typically used for surface finishes according to the British standard ‘ASME B46.1-2019’ recommended by the AIAG. In this application example, Table 9 shows a statistically significant bias that is too large. Additionally, the measuring system records values that exceed the required tolerance, which can be statistically expected to occur even beyond the upper tolerance limit with a confidence interval of 95.45% (refer to Tab. 13, value d1).

Table 15. Result d_1 and d_2 for Ra characteristic $f(x_3)$.

Result / Class K	Max value [μm]	Min value [μm]	d1	d2
12	0.408	0.291	66.769	6.308
27	2.706	1.820	10.571	2.821
33	4.932	3.737	10.719	0.072

Table 16. Results for position parameters $f(x_3)$.

Result d	Distance to the tolerance limit
0	0
1	0.33
2	0.67
3	1
4	1.33
5	1.67
≥ 6	2

The result for Ra is:

$$c_{rk} = \sum f(x_1) + f(x_2) + f(x_3) = 0.5 + 0.5 + 0 = 1.0.$$

The result of 1.0 is better than the result for the Rz feature, although it is still below the required capability index value of 1.33. Thus, the measuring system should not be used for Ra measurements in this specific application without further optimization. If only class 27 were considered, the result of 1.67 would be even better and could be considered capable for class 27. However, the customer requested an examination of the measuring system for all three classes regarding the Rz and Ra characteristics. To ensure user-friendliness, assumptions are made that limit the method for the tables and formula. It is selected an additive model with the main influencing factors and normal distribution to account for the GUM approach. For comparability, it is applied a comparative standard defined in accordance with VDI standard 3400, which is available only without a calibration certificate.

4 Conclusions

The purpose of this work was to create a new formula for measurement system users that takes into account roughness-specific information and conclusions. This was achieved through the following steps:

- This work analyzes internationally recognized approaches for generating information about a measurement system. The GUM guideline provides a procedure for representing measurement uncertainties to the user. However, this approach only offers a limited basis for deciding whether to accept the measurement system for a specific application, as it does not include the given tolerance in the calculation. The AIAG MSA guideline

outlines a procedure that generates a capability index for decision-making. This approach considers roughness-specific characteristics only to a limited extent.

- In this work, the characteristics that describe the surface finish are understood and taken into account by international standards.
- There are no traditional standards, such as gauge blocks or test pins, for measuring roughness characteristics. However, a roughness comparison standard has been developed according to an international standard and is available for the roughness characteristics Ra and Rz. The new formula takes this surface comparator into account, providing a new approach.
- The formula, particularly for roughness characteristics, considers both the MSA and GUM guidelines. It takes into account all information, distinguishing between existing and experimentally generated data.
- This work presents the entire information in three tables and uses a specific application example to illustrate a new capability index for decision-making, particularly for roughness characteristics. The application example did not achieve the new capability index of 1.33 due to bias and scatter exceeding the given tolerance. Values outside the upper tolerance limit are expected in the application example.
- In comparison to the MSA procedure 1, the new method also takes into account the GUM uncertainties. For instance, the experimental investigation reveals that the bias uncertainty $u_{BI} = 2.057 \mu\text{m}$ is the greatest uncertainty for the Rz results. This information enables an approach to optimize the measurement system that is not feasible according to the MSA Guideline.
- The new method considers the expected uncertainty in a limit value analysis. The experimental results indicate that Rz values at the maximum (d1) for class 27 are expected to be almost 2s outside the upper tolerance limit. These results support the new thesis.
- The experimental results indicate that as the Ra values increase, the distance to the lower tolerance limit tends to become smaller. This statement would not have been possible with the old method and supports the new thesis.

Limitations were identified:

- Each class was measured only ten times. For future analyses, additional measurements may help to better analyze and understand the bias and scatter.
- According to the current standard, the surface comparator is only available for surface characteristics Rz and Ra. Further research and investigation can improve this situation, particularly for areal surface characteristics.
- The formula for calculating uncertainties is based on the additive model and normal distribution. Additional investigations, such as using the Monte Carlo method, can further refine the formula and results.
- The newly developed method is specifically designed for roughness parameters and cannot be applied to other characteristics. It requires more statistical knowledge and complex analyses, which can be automated in many statistical programs. The experimental results presented in points six to eight in the conclusion justify this additional effort and support the new method.

