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Design and verification of geometric roughness standards by reverse engineering

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Abstract

In order to ensure a reliable calibration of surface topography measuring instruments the use of practical calibration strategies is required. This requirement can be fulfilled when measurement standards with a defined surface structure in accordance to the later obsessed application are used. Different examples for the design and manufacturing of accordant measurement standards have been investigated by the authors. Within this publication a generic reverse engineering approach for the design of geometrical measurement standards is deducted from these results. The physical effects that occur because of the manufacturing with an ultraprecision turning machine and the sampling of the measurement standards are mathematically inversed and considered. The practical abilities of the approach are illustrated exemplarily. These theoretical considerations for the design can be verified experimentally by the manufacturing of the samples with an ultra-precision turning process. In doing so, the high precision of the new design approach can be validated. The examinations confirm the universality of the reverse engineering approach for the design of measurement standards.

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1. Introduction

In the field of geometric product specification different "material measures" are currently utilized which are standardized in ISO 5436-1 [1] and ISO 25178-70 [2]. An overview considering the current state of the art was given by Leach et. al. [3]. Relevant metrological properties for the calibration were introduced with the ISO 25178-600 [4] series.

In order to examine the design of measurement standards, their definition as given in the international vocabulary of metrology is applied [5]: a measurement standard is a "realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference" [5]. The evaluation of measurement uncertainty of calibration procedures with roughness standards was examined by Haitjema [6].

The current standardized measurement standards are mostly surfaces whose structures are not systematically deducted from the later application. In order to cope with the increasing requirements of measurement and calibration within the industry, a new approach for the design of measurement standards is suggested which utilizes reverse engineering [7]. This approach has been verified for specific applications and parameters. Within section 2, a generic description is derived based on the achieved results.

Currently, roughness standards are manufactured with defined manufacturing parameters and then a calibration of the manufactured measurement standard is executed (see e.g. [8]). This is done with a calibrated reference measurement device in order to ensure the connection towards the SI unit meter with a traceability chain [9].

The new approach is to define a calibrated value that is desired as a calibration standard and then to inverse the entire signal chain of manufacturing, sampling and evaluating in order to calculate relevant physical effects of these processes for the design of the standard. The iteration leads to the manufacturing dataset for the desired surface parameters which can be processed by a manufacturing device.

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This approach works for different measurement principles as well as different surface properties to be calibrated. First examples for a specific application have been published with the R_k-standard [7] and the profile linearity standard [7] which are intended for the use with stylus instruments [7]. The 3D-topography linearity standard [11] which can calibrate optical topography measurement devices is another example [11]. In section 2, a generalized approach is introduced based on these specific applications. Results of the applications are provided within sections 3 and 4.

2. Defining a generalized design approach

The general idea of the new approach is that the calibration can be executed more accurately when it is closely related to the measurement task and physical effects of the signal chain are considered [7]. As stated, different specific applications of the approach have been introduced. However, it is possible to define the approach generically without the limitation to a specific measuring method.

This means that the current design approach for measurement standards needs to be revised. We propose to change the design process towards a utilization of a reverse engineering approach. A schematic comparison between the traditional approach for the design of measurement standards and the new approach is shown in Figure 1.

Traditionally (Figure 1a) the target values are defined and then a manufacturing process which generates statistical surface structures (e.g. grinding or lapping [10]) is applied. For the superfine roughness standards, a turning process is applied for the manufacturing of a deterministic surface [8]. The manufactured measurement standards are measured with a reference sampling which leads to a calibrated value of the standard after the compulsory evaluation. This calibrated value can then be used to adjust the manufacturing process in order to image the desired values more accurately.

