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Towards uncertainty in dimensional metrology of surface features for advanced manufacturing

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Abstract

In previous work, an original approach was developed for the dimensional characterisation of surface features on parts and test artefacts, aimed at supporting researchers involved in the study of advanced manufacturing processes. In the approach, methods and algorithms from image processing, coordinate metrology, surface metrology and reverse engineering are merged into an original framework for feature identification, extraction and dimensional characterisation, starting from areal topography data. With the ultimate goal of associating uncertainty to the results obtained in dimensional characterisation, this paper focuses on specifically investigating reproducibility and repeatability of dimensional characterisation results obtained on a test dataset consisting of a step-like feature manufactured by material jetting.

Surface metrology, advanced manufacturing processes, dimensional characterisation, uncertainty in measurement, repeatability, reproducibility.

1. Introduction

An emerging trend in surface metrology is the development of data analysis solutions that complement the computation of surface texture parameters [1]. In particular, approaches aimed at the dimensional characterisation of individual surface features provide new perspectives to the problem of characterising complex three-dimensional topography information at the micrometric and sub-micrometric scales. A novel framework for dimensional characterisation of individual surface features has been recently proposed [2]. The framework borrows ideas and methods from image processing, reverse engineering and coordinate metrology of standard-sized parts and merges them into an original method that operates on areal topography data as obtainable by three-dimensional microscopes and profilometers. The framework can be tailored to each specific application, to provide dedicated solutions for algorithmic identification of the target surface feature and algorithmic computation of its desired dimensional and geometric attributes [2]. However, as the number of applications of the framework increases, a growing demand for metrological performance drives the need for a more complete assessment of error associated with the dimensional feature characterisation. Error is originated at topography measurement, and propagates through the algorithms used for levelling, feature identification and ultimately extraction of the geometric attributes of the target feature. While a more complete and mathematically rigorous approach to error characterisation is being developed by the authors, that targets both measurement and data analysis through the incorporation and modelling of all the major error sources, parallel experimental research work is being carried out in order to obtain quantitative data pertaining to measurement error from replicate measurement tasks, in particular under repeatability and reproducibility conditions. In this paper, an individual, step-like feature fabricated via material jetting of a polymer on a flat substrate is selected as test case. The feature is part of a larger research effort at the University of Nottingham, aimed at investigating the possibility of building designed geometries by material jetting, and for investigating limitations in terms of what shapes and sizes accuracies are obtainable [3]. In order to assess the performance capability of the manufacturing process, thickness, footprint area and volume of the fabricated feature need to be obtained. The specific topic discussed in this paper is the assessment of dimensional characterisation error in reproducibility and repeatability conditions, in a purely experimental setup where the specimen is measured multiple times, and topography is processed via a dedicated algorithmic pipeline designed to compute the desired feature attributes. The error being assessed, therefore, pertains to the characterisation solution taken as a whole, i.e. measurement and data analysis together. The investigation is almost entirely focused on random error components, although the presence of some systematic effects is partially investigated.

2. Materials and methods

The target surface feature is a step-like protrusion of approximate square footprint 2 mm × 2 mm and approximate height 80 µm (thickness), built on a planar support by material jetting.

2.1. Measurement

An Alicona Infinite Focus G5 focus variation microscope (FV) with 20× objective was selected for measurement. As the measurand is translucent, a physical replica was obtained with the AccuTrans AB casting silicone. The use of a replica does not invalidate the study, as the goal is the assessment of measurement error in specific measurement conditions, not the intrinsic error of the measurement instrument; the use of physical replicas is a common scenario for FV. The specimen was imaged at ten different placements (poses) under the microscope, each characterised by a different rotation about the instrument vertical axis. Placements were executed manually with no particular care in replicating the same centring (to simulate manual placement by an operator). At each pose, a new measurement set-up was executed on the instrument to find the vertical ranges for the focal planes, and the lateral range that would cover the entire feature plus a sufficient portion of the surrounding regions (needed by the feature characterisation algorithms, see later). This led to a variable number of individual images needed to cover the field of view of the feature, depending on pose (2×2 or 3×3). Complete images were obtained by automated stitching within the FV proprietary software. The coaxial illumination provided by the FV instrument was left unchanged. At each pose, the entire acquisition process was repeated ten times without changing any controllable parameter. An example result of one acquisition is shown in Figure 1.a. The measurements were taken consecutively, in a humidity and temperature controlled clean room (20 °C ± 1 °C). The whole experimental campaign (total: 100 measurements) took approximately six hours.

2.2. Feature characterisation

A dedicated analysis pipeline was developed to implement automated feature identification, extraction and computation of its geometric attributes (see Figure 1).