This new approach can be used for future tests or a Design of Experiment (DoE) to improve the parameters and settings of the confocal laser scanning microscope. Additional investigations can define the surface comparator for additional surface characteristics. Further investigations on the additive model may optimize and refine the formula.

Abbreviations

MSA	Measurement System Analysis
AIAG	Automotive Industry Action Group
GUM	The Guide to the Expression of Uncertainty in Measurement
ISO	International Organization for Standardization
VDA	The German Association of the Automotive Industry
USL	upper specification limit
LSL	lower specification limit
DIN	The German Committee of Standards
EN	European Standard

Biographical notes

Carsten Engler is a PhD student at the Institute for Product and Process Innovation at Leuphana University Lüneburg. His research fields include metrology, optical measurement, quality management, autonomous driving, and production processes.

Prof. Dr. Anthimos Georgiadis studied Physics in Aachen and Cologne in Germany. He was Visiting Professor of Physics, University of Crete (1986–1992), Co-founder and Managing Director of the Institute for Medical Laser Technologies in eye surgery (VEIC) of the University of Crete (1990–1995), Visiting Professor University of Thessaly (1992–1995), since 1995 Professor of “Measurement and Intelligent Systems” at the Leuphana University Lüneburg; Dean of the department for automation between 1997–2003 of FH NON, visiting Professor at the Democritus University of Thrace in Greece 2003/2004; reviewer in several scientific Journals, for the European commission and quality assurance agencies.

Hon.-Prof. Dr. Dirk Lange is Head of Development at Marposs Monitoring Solutions GmbH, Germany and has been with the company since 1998. He is responsible for research and development activities in the field of machine tools and measurement technology. Other fields of work include machine learning and 5G technologies. He studied electrical engineering in Braunschweig and completed his doctorate at the Institute for Machine Tools and Manufacturing Technology (IWF) with his thesis on measurement technology and control loops in profile grinding. Since 2013 he has held a lectureship in production metrology at Leuphana University Lüneburg. In 2019, Dr. Lange was appointed honorary professor at the University of Lüneburg.

Dr. Nicolas Meier received his M.Sc. in Management and Engineering in 2012 and his doctoral degree in 2018 from the Leuphana University of Lüneburg. Nicolas

worked as a research associate at the Institute of Product and Process Innovation (PPI) as part of the EU project IFaCOM, where the focus was on quality monitoring systems using integrated sensors that allow online feedback of the measurement data in the manufacturing process, thus improving the quality of the respective products. Since 2018, Nicolas has been working at the Digital Transformation Research Center (RCDT) dealing with topics such as condition monitoring, predictive maintenance, smart factory.

Funding

No funding was received for conducting this study.

Author contribution statement

Carsten Engler: Resources, Conceptualization, Methodology, Validation, Project administration, Formal analysis, Visualization, Supervision, Writing-original draft. **Anthimos Georgiadis:** Conceptualization, Methodology, Validation, Supervision, Formal analysis. **Dirk Lange:** Conceptualization, Methodology, Validation, Formal analysis. **Nicolas Meier:** Validation, Formal analysis

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data will be made available on request.

