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USING IMAGE REGISTRATION AND ALIGNMENT TO COMPARE ALTERNATIVE 2D MEASUREMENTS

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Abstract: We present in this paper a novel method for comparing alternative 2D measurements. The method is based on a new image registration algorithm developed for the automatic registration and alignment of randomly textured image data. Our aim in the algorithm development has been to enable fast registration of the measured 2D property maps without the need for special registration marks. To improve robustness, the maps are registered in two steps; the first step exhibits plain translation and the second phase iteratively refines the transformation estimate. Sub-pixel registration accuracy is achieved. Several experiments have been conducted showing that the algorithm is able to register various 2D property maps successfully. After the registration we align the alternative 2D measurements. This enables the comparison and statistical joint analysis of several 2D property maps measured from the same target area. The high amount of independently measured data points in the property maps provides a firm statistical ground for conclusions. We have used the new registration algorithm to align various 2D surface profile measurements of paper and board. The analysis of the aligned measurements has confirmed the feasibility of our registration method and revealed fundamental differences between the measurement devices.

Keywords: image registration, 2D profile measurement

1. INTRODUCTION TO PROPOSED METHOD

An increasing number of applications today make use of photographic imaging, laser scanning, and other measurements that produce 2D property maps (images). For example, 2D maps of surface topography offer promising ways to characterize surface structure and smoothness. Some of the topography measurements are probing directly the surface height but are slow whereas other methods are less direct but fast. In this paper we address the problem of analyzing the correspondence and accuracy of indirect 2D measurement methods when direct measurements are available as a reference. Our interest is in cases when the image resolution varies between the measurement methods and when the measurement devices do not automatically provide aligned images but alignment must be achieved based on the content of the measured images.

Image registration and alignment means that a set of 2D measurements of a sample are overlaid so that the pixels with the same coordinates in the measured images correspond to the same point in the sample. Image registration has had applications in cartography already when the work was performed by hand and eye. In last years, computational methods for automatic registration and alignment have been developed in several application areas; stereo vision, stereo cartography, close-range photogrammetry, medical imaging, image fusion and super-resolution [1, 2]. The computational load is quite suitable for modern personal computers.

We have developed a new image registration procedure that enables the alignment of textured 2D property maps with sub-pixel accuracy. The idea of using separate pixel clusters is similar to that presented in [3]. The main advantage of the new method is its robust automatic operation, even in cases when the maps have been acquired by different devices. Special registration marks are not needed because the method makes use of the texture contained in the data. The similarity measure used in the procedure is the 2D cross-correlation function.

The possibility to use aligned images provides considerable added value to image based measurement applications. It is practical to compare several alternative measurements of the same quantity. The comparison provides valuable information about the differences and similarities between the measurement devices and enables calibration. Sometimes it is useful to measure the same area several times with the same instrument to analyze noise. It is also possible to align multiple measurement arrays of different quantities measured from the same area to get information about the interactions of the variables.

We have applied image registration and alignment to compare alternative surface topography measurement methods. In our approach the same target area is first measured with all the methods. Next the data matrices are aligned together at sub-pixel accuracy using the new registration method introduced in this work. The dependencies between the aligned maps and their quality parameters can then be analyzed by multivariate statistical methods [4, 5]. Property maps – including surface topography maps – typically have a large number of independently measured data points, which provides a firm statistical ground for conclusions. Even low correlations and relationships are of significant statistical confidence.

This paper is organized as follows. Our new automatic image registration and alignment procedure will be described in Section 2. The measurement data analyzed in this work will be introduced in Section 3. Section 4 will present the methods used to analyze the aligned 2D measurements and introduce the results of the analysis. Section 5 will conclude the presentation.

2. AUTOMATIC IMAGE REGISTRATION AND ALIGNMENT

Transforming two images – the reference image and the input image – into the same coordinates consists of registration and alignment. Registration is the phase where a set of corresponding points (or features) are found from the two images and a transformation is estimated based on these points. At the alignment phase the transformation is applied to all the coordinates of the input image in order to overlay them with those of the reference image. Alignment involves interpolation to compute the input image values in the new, non-integer, coordinates. Accurate alignment of measured images is a pre-requisite for reliable joint analysis.

We have created a new image registration and alignment procedure for 2D measurements that contain random texture. The registration phase will be described in subsection 2.1 and alignment in subsection 2.2. Our method has the following three requirements: a) the areas measured with different instruments must overlap; b) the measurements have to correlate sufficiently with each other to facilitate the registration; c) the 2D sampling frequency of at least one of the measurements must be high enough to enable the interpolation of the measured values between the grid points.

2.1. Image Registration

The primary approach to register maps with random texture uses point mapping [1] which is also the basis of our method. In point mapping, control points are first selected from the reference map. Small areas around the control points are then selected and similar areas are searched in the input image(s). We have used 2D cross-correlation function as the similarity measure in the point search. The exact points of maximum similarity are interpolated from the 2D cross-correlation surface to achieve sub-pixel accuracy.

