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Comparison of surface texture measurement systems

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Abstract

The objective of this work is to develop a rigorous set of tests for comparing texture measurement systems and determining the uncertainty in the height measurements. Surface measurement systems are being used for increasingly finer scale metrology, and the criteria for surface textures are becoming more stringent. This work should facilitate the establishment of functional correlations. Traditionally, instrument comparisons have been made by measuring standard artifacts, or by using simple surface texture characterization parameters, like arithmetic average roughness, Ra. Our approach is to make the comparison based on measurements of any surface of interest, and to make them with respect to three aspects of the measurements: location, heights, and the scale, or wavelength, on the measured surfaces. The standard deviations of the heights measured at a location in repeated scans of the same region are used to determine the uncertainties of local height measurements. Measurement systems are compared on cumulative uncertainty plots normalized by the mean Sq. Height difference maps show that disparities are the typically the greatest in regions of steep inclinations. The regression coefficients comparing the heights measured by two systems are surprisingly low. Area-scale fractal analysis clearly shows the scales where the sensitivities of measurement systems differ. The differences between measurements are obvious differences, sometimes even between sequential measurements on the same instrument.

1. Introduction

The objective of this work is to develop a rigorous set of tests for comparing texture measurement systems and determining uncertainties in height measurements on surfaces of practical engineering interest. The results of these tests should be sufficient to quantify the degree of similarity between the measurements and the relative uncertainty of the measurements. The tests are intended to indicate the differences between measurement systems and to elucidate the nature of the differences. This work is intended to advance the accuracy and repeatability of surface measurements by supporting more comprehensive comparisons between measurement systems.

As surface measurement systems are being used for increasingly finer scale metrology, and because the criteria for surface textures are becoming more stringent, more precise understanding of the differences between measurement systems, an indication of the uncertainty in measurement, becomes increasingly important. Not understanding the difference between measurement systems can lead to problems in manufacturing and quality assessment, and to disputes between customers and suppliers. Additionally, the ability to establish functional correlations based on surface measurements depends on the accuracy of the measurements. Functional correlations are the basis for the engineering design of surface textures and design of the process that produce them. Establishing the accuracy of the measurement of surface textures depends on understanding the reproducibility, repeatability and bias of texture measurement systems, which is what these tests are intended to advance.

Traditionally, instrument comparisons have been made by comparing measurement on step height standards or on other standard artifacts, usually intended to be Euclidian in shape, i.e., perfectly smooth at some fine scale. These surfaces typically do not contain the same wavelength spectra as surfaces of practical interest, and cannot guarantee that the systems that compare well on the standard artifacts will also compare well in practice. Comparisons have also been made using simple surface texture characterization parameters, like arithmetic average roughness, Ra, calculated from selected test surfaces. Similar values of traditional parameters, like Ra, are necessary but not sufficient to guarantee any degree of similarity between instruments. Length-scale analyses [1,2] appear to facilitate for comparisons stylus instruments used in industry better than power spectral density spectra [3]. Area-scale plots [1] have been used by Cohen [4] to compare filters on surface measurements.

Our approach is to make the comparison based on measurements of surfaces of practical interest, and to make them with respect to three aspects of the measurements: location, heights, and the scale, or wavelength, on the measured surfaces. Direct comparisons of heights by location and height difference maps, are used to determine regions of similarity and disagreement. Standard deviations of heights measured at one location are used to determine the uncertainty. The influence of the heights themselves on differences in heights measured on two measurement systems can be shown when the heights measured on one system are plotted versus the heights, at the same location, measured with the other system. The resulting plot can be analyzed using a linear regression. We find that for many cases the regression coefficients are disappointingly low. These comparisons of height measurements by location are influenced by the alignment of the two measurements. Finally we compare the wavelengths in the measurements using length-scale and area-scale fractal analyses. These analyses show, as a function of the scale of observation, i.e., wavelength, the details to which the measurements are sensitive.

2. Methods

This section describes the developed methods are described in detail. Then the tests of the methods, and the measurement systems used for the testing are described.

All of the methods presented here are demonstrated on 3D surface measurements, i.e., measurements of heights (z), or elevations, on a surface as a function of position in a nominally horizontal (x,y) plane (z=z(x,y)). These methods could easily be applied to 2D profile measurements (where z=z(x)).

2.1 Comparison Test Methods

2.1.1 Height sampling variation maps

The variation in height measurements as a function of location is shown in height variation maps. These maps are constructed by taking some measure of the variance of heights measured at the same location and plotting that difference at that location. The measure of variation can be as simple as the difference in heights at the same location between two successive measurements of the same region, or can be the standard deviation or range or some other measure of variance of the heights at one location for a larger number of measurements of the same region. Mountains software by DigitalSurf (www.digitalsurf.fr) was used to generate the maps.

2.1.2 Cumulative uncertainty plots

The uncertainty of height measurements, or samples, regardless of location can be represented in a plot. The vertical axis is the cumulative frequency, or total fraction, of the locations with an uncertainty below that indicated on the horizontal axis. There are many ways to represent uncertainty in measurements [5]. The standard deviation is used here. Several measurements are taken successively with the same instrument at the same location using the same measurement parameters. The standard deviation of the height at each location is calculated and then normalized by the mean of the standard deviations (Sq values) of the all the measurements at that location. The horizontal axis is the ratio of the standard deviation of the height measurements at a location divided by the mean Sq for all the surface measurements at that location. Custom programs were written in Matlab (www.mathworks.com) to generate these plots.

2.1.3 Height v. height plots and regression analyses

The height v. height plots compare two height measurements at the same location. This requires that the measurements have the same sampling intervals, the same number of height samples taken in the same pattern and are aligned. The x-axis represents the heights of one measurement and the y-axis the heights sampled from the other measurement. Each point on the plot represents the corresponding heights of the samples measured at the same location. Custom programs were written in Matlab (www.mathworks.com) to generate these plots.

2.1.4 Area-scale comparison (area-scale plots)

The area-scale comparisons are generated using area-scale fractal analysis (ASME B46.1 2002, Brown et al. 1993), which shows the relative areas (y axis) as a function of scale of measurement (x-axis). The area-scale relation for a measured surface are determined from a series of virtual tiling exercises. The scale of measurement, or observation, is the area of the triangular tiling elements. Each tiling exercise is done with triangles of identical areas. The shapes and orientations of the triangles are allowed to vary. In general, the smaller the triangle used in the tiling exercise, the larger the relative areas. The relative areas are the measured areas, the product of the tiling triangle area and the number of triangles used in the tiling, divided by the nominal areas, i.e., the total areas of the projections of the tiling triangles on the x-y plane. Kfrax by Surfract (www.surfract.com) was used to calculate the area-scale relations.

2.2 Measurement systems

Two instruments were used in this work. They are described below and in Table 1. A series of tests were done to show measurement system repeatability and to compare measurements from different systems (Table 2.).

The WPI-SLM (scanning laser microscope) uses a Keyance LC 2210 triangulation height sensor for height sampling and uses ball-screw stages with stepper motor with 0.20μm step resolution for positioning. The locations are determined by polling a rotary encoder with a 1.27 μm resolution. The WPI-SLM was developed during a research project funded by NASA's Langley research center. It was designed to measure pavement micro-textures, in-situ, on runways (Johnsen 1998).

The UBM Microfocus SLM (Solarius Development Inc., Sunnyvale, CA) uses a Keyance LT 8010 confocal height sensor for height sampling. It is capable of running in two modes, one where an encoder and another control the sampling position, and another where it is based on tracing speed and time. The latter is faster. For the measurements reported in this paper the latter mode of positioning was used.

The lateral resolution of the height sensors is not easily determined, but it is probably larger than the lateral control on the WPI-SLM and smaller that lateral control on the UBM, at least when the lateral control is used in tracing speed – time mode.

Table 1. Measurement instruments

Instrument name	Sensor technology	Vertical range	Vertical resolution	Horizontal range	Horizontal resolution
WPI-SLM	Triangulation Laser	60 mm	12 μm	150 mm	~25 μm
UBM-SLM	Confocal Laser	0.6 mm	1 μm	300 mm	1 μm

2.3 Test measurements

Four series of measurements were made with two instruments on three different surfaces (Table 2). The pavement surface (roughly finished mortar mix) and a replica made from it were measurement with the WPI-SLM using a relatively large sampling interval. Two different sized regions on the alfalfa seed were measured with the two different instruments at different sampling intervals.

Table 2. Measurements and system comparisons

Surface	Instrument	Number - Region Sampling interval	Area-scale plots	Height difference maps	Height v. height plots	Cumulative uncertainty plots
Pavement & replica	WPI-SLM	5 pairs-40x40mm 25.4 μm	Fig. 1			
Alfalfa Seed	WPI-SLM	5 – 3x3mm 10.16mm		Fig. 2	Fig. 3	Fig. 5
Alfalfa Seed	UBM	7 – 0.5x0.5mm 1 μm			Fig. 4	Fig. 5

3. Results

3.1 Area-scale comparison of original and replica

Area-scale plots comparing the five measurements of the original pavement surface and a replica of the surface are shown in Fig. 1 along with height images of the surfaces. At scales finer than 0.1mm² the relative areas for the five replica measurements are clearly smaller than those for the original. At scales above 0.5 mm² the replica and original are more difficult to differentiate.

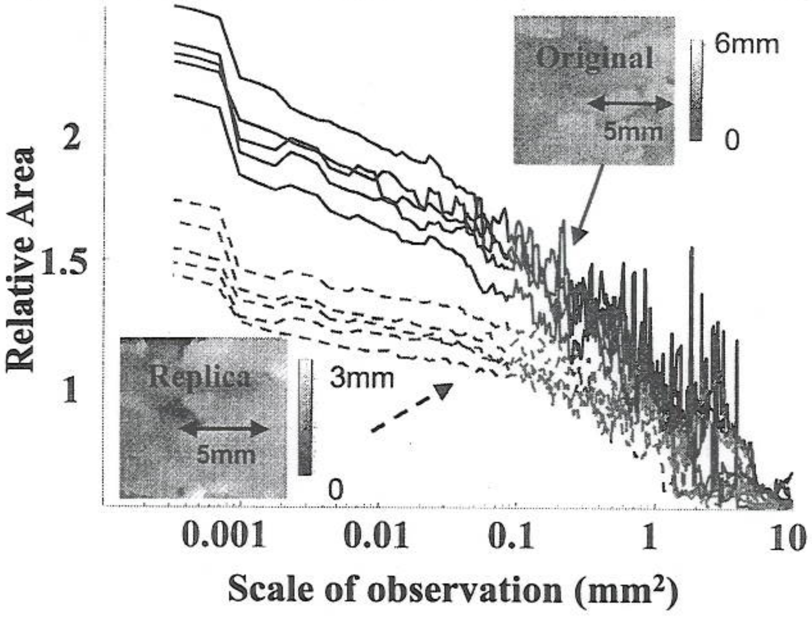

Fig. 1. Area-scale plots of measurements from a pavement surface and replica from the surface.

3.2 Height variation maps

A height difference map is shown in Fig. 2, along with a height map and a standard deviation map, all from measurements made by the WPI-SLM on an alfalfa seed. The height difference map shows the differences in height from two measurements from the alfalfa seed. The standard deviation map is based the standard deviations of the heights on five successive measurements. The largest differences on the height difference maps are in the regions with the largest gradients on the height map. A similar pattern is not evident on the standard deviation map.

3.3 Height versus height plots

Plots of heights on one measurement versus another from the alfalfa seed are shown in Figures 3 and 4, for the WPI-SLM and the UBM respectively. The regression lines from both plots have slopes close to one and intercepts close to the origin. The regression coefficient for the plot on the WPI-SLM is six percent greater than that for the measurements made with the UBM.

3.4 Uncertainty comparisons

The uncertainties of height measurements are compared for measurements taken with the WPI-SLM and the UBM in Fig. 5. The cumulative surface fraction is shown on the y-axis and the normalized uncertainty, as indicated by the standard deviation normalized by the mean standard deviation for the measurement, is shown on the x-axis. About 90%

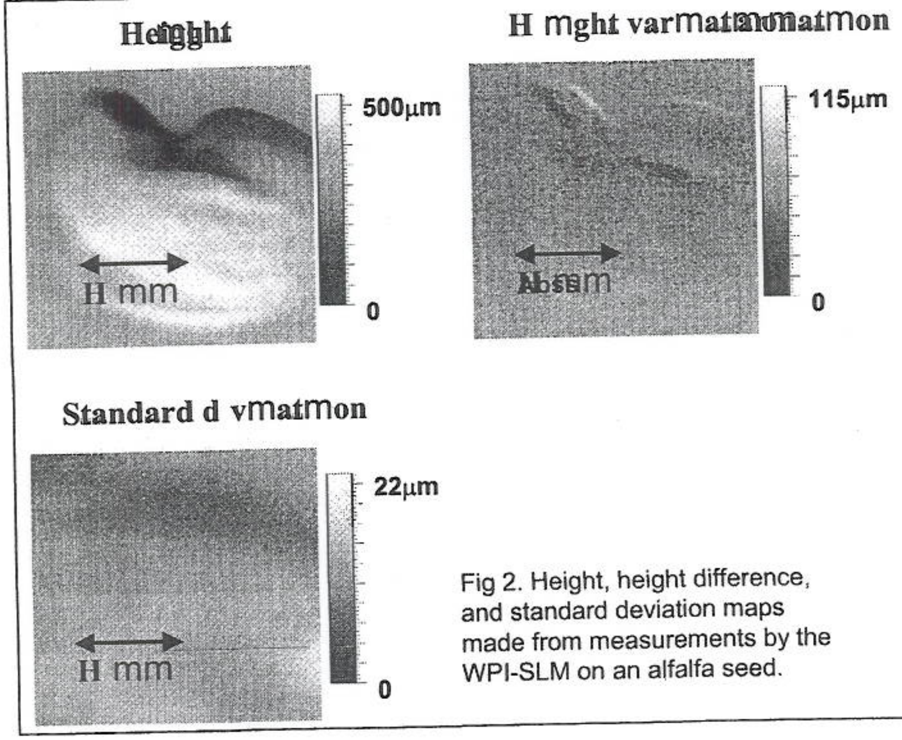

Fig 2. Height, height difference, and standard deviation maps made from measurements by the WPI-SLM on an alfalfa seed.

of the sampled height locations on the WPI-SLM have a normalized uncertainty of 0.1 or greater, whereas about 20% of the sampled height locations for the UBM do.

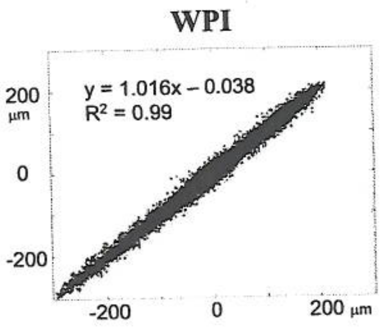

Fig. 3. Height versus height plot for two measurements of an alfalfa seed made with the WPI-SLM on a 3x3mm region with a 10.16μm sampling interval

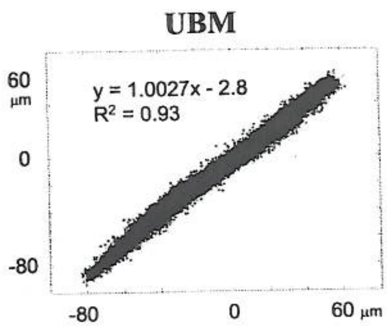

Fig. 4. Height versus height plot for two measurements of an alfalfa seed made with the UBM on a 0.5x0.5mm region with a 1μm sampling interval.

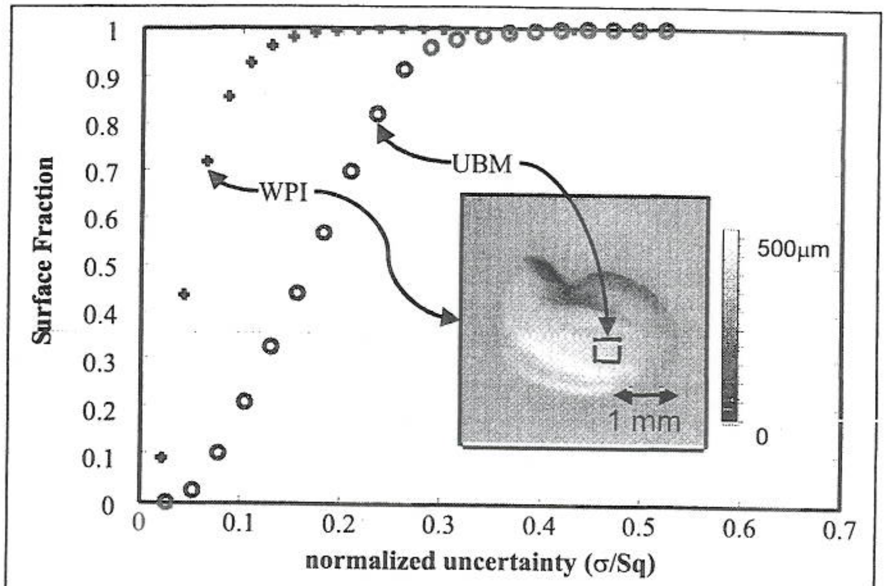

Fig. 5. Plots of surface fraction versus normalized uncertainty, as indicated by the standard deviation at a location normalized by the Sq for all the measurements, for measurements on the alfalfa seed by the WPI-SLM and the UBM. The mean Sq for the WPI-SLM is 70.1μm and for the UBM was 32.7μm.

4. Discussion

The comparison methods demonstrated here have potential utility for advancing the understanding of surface metrology instruments and measurement systems.

4.1 Area-scale plots original versus replica

The comparisons of the relative areas as a function of scale for the original and the replica, Fig.1, indicate that there is a significant loss of complexity, i.e., detail or information, in the replica at scales finer than 0.1mm². On the area-scale plots the complexity is proportional to the absolute value of the negative slope. The relatively small slope on the replica indicates that topographic details that are present in the original are not being replicated well. This comparison is based on five measurements at randomly selected locations on each surface, and therefore does not depend on alignment of the measurements. The plots show that relative areas can differentiate measurements of the replica from measurements of the original with a high degree of confidence at the finer scales of observation. It can be surmised that the replicas should not be used to represent the original surface when the situation involves scales of interaction where the replica does not reproduce the surface well.

4.2 Height difference maps

While the map shown is constructed from the difference in heights measured between two measurements, it could also be constructed from the range of several measurements, just as it is shown constructed from the standard deviations.

The height difference map shown in figure 2 can be used to show locations where the differences are large. These tend to be regions of high slopes. In these regions, small differences in the location where the height is sampled will appear as relatively large differences in the measured height. Even in successive measurements, where the surface is left stationary in the measurement instrument, there will be changes in the location of the samples due to positioning errors. Therefore these maps are influenced by the repeatability of the scanning stages. It is interesting to note that the standard deviation map does not show the same tendency to highlight the regions with steep slopes as clearly as the height difference map.

4.3 Height v. height plots

The height versus height plots (Figures 3 and 4) are limited in that they compare only two measurements, and are, therefore, more anecdotal and lack statistical confidence. One approach to improve statistical confidence would be to make many of these maps and to use statistical analyses of the regression analysis results. Another approach would be to calculate regression coefficients from a line represented by y=x, which is the ideal for perfect agreement, rather than on the best fit line. These kinds of plots could also be used to compare two measurements made using different measurement systems, although some kind of alignment strategy needs to be developed and the plot would largely be a measure of how well the measurements h ad been aligned.

4.4 Uncertainty

The comparisons of uncertainty (Fig. 5) are an initial illustration of a method. This method appears to show potential in advancing the understanding of uncertainty in surface measurements. The plot displays important aspects of the uncertainty.

The differences that appear might be explained by several factors, including the different resolutions at which the measurements were made, the differences in the positioning systems on the two instruments, and the ratios of the resolution of the positioning systems to the spatial resolutions of the height sensors.

5. Conclusions

5.1 Area-scale plots of original versus replica are capable of showing the scales at which the topographic details, or complexity, in the replica differ from those in the original surface.

5.2 Height difference maps can be used to show regions on a surface where there tend to be differences in the measurements.

5.3 Plots of height v. height are a means of representing the reproducibility of repeat measurements on a surface.

5.4 A potentially useful method for estimating and displaying the uncertainty in surface metrology applications has been developed.

6. Acknowledgements

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