References

1. G.M. Mahmoud, R.S. Hegazy, Comparison of GUM and Monte Carlo methods for the uncertainty estimation in hardness measurements, *Int. J. Metrol. Qual. Eng.* **8**, 14 (2017)
2. V. Ramnath, Analysis of approximations of GUM supplement 2 based non-Gaussian PDFs of measurement models with Rosenblatt Gaussian transformation mappings, *Int. J. Metrol. Qual. Eng.* **11**, 2 (2020)
3. F. Pavese, Corrections and input quantities in measurement models, *Int. J. Metrol. Qual. Eng.* **3**, 155–159 (2012)
4. H. Mezouara, L. Dlimi, A. Salih, M. Afechcar, H. Zniker, Evaluation of the measurement uncertainty of the stiffness modulus: test case of indirect tensile on cylindrical specimens, *Int. J. Metrol. Qual. Eng.* **12**, 8 (2021)
5. P. Bharti, Q. Yang, A.B. Forbes, Y. Koucha, UML knowledge model for measurement process including uncertainty of measurement, *Int. J. Metrol. Qual. Eng.* **12**, 26 (2021)
6. G. Wübbeler, M. Marschall, K. Kniel, D. Heißelmann, F. Härtig, C. Elster, GUM-compliant uncertainty evaluation using virtual experiments, *Metrology* **2**, 114–127 (2022)

