Towards uncertainty in dimensional metrology of surface features for advanced manufacturing

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Giuseppe Musso[1,3], Nicola Senin[1,2], Maurizio Galetto[3], Richard Leach[1]

[1] Faculty of Engineering, University of Nottingham, UK; [2] Dipartimento di Ingegneria, Università di Perugia, Italy; [3] Dipartimento di Ingegneria Gestionale e della Produzione, Politecnico di Torino, Italy.

Introduction

A novel framework for dimensional characterisation of individual surface features has been recently proposed [2] that complements the computation of surface texture parameters [1]. The framework is comprised of methods for automated surface feature identification, extraction and characterisation through the computation of its geometric attributes of size, shape and localisation.

Problem: 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 characterization. However, error estimation is not straightforward, because of the process of uncertainty propagation through the analysis steps. (figure I).

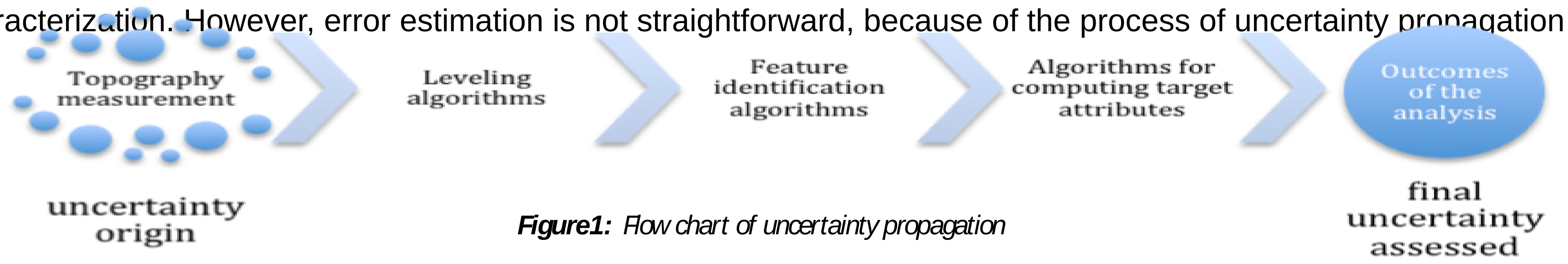

Figure1: *Flow chart of uncertainty propagation*

A throughout estimation of error sources and how they combine through the analysis steps represents a significant undertaking, and implies rigorous mathematical models.

TRADE OFF: In this work a preliminary investigation was carried on, consisting of the investigation of error in reproducibility and repeatability conditions by adopting a purely experimental approach. A step-like feature was selected as test case, it was measured multiple times (in repeatability and reproducibility conditions) and its target geometric attributes were computed using the aforementioned framework.

ADVANTAGES: Easier approach than the pure analytic method, reduced computational time and set up time;

Materials and Methods

Sample and measurements:

The target surface feature is a step-like protrusion of approximately square footprint 2 mm × 2 mm and approximate height 80 μm (thickness), built on a planar support by material jetting; the feature is part of a larger research project aimed at investigating the possibility of building structured topographic features by material jetting [3].

An Alicona Infinite Focus G5 focus variation microscope with 20× objective was selected for the measurement (figure 2). As the measurand is translucent, a physical replica was obtained with the AccuTrans AB casting silicone (figure 3). The specimen was placed in ten different poses, each characterised by a different angular and lateral orientation (reproducibility conditions). At each pose, the entire acquisition process was repeated ten times without changing any controllable parameter (repeatability conditions).

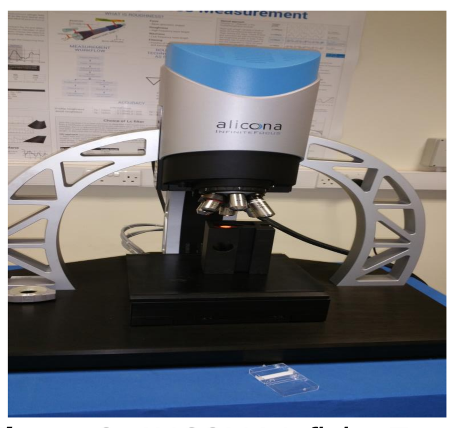

Figure 2: *ALICONA Infinite Focus G5*

Figure 3: *image of the silicone replica*

Feature Characterisation

The following target feature attributes were selected: thickness, footprint area and material volume. For computing them, the following algorithmic procedure was implemented (figure 4):

i) removal of voids and outlier points;
ii) algorithmic identification of the feature surroundings (background) through a proprietary segmentation method [4];
iii) selective levelling by least-squares mean plane subtraction, to align the surroundings with the z=0 plane;
iv) algorithmic feature extraction through a proprietary segmentation method [1];
v) computation of the attributes using the levelled surroundings as datum [4]. Thickness: mean height of the feature measured from tl[...] plane; volume: feature heights integrated ove[...]