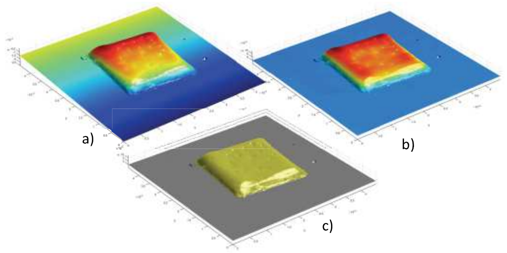

Figure 1. Example measurement and processing of the surface feature at a given angular position; a) original measurement (2×2 stitched image); a) selective-levelled topography; b) result of algorithmic feature identification.

As target attributes for this study, thickness, (footprint) area and volume of the feature were selected. Thickness is defined as the average height of the feature with respect to the support plane (aligned to the *xy* axes); area is defined as the *xy* area covered by the image pixels classified as belonging to the feature (*xy* area computed as the number of pixels, times pixel *x* and *y* widths); volume is defined as the material volume in correspondence of the feature pixels, heights measured between the top feature surface and the interpolation of the supporting plane directly underneath. For computing the feature attributes, the following algorithmic procedure was implemented: i) the topography is levelled by subtraction of the least-squares mean polynomial surface of 2nd order (the surrounding topography is slightly non-planar); the levelling is selective in that it only considers the feature surroundings to compute the best-fit surface (Figure 1.b). For levelling, the surroundings are automatically identified by means of a segmentation algorithm, illustrated elsewhere [4], and configured to identify regions with more uniform local slopes as the background; ii) another segmentation is run on the levelled topography in order to achieve a more accurate discrimination of feature and surrounding regions. The segmentation is based on the same methods as the previous, but runs at higher resolutions to achieve a finer discrimination (Figure 1.c). A sequence of post-processing operations based on morphological operators ensures a clean separation of the feature from the surrounding regions; iii) thickness, footprint area and volume are finally computed on the levelled topography, by using the final segmentation result as a reference to identify the feature pixels. Attributes are computed according to their definitions provided earlier.

3. Results

The aggregation of the results obtained for each attribute *x* (i.e. ten replicates × ten poses) yields the means: thickness = 83.09 µm, area = 4.51 mm^2, volume = 0.37 mm^3. Error in repeatability conditions can be obtained by computing the standard deviation of *x* for each pose (population estimate from the ten values available for the pose) and then by computing the mean of the ten standard deviations and correcting by the $c_4(10)$ factor. Therefore, in repeatability conditions: $E_{\text{thickness}}$ = 0.025 µm; E_{area} = 0.001 mm^2; E_{volume} = 0.0001 mm^3. In percentages with respect to the means: $E_{\text{thickness}}$ = 0.03%; E_{area} = 0.03%; E_{volume} = 0.03%. To obtain error in reproducibility conditions, ten estimated standard deviations were computed over ten aggregates of *x*, each obtained by random extraction of one value of *x* amongst the ten available for each pose (with no repetitions), and then by computing the mean of the ten standard deviations, corrected by $c_4(10)$. Therefore, in reproducibility conditions: $E_{\text{thickness}}$ = 0.107 µm; E_{area} = 0.007 mm^2; E_{volume} = 0.0008 mm^3. In percentages: $E_{\text{thickness}}$ = 0.13%; E_{area} = 0.15%; E_{volume} = 0.22%. While the probability distributions of each attribute in repeatability conditions were found normal (using a Kolmogorov-Smirnov non-parametric test [5]), the distributions of the same attributes in reproducibility conditions showed a distinct bimodality. Further investigations allowed the identification of a strong correlation between bimodality and the two possible sizes of the stitched image (2×2 or 3×3 depending on the orientation of the feature within the FoV). This hinted at the levelling operation (subtraction of best-fit third-order polynomial) as being the source of a systematic error component, due to the sensitivity of polynomial fitting when applied to wider point sets. Further investigations are in process to better explain such relationship, and to understand additional systematic effects, e.g. a slight time-based drifting, which was also observed.

4. Conclusions

A solution for measuring and characterising an individual surface feature was applied for assessing reproducibility and repeatability error. The solution consisted in measuring the three-dimensional topography of the feature with a FV microscope, and applying a dedicated, algorithmic solution for data analysis in order to extract the feature-relevant geometric attributes (thickness, area and volume). The analysis of the results allowed for an estimation of random error components in reproducibility and repeatability conditions, and indicated the presence of a systematic effect presumably linking the extents of the FoV to the performance of the algorithmic levelling operation. More thorough investigations are needed to better understand this and additional systematic error components.

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