7. L.R. Pendrill, Using measurement uncertainty in decision-making and conformity assessment, *Metrologia* **51**, S206–S218 (2014)
8. H. Figueiredo Junior, R.M. Moreira, P. Bastos Costa, Discontinuity measurement uncertainty evaluation using the Feeler PIG, *Int. J. Metrol. Qual. Eng.* **13**, 15 (2022)
9. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, OIML, *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*. Joint Committee for Guides in Metrology, JCGM 100: 2008, 2008. URL: https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6.
10. M. Marschall, G. Wübbeler, C. Elster, Rejection sampling for Bayesian uncertainty evaluation using the Monte Carlo techniques of GUM-S1, *Metrologia* **59**, 15004 (2022)
11. M. Mussatayev, M. Huang, M. Nurtas, A. Arynov, Improved calibration uncertainty assessment technique in coordinate metrology considering thermal influences (2023), *Metrol. Meas. Syst.* **28**, 609–626 (2021)
12. M. Dorozhovets, Uncertainty of the conversion function caused by systematic effects in measurements of input and output quantities (2023), *Metrol. Meas. Syst.* (2023), <https://doi.org/10.24425/mms.2023.146422>
13. M. Wojtyła, P. Rosner, W. Płowucha, A.B. Forbes, E. Savio, A. Balsamo, Validation of the sensitivity analysis method of coordinate measurement uncertainty evaluation, *Measurement* **199**, 111454 (2022)
14. M. Wojtyła, P. Rosner, W. Płowucha, A. Balsamo, A. Piccato, A.B. Forbes, E. Savio, Determination of uncertainty of coordinate measurements on the basis of the formula for EL, MPE, *Measurement* **222**, 113635 (2023)
15. M.A. Silva, C. Amado, Á. Ribeiro, D. Loureiro, Uncertainty evaluation in time-dependent measurements, *Measurement* **196**, 111196 (2022)
16. X. Liu, Y. Xia, X. Rui, Uncertainty evaluation of multi-lateration-based geometric error measurement considering the repeatability of positioning of the machine tool, *Metrol. Meas. Syst.* 49–63 (2023)
17. DIN Deutsches Institut für Normung e.V. (September / 2018). *DIN EN ISO 115530-3: Geometrische Produktspezifikation (GPS) – Verfahren zur Ermittlung der Messunsicherheit von Koordinatenmessgeräten (KMG) – Teil 3: Anwendung von kalibrierten Werkstücken oder Normalen*. [Geometrical product specification (GPS) – Methods for the determination of measurement uncertainty of coordinate measuring machines (CMMs) – Part 3: Use of calibrated workpieces or standards. Deutsche Fassung EN ISO 115530-3:2011. Berlin. DIN Deutsches Institut für Normung e.V.
18. Measurement systems analysis: *MSA. reference manual* (4. ed.) (Automotive Industry Action Group, 2010)
19. S.F. Beckert, W.S. Paim, Critical analysis of the acceptance criteria used in measurement systems evaluation, *Int. J. Metrol. Qual. Eng.* **8**, 23 (2017)
20. M. Abdelgadir, C. Gerling, J. Dobson, Variable data measurement systems analysis: advances in gage bias and linearity referencing and acceptability, *Int. J. Metrol. Qual. Eng.* **11**, 16 (2020)
21. S. Belouafa, F. Habti, S. Benhar, B. Belafkih, S. Tayane, S. Hamdouch, A. Bennamara, A. Abourriche, Statistical tools and approaches to validate analytical methods: methodology and practical examples, *Int. J. Metrol. Qual. Eng.* **8**, 9 (2017)
22. A. Kistner, B. Schäfer, *Prüfmittelmanagement. [Gage management] DGQ-Band: 13–61*. Hanser, 2015. <https://doi.org/44264>
23. F.A.C. Alegria, Bias of the independently based gain and offset error in ADC testing using the histogram method, *Measurement* **218**, 113181 (2023)
24. P. Blecha, M. Holub, T. Marek, R. Jankovych, F. Misun, J. Smolik, M. Machalka, Capability of measurement with a touch probe on CNC machine tools, *Measurement* **195**, 111153 (2022)
25. DIN Deutsches Institut für Normung e.V. (2010). *DIN EN ISO 4287. Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Tastschnittverfahren – Benennung, Definitionen und Kenngrößen der Oberflächenbeschaffenheit* [Geometrical Product Specification (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters] (ISO 4287:1997 + Cor 1:1998 + Cor 2:2005 + Amd 1:2009). Berlin. DIN Deutsches Institut für Normung e.V.
26. C. Engler, A. Georgiadis, D. Lange, N. Meier, Improving the surface quality of AlMgSi1 alloy with the selection of the appropriate vibration grinding stones, *J. Eng. Appl. Sci.* **71** (2024)
27. DIN Deutsches Institut für Normung e.V. (Juni / 2010). *DIN EN ISO 25178-6: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Flächenhaft – Teil 6: Klassifizierung von Methoden zur Messung der Oberflächenbeschaffenheit* [Geometrical Product Specification (GPS) – Surface texture: Areal – Part 6: Classification of methods for measuring surface texture]. (ISO 25178-6:2010); Deutsche Fassung EN ISO 25178-6:2010. Berlin. DIN Deutsches Institut für Normung e.V.
28. B. He, S. Ding, Z. Shi, A comparison between profile and areal surface roughness parameters, *Metrol. Meas. Syst.* (2023)
29. A. Abdelkawy, Modelling of cutting force and surface roughness of ultrasonic-assisted drilling using artificial neural network, *J. Eng. Appl. Sci.* **69** (2022)
30. DIN Deutsches Institut für Normung e.V. (Dezember / 2022). *DIN EN ISO 21920-2: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Profile – Teil 2: Begriffe und Kenngrößen für die Oberflächenbeschaffenheit* [Geometrical Product Specification (GPS) – Surface texture: Profile – Part 2: Terms, definitions and surface texture parameters]. (ISO 21920-2:2021, korrigierte Fassung 2022-06); Deutsche Fassung EN ISO 21920-2:2022. Berlin. DIN Deutsches Institut für Normung e.V.
31. DIN Deutsches Institut für Normung e.V. (Juni / 2010). *DIN EN ISO 25178-6: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Flächenhaft – Teil 6: Klassifizierung von Methoden zur Messung der Oberflächenbeschaffenheit* [Geometrical Product Specification (GPS) – Surface texture: Areal – Part 6: Classification of methods for measuring surface texture]. (ISO 25178-6:2010); Deutsche Fassung EN ISO 25178-6:2010. Berlin. DIN Deutsches Institut für Normung e.V.
32. DIN Deutsches Institut für Normung e.V. (April / 1998). *DIN EN ISO 4288. Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Tastschnittverfahren – Regeln und Verfahren für die Beurteilung der Oberflächenbeschaffenheit* [Geometrical Product Specification (GPS) – Surface texture: Profile method – Rules and procedures for the assessment of surface texture (ISO 4288:1996). Berlin. DIN Deutsches Institut für Normung e.V.