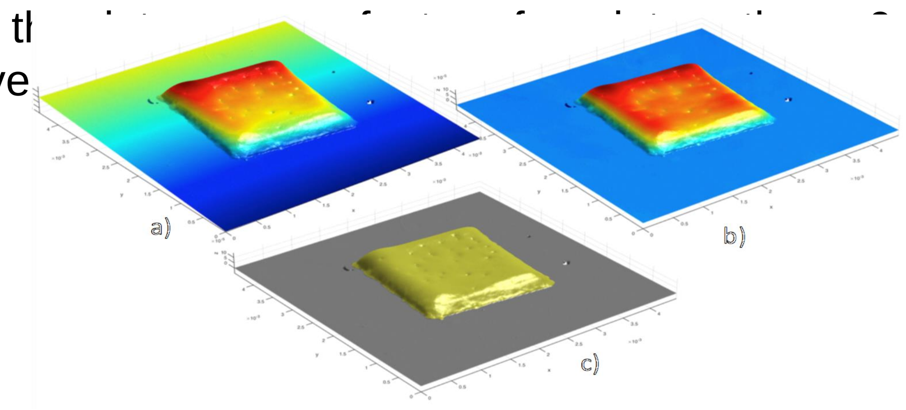

Figure 4: Some steps of the procedure
a) original dataset (2×2 stitched image);
b) selective-levelled topography;
c) result of algorithmic feature identification.

Statistical analysis:

Repeatability: error in repeatability conditions was obtained by aggregating data of the attribute "*x*" (thickness, area or volume) associated to each pose, and by computing the standard deviation for each aggregate (eq 1), and then the mean of the ten standard deviations, corrected by the (c_4) factor to eliminate the bias (eq 2).

$$\hat{\sigma}_i = \sqrt{\frac{\sum_{j=1}^{m}(x_{ij}-\bar{x}_i)^2}{m-1}} \qquad (1)$$

$$\hat{\sigma}_{rept} = \frac{\sum_{i=1}^{n}\hat{\sigma}_i}{n}\times\frac{1}{c_4} \Rightarrow E_{rept} \qquad (2)$$

Reproducibility: ten estimated standard deviations were computed over ten aggregates of the *x* attribute, each aggregate being obtained by random extraction of one value of *x* amongst the ten available for each pose with no repetitions (eq 3). Reproducibility error was obtained by computing the mean of the ten standard deviations, corrected by c_4 factor (eq 4).

$$\hat{\sigma}^z_{repr} = \sqrt{\frac{\sum_{i=1}^{n}(x_i^z-\bar{x}^z)^2}{n-1}} \qquad (3)$$

$$\hat{\sigma}_{repr} = \frac{\sum_{z=1}^{m}\hat{\sigma}^z_{repr}}{m}\times\frac{1}{c_4} \Rightarrow E_{repr} \qquad (4)$$

Results

The overall aggregation of the results obtained for each attribute *x* (i.e. ten replicates × ten poses) yielded the following means:

thickness = 83.09 μm, area = 4.51 mm², volume = 0.37 mm³.

Table 1 reports repeatability and reproducibility error results. The plots in figure 5 show the mean attribute values of each repeatability and reproducibility aggregate. The probability distributions of each attribute in repeatability conditions were found normal (using a Kolmogorov-Smirnov non-parametric test [5]), while bimodality was observed for the same attributes in reproducibility conditions.

Table 1: Repeatability and reproducibility errors

Repeatability Error Results			Reproducibility Error Results		
$E_{thickness}$ = 0.025 μm	E_{area} = 0.001 mm^2	E_{volume} = 0.0001 mm^3	$E_{thickness}$ = 0.107 μm	E_{area} = 0.007 mm^2	E_{volume} = 0.0008 mm^3
$E_{thickness}$ = 0.03%	E_{area} = 0.03%	E_{volume} = 0.03%	$E_{thickness}$ = 0.13%	E_{area} = 0.15%	E_{volume} = 0.22%

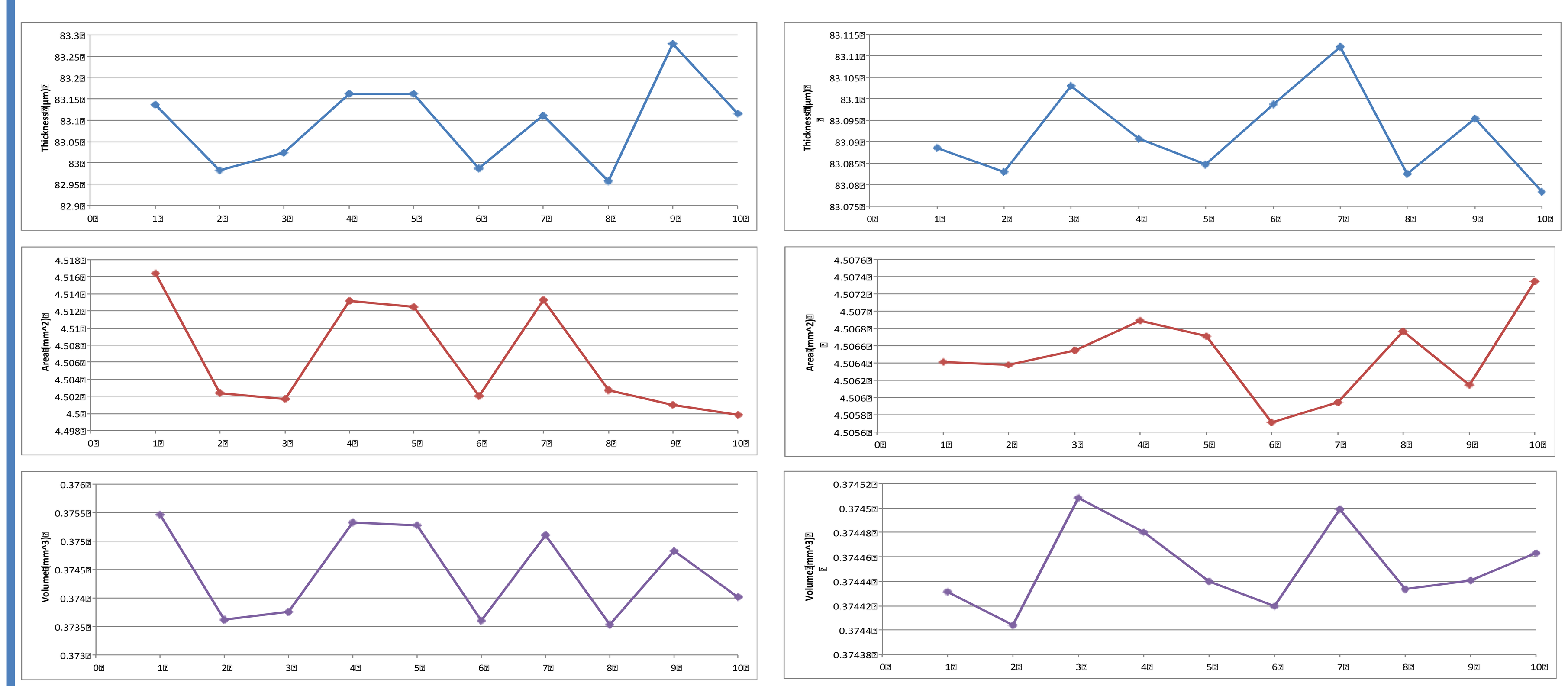

Figure 5: Mean values of the attributes in the repeatability and reproducibility aggregates.

Further investigations allowed to identify strong correlation between attribute value, and size of the stitched image (2×2 or 3×3, depending on feature orientation within the field of view). The correlation was found to be due to the support surface being slightly curved, influencing the levelling operation and thus displacing the z=0 datum, to a different degree depending on extents.

Conclusions and future work

A purely experimental approach allowed to obtain reproducibility and repeatability error associated to the dimensional characterisation of a surface feature produced by material jetting starting from areal topography data. The method is simple to apply, and can be used to obtain an estimate of repeatability and reproducibility error components to account for in the uncertainty budget associated to any surface feature dimensional characterisation task. In the specific test case, the analysis of the results allowed also to gain deeper insight on the behaviour of the characterisation method, in particular isolating a source of systematic error related to levelling on non-planar substrate. Further investigations are needed to obtain greater insight on how error generates and propagates through the characterisation procedure.

References

[1] Senin N, Blunt L 2013 In: Characterisation of Surface Texture, Leach R (Ed) (Springer) Chap 8

[2] Leach R K (Ed) 2013 Characterisation of Surface Texture (Springer)

[3] Husler A, Wildman R D, Alexander M R 2015 Intl. Sld. Freef. Fab. Symp. 1679-1985

[4] Senin N, Ziliotti M, Groppetti G 2007 Wear 262 395-410

[5] Wayne W D 1990 *Appl. Nonparm. Stat.* (Cengage Learning). pp. 319–330

Acknowledgements:

The authors would like to acknowledge the funding sources: EPSRC EP/I033424/1 and FP7-PEOPLE- IEF/METROSURF