

Efficiency of adaptive sampling in surface texture measurement for structured surfaces

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Abstract

Adaptive sampling has been used as an efficient sampling strategy in metrology for many years. However, most of the research into adaptive sampling has concentrated on the area of form measurement by coordinate measuring machines. This paper will discuss the use of adaptive sampling, primarily to reduce the measurement time when making high density areal surface measurements, for instruments that measure surface texture using scanning mechanisms, such as stylus profilometers. Specifically, the paper will concentrate on a common adaptive sampling method known as indirect sampling and a modified version is proposed in this paper. Simulated sampling analyses and three typical micro-scale structured surfaces (a vee-groove-like surface, a rectangularly tessellated micro-lens array and a MEMS device surface) are used as test cases. Using the tensor product order 2 B-spline reconstruction, the root mean square deviation from the original surface is calculated. By comparison with the widely used uniform sampling technique, the performance analysis results show that the modified adaptive sampling has advantages by improving the measurement accuracy, reducing the data size and reducing the measurement duration.

Keywords: adaptive sampling, indirect sampling, stylus profilometer, structured surfaces

1. Introduction

In surface measurement, a part of the measuring error comes from the sampling process in which the continuous surface is digitised. Although Shannon's sampling theory [1] states that a band-limited signal can be completely reconstructed from its discrete samples, exact band-limited signals do not usually exist in practice. For this reason, information about the unsampled regions is inevitably lost. Some intelligent sampling designs have been proposed during the past two decades that optimize the sampling positions aiming to reduce the logical error. This paper focuses on minimisation of the logical error using a sampling design known as adaptive sampling.

Adaptive sampling has been used in dimensional metrology for many years, particularly when using coordinate measuring machines (CMMs). Although uniform, or regular, sampling is the mainstream for practical measurement, adaptive sampling has been shown to have an advantage in terms of efficiency. The origin of the methodology derives from allocation of dense sampling in key regions such as high curvature parts or high frequency parts, followed by use of less dense sampling in other regions. In this way, the measuring efficiency can be improved without significant deterioration in accuracy. Adaptive sampling is a sampling design which can redirect its sampling effort in response to the observed values [2].

Generally two main categories of the sampling design can be formed: these are CAD model based methods and non-CAD model based methods. The former specifies the sampling positions based on a given nominal CAD model by analyzing its local surface properties such as the mean curvature. Most previous work has developed sampling methods based on CAD models [3-6]. For example, two novel algorithms known as automatic sampling and surface curvature-based sampling were proposed by Elkott [3] for a given freeform model. In the work of Shih et al [5], three main sampling design methods – direct sampling, indirect sampling and local adjustment sampling – have been developed for general CAD model measurements. These methods have been shown to be advantageous in terms of sample size saving or accuracy improvement for most general cases. However, CAD model based solutions do not consider unexpected defects produced in common manufacturing practice and the positioning error in clamping the given work-piece may cause a significant positioning error. In contrast, the non-CAD model based method has the ability to adjust its sampling points in real time [7, 8] Edgeworth and Wilhem [7]

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proposed a real-time adaptive sampling method based on surface normal measurement. This solution avoids the potential positioning error and is able to effectively pick up the necessary information to identify potential defects. However, its sampling design may not be as optimized as in the case of the CAD-model based method. Also, the result is sensitive to the initial conditions, such as the initial sample position. It is clear that none of these methods are perfect and selection of the method used depends on the specific work-piece, and the required measurement efficiency.

In surface metrology, adaptive sampling has not previously been introduced in practical measurement. In fact, most of the existing characterisation parameters of surface texture, such as Sq , Sz and Ssk , are derived from statistical theory. Consequently an unbiased estimation of the population based on the selected samples is expected [9]. The uniform sampling method ensures each unit of a population has the same selection probability and this method is widely accepted and used at the present time. Although a few sampling methods such as the spiral sampling [10] have been introduced, the emergence of structured surfaces provides a situation in which novel sampling methods will be required.

Structured surfaces [11] are those whose surface texture is dominated by a deterministic feature pattern [12]. They are often on the micrometre scale and anisotropic in different directions. For example, a vee-groove structure on a blazed grating usually has a micrometre scale in one direction but millimetre scale in the perpendicular direction. Measurement of this kind of surface needs special attention because of the following.

1. Evaluation of micro-scale dimensions and form error parameters are usually of more importance than the more standard surface texture parameters.
2. CMM are usually not able to probe or resolve such micro-scale surface structures. Extraction of the dimensional or form error parameters from the surface texture data is the general measurement requirement.
3. Most surface structures require both large measuring range and small resolution as it is common for sharp curvature changes to be observed in practical applications and features may have high aspect ratios.

The above requirements mean that efficient sampling methods need to be generated and adaptive sampling is a novel solution to this problem. Unlike uniform sampling [13], spiral sampling [10] and low-discrepancy sampling [14] - which has a fixed sampling design if some sampling conditions (e.g. the sample size) are specified - adaptive sampling determines its sampling positions by responding to the prior sampling observations thereby self-optimising. By analysing the effect of initial sampling, the method is able to predict the position of areas of high curvature. This means that dense sampling can be targeted in these areas. Using this technique in combination with proper reconstruction algorithms [15] the original continuous surface can be steadily rendered for visual presentation and post-process geometry analysis.

Considering stylus profilometers that have a mechanism allowing for raster-scanning of samples, an adaptive sampling method known as indirect sampling [5] is further developed in this research. This proposed method has been tested on some typical structured surfaces by numerical simulation. The results have shown promising performance by reduction of the sampling duration and minimisation of the sampling error.

2. Methodology

The sequential section adaptive sampling method is developed based on the indirect sampling method [5]. Considering the raster scanning mechanism used in stylus profilometry, this methodology comprises a two-stage algorithm: (1) profile adaptive compression sampling and (2) areal adaptive sampling.

2.1. Profile adaptive compression sampling

The core of the profile adaptive compression sampling method is a compression algorithm that is proposed in order to prune out the unnecessary samples for a given uniform sampling result. The method does not aim to reduce the sampling duration; on the contrary, it reduces the sample size by maintaining necessary reconstruction accuracy. After this process, those key samples which have significant influence on minimizing the reconstruction error are retained. A simulation result of this method is shown in Fig 1 and it can be seen that dense samples are retained near the high curvature regions. The method proceeds as follows

1. For a given surface profile, obtain its digital measuring result using the instrument-permitted dense sampling setting (blue line fig 1).

2. Divide the digital profile at inflection points, if any, into several segments that are solely concave or convex.
3. For each segment, evaluate the approximation error (usually the residual error between the original profile and the approximated/interpolated profile) of each segment.
4. If the error exceeds an initially set threshold (usually a fraction of the initial error from step 3), an extra sampling point is inserted on the profile curve at the midpoint. Otherwise, stop.
5. For each subinterval formed by insertion of a new point, repeat steps 3 and 4 until the approximation error is smaller than the threshold value.

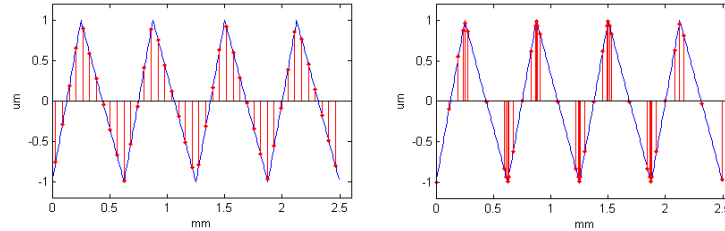


Figure 1. Comparison of the results of (a) the uniform sampling and (b) the profile adaptive comparison.

2.2. Areal adaptive sampling

Since profile adaptive compression sampling is simply a compression process, the real efficiency of this method comes from the areal adaptive sampling method. For a given surface, the methodology searches the key sample positions in the direction perpendicular to the main measuring axis; and then implements the profile adaptive compression for all the main axis profile measurements at the key positions. The technique comprises five steps as follows and as illustrated in Fig. 2.

1. Randomly (or uniformly) select N (usually ten) profiles parallel to the main measuring axis (X-axis in Fig. 2).
2. Implement profile adaptive compression sampling for each profile. Thus the key positions can be found.
3. Re-sort all the pruned key samples in accordance with their positions along the measurement axis (Y-axis in Fig. 2).
4. Downsample the key samples list produced in Step 3 by the factor N to prune out samples that are too dense.
5. For the downsampled key sample positions, implement the profile adaptive compression sampling for each profile on the main axis direction.

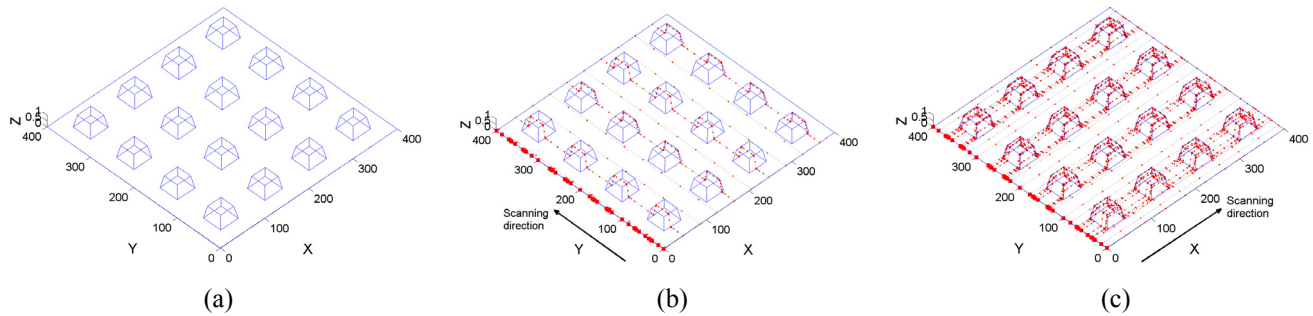


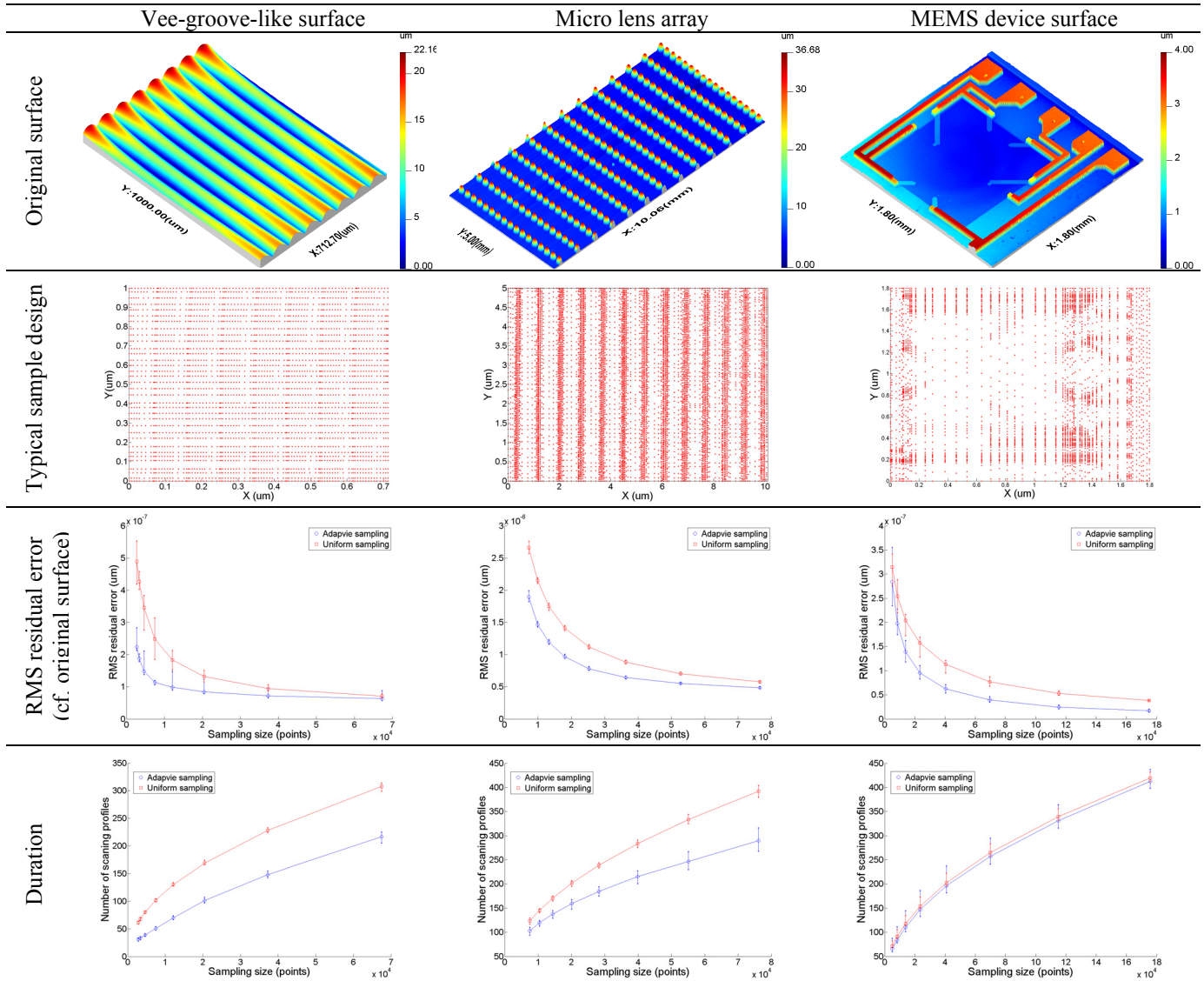
Figure 2. Illustration of areal adaptive sampling procedures (a) the original structured surface. (b) Implementation of ten profile adaptive compression sampling (dashed lines); and based on the pruned key sample positions (red dots), the downsampled key sample positions are selected (red squares). (c) Implementation of the profile adaptive compression sampling for each selected main axis (X-axis) profiles.

An improvement in measurement efficiency has been presented by the adaptive sampling result shown as the red sample points in Fig2(c). Dense sampling intervals are arranged near the edges of the square step structures; while the low curved regions have a sparse allocation of samples. This method is thought to be useful for efficient measurement of linear and rectangularly tessellated structures for raster scanning profilometers. Using this method, the measuring size and duration can be effectively reduced and simultaneously reconstruction error, such as the residual root mean square (RMS) error and the error of the dimensional parameter evaluation, can be minimized. However, in the simulation results presented here, most of the general structured surfaces such as MEMS devices are also able to benefit from it.

3. Reconstruction and performance comparison

Since the sampling process transforms a continuous signal into its discrete form, reconstruction is necessary to make the representative continuous signal available from its discrete samples. Thus subsequent numerical analysis, such as FFT analysis and the extraction of surface texture parameters of the representative surface, can be implemented. Cubic spline interpolation has been introduced in profile reconstruction from non-uniform samples [16]; however, no robust reconstruction methods have been widely used in areal reconstruction of scattered sampling points. Considering that the scattered samples produced by the areal adaptive sampling usually have a parallelized distribution, a tensor product order 2 B-spline approximation solution [15] is used because of its computing efficiency and numerical stability. To quantitatively reveal the involved accuracy improvement, the uniform sampling and bilinear interpolation are used for comparison.

Table 1. Performance comparison of uniform sampling and the areal adaptive sampling.



Two typical structured surfaces (vee-groove-like array structure and micro lens array structure) and a MEMS device surface are used as reference samples. They are presented in Table 1 with an initial measurement using an extra dense sample setting. After that, areal adaptive sampling and uniform sampling are simulated. Three typical adaptive sample designs have been illustrated. By applying the reconstruction methods described earlier, the root mean square (RMS) residual errors

compared to the original surfaces are analyzed. Simultaneously, the number of measuring profiles that are directly related to the measuring duration was computed. One hundred simulations were carried out with differing sample sizes so that repeatability could be quantified. By observing the results in Table 1, aspects of performance improvement can be summarized.

1. This proposed adaptive sampling usually produces 20 % to 50 % lower RMS residual error than uniform sampling when using the same sample size.
2. When using the same sample size, the adaptive sampling usually uses 20 % to 50 % less measuring time than uniform sampling for the measurement of linear patterns and rectangular tessellations; while for general MEMS surfaces, no obvious difference can be observed.
3. At the same accuracy level, the adaptive sampling usually needs 40 % to 60 % less sample size than uniform sampling. It indicates that the adaptive sampling is able to achieve a 50 % to 80 % improvement in measuring duration saving when keeping the same accuracy level as uniform methods.
4. The two methods have nearly the same repeatability level while maintaining accuracy. However, on measurement duration estimation, the adaptive method generally presents a slightly reduced repeatability.

By applying this method to the case of raster scanning stylus profilometers, the sample size and measurement duration are able to be reduced effectively or the sampling accuracy can be improved significantly.

4. Conclusions

Based on the indirect sampling algorithm proposed by Shih et al [5], a novel areal adaptive sampling method has been developed. Applying this method to the case of raster scanning mechanism-based profilometers, the measurement efficiency for structured surfaces is expected to be significantly improved. In this work through simulation, the adaptive method has shown evidence of performance improvement compared to the currently used uniform sampling methods, although the repeatability remains relatively unchanged. Using this method in the measurement of the majority of structured surfaces such as linear patterns, rectangularly tessellated patterns and general MEMS device surfaces, the sampling reconstruction accuracy can be significantly improved or the sample size can be reduced at a significant level. The practical measurement duration can also be reduced for linear patterns and rectangular tessellations. Considering that current areal measurement duration for scanning system can often be hours, the proposed method is able to considerably increase measurement efficiency.

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