33. K.-J. Conrad, Taschenbuch der Konstruktionstechnik [Pocketbook of construction technology]. 3., *vollständig überarbeitete und erweiterte Auflage* (Hanser (Hanser eLibrary), München, 2021)
34. DIN Deutsches Institut für Normung e.V. (Dezember / 2022). *DIN EN ISO 21920-3: Geometrische Produktspezifikation (GPS) – Oberflächenbeschaffenheit: Profile – Teil 3: Spezifikationsoperatoren* [Geometrical Product Specification (GPS) – Surface texture: Profile – Part 3: Specification operators. Deutsche Fassung EN ISO 21920-3: 2022
35. M. Singh, Development of a portable Universal Testing Machine (UTM) compatible with 3D laser-confocal microscope for thin materials, *Adv. Ind. Manuf. Eng.* **4**, 100069 (2022)
36. L.C. Díaz-Pérez, M. Torralba, L. Muro, J.A. Albajez, J.A. Yagüe-Fabra, Uncertainty budget of a large-range nanopositioning platform based on Monte Carlo simulation, *Measurement* **208**, 112469 (2023)
37. M. Grazia Guerra, F. Lavecchia, Measurement of additively manufactured freeform artefacts: the influence of surface texture on measurements carried out with optical techniques, *Measurement* **209**, 112540 (2023)
38. M. Niemczewska-Wójcik, M. Madej, J. Kowalczyk, K. Piotrowska, A comparative study of the surface topography in dry and wet turning using the confocal and interferometric modes, *Measurement* **204**, 112144 (2022)
39. P. Podulka, W. Macek, D. Rozumek, K. Zak, R. Branco, Topography measurement methods evaluation for entire bending-fatigued fracture surfaces of specimens obtained by explosive welding, *Measurement* **224**, 113853 (2024)
40. L. Newton, A. Thanki, C. Bermudez, R. Artigas, A. Thompson, H. Haitjema, R. Leach, Optimisation of imaging confocal microscopy for topography measurements of metal additive surfaces, *Metrology* **3**, 186–221 (2023)
41. B. He, H. Zheng, S. Ding, R. Yang, Z. Shi, A review of digital filtering in evaluation of surface roughness, *Metrol. Meas. Syst.* (2023), <https://doi.org/10.24425/mms.2021.136606>
42. Experimental study of non-measured points on surface measurement using structured illumination microscopy, *Metrol. Meas. Syst.* (2023). <https://doi.org/10.24425/mms.2022.143071>
43. Verein Deutscher Ingenieure, VDI-Gesellschaft Produktionstechnik (ADB), Fachbereich Fertigungsverfahren, Ausschuß Elektroerosives Bearbeiten. (1975). *VDI Richtlinie 3400 Elektroerosive Bearbeitung: Begriffe, Verfahren, Anwendung* [Electrical Discharge Machining (EDM): Definitions, processes, application (VDI 3400). Düsseldorf.
44. R. Fang, H. Yi, S. Wang, Y. Niu, Classification and inspection of milling surface roughness based on a broad learning system, *Metrol. Meas. Syst.* 483–503 (2022)
45. VDI/VDE Verein Deutscher Ingenieure/Verband der Elektrotechnik, Elektronik und Informationstechnik. (Dezember/ 2015). *VDI/VDE 2627 Part 1: Measuring rooms, classification and characteristics, planning and execution*. Berlin Beuth Verlag.xx
46. C. Engler, A. Georgiadis, D. Lange, N. Meier, Way out of the supply crises through risk minimization - metrological comparison of two polypropylene materials and examination with six sigma methods, *Int. J. S Prod. Qual. Manag.* (in press), DOI: [10.1504/IJPQM.2023.10060471](https://doi.org/10.1504/IJPQM.2023.10060471)
47. The American Society of Mechanical Engineers. (June/ 2020). *Surface Texture (Surface Roughness, Waviness, and Lay)*. The American Society of Mechanical Engineers (ASME) Two Park Avenue, New York, NY 10016–5990.

Cite this article as: Carsten Engler, Anthimos Georgiadis, Dirk Lange, Nicolas Meier, New method for assessing the repeatability of the measuring system for roughness measurements, *Int. J. Metrol. Qual. Eng.* **15**, 10 (2024)