We have concentrated on making all the registration operations automatic. A priori knowledge about the nature of misregistration between the reference and input images has been essential in this work. The images acquired from the different measurement devices are known to be translated and moderately rotated with respect to each other. There may also be minor scale differences and slight errors in the orientation of the coordinate axes of the devices, which causes obliqueness. Hence affine transformation [6] has been chosen to map the input to the reference image.

Robustness is necessary for an image registration algorithm to be automated. Therefore each pair of images is registered in two phases: a coarse translation estimation phase and an iterative refinement of the transformation

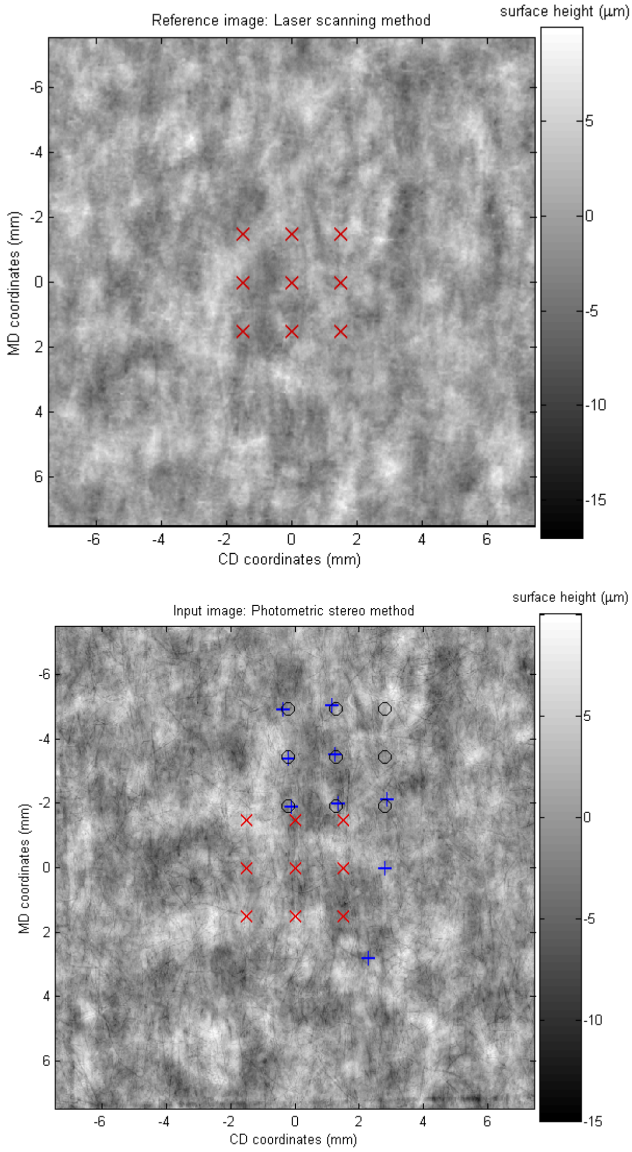

Fig. 1. First phase of image registration. Upper: reference topography image and search points (x). Lower: input image with predicted (x), found (+) and chosen (o) matching points.

estimate. In order to estimate the required translation within a moderate delay, the first phase employs a small number of control points. They are placed around the center of the reference image, as illustrated in the upper part of Fig. 1. Small areas around the control points are selected and similar areas are located automatically in the input image as the matching points. The lower part of Fig. 1 shows the matching points located by the algorithm as blue plus marks on the input image. It can be seen that not all of the points indicate a similar translation. An approximation for the translation in horizontal and vertical directions is computed as a weighted median value of the nine translation estimates. It is indicated in the lower part of Fig. 1 by the black circles.

The use of a large search area, which is necessary in the beginning, often causes false matches. However, the success of the registration depends critically on the reliability of the initial transformation estimate. It is therefore verified by cluster analysis that more than half of the points found indicate, within a small deviation, the same amount of translation between the reference and input images. In Fig. 1, seven of the nine search points show coherent results. The translations indicated by these seven points thus form a dense cluster around the weighted median based translation estimate when plotted in coordinate axes. If the matching points located by the algorithm are very much scattered around the map, no such cluster can be found and the registration is attempted again a few times with slightly adjusted search parameters.

Provided the first phase of the registration algorithm completes successfully, the latter phase then iteratively refines the transformation estimate according to further control points. At each iteration step, a set of new control points is automatically selected from the reference image. The locations of these points in the input image are predicted based on the latest transformation estimate. The exact locations are determined by the search procedure similar to that of phase one, but with a very small search area size. This efficiently constricts the computation time.

The grid of control points selected on the latter registration phase expands towards the corners of the reference image, which improves the overall registration accuracy. When the control point set finally spans the whole