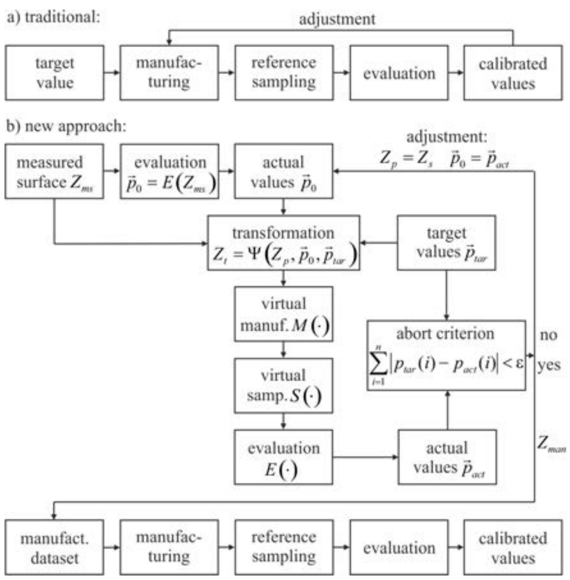

Fig. 1. (a) traditional approach for the design of roughness standards; (b) new approach.

Within our new approach (Figure 1b) a measured surface Z_{ms} is evaluated in order to calculate the initial values for the roughness parameters $\vec{p}_0$ to be calibrated. The approach as imaged in Figure 1b is a more systematic procedure which works very generically for arbitrary surfaces, measuring systems and parameters. The input surface can be either a profile, mathematically represented by a row or column vector, or a 3D-topography, represented by a matrix. The target values for the parameters are defined as a vector $\vec{p}_{tar}$ with the length n :

$$\vec{p}_{tar} = (p_{tar}(i)), i = 1, 2, \ldots, \text{n} , \quad (1.1)$$

and afterwards, after a preprocessing, a transformation step $\Psi(\cdot)$ is applied to measured data of an actual surface, followed by a virtual manufacturing $M(\cdot)$, measurement $S(\cdot)$ and evaluation $E(\cdot)$ [11]. This signal chain considers the relevant physical effects of these processes on the surface. With the pre-processed surface $\vec{z}_p$, the transformation $\Psi(\cdot)$ can be generically described as:

$$Z_t = \Psi(Z_p, \vec{p}_0, \vec{p}_{tar}) . \quad (1.2)$$

The transformed dataset $\vec{z}_t$ serves as the input dataset for the signal chain [11]:

$$(Z_s, \vec{p}_{act}) = E(S(M(Z_t))) . \quad (1.3)$$

$\vec{z}_s$ is the resulting evaluated profile and $\vec{p}_{act} = (p_{act}(i)), i = 1, 2, \ldots, \text{n}$ are the evaluated parameters. The parameters are compared with the target values using for example the following abort-criterion [11]:

$$\sum_{i=1}^{n} |p_{tar}(i) - p_{act}(i)| < \varepsilon , \quad (1.4)$$

with the maximum residual ε . As the approach is executed as an iteration, the described steps are repeated until the virtual evaluation results in the desired target value(s) and a given abort criterion is fulfilled [11]. The result of the appropriate algorithm is the virtual dataset $\vec{z}_{man}$ of the new sample. This dataset is then manufactured as a measurement standard and serves as the control dataset for an ultra-precision manufacturing process. If the abort criterion is not fulfilled in the current iteration, the initial value is adjusted:

$$\vec{p}_0 = \vec{p}_{act} , \quad (1.5)$$

as well as the profile to be transformed:

$$\vec{z}_p = \vec{z}_s . \quad (1.6)$$

According to the parameters to be calibrated, the transformation steps are adjusted. Within the traditional approach, a “physical iteration” of the manufactured geometry was performed as the parameters of the manufacturing process were adjusted towards the desired target values of the surface parameters to be calibrated.

The new process applies a “virtual iteration” and therefore reduces the effort for the design of measurement standards. Further, the consideration of the signal chain guarantees that present physical effects are considered within the manufacturing dataset.

The introduced general approach works similar for different measuring principles. Besides the transformation step as well the virtual descriptions of the manufacturing and sampling need to be adapted according to the application. Examples for this procedure are given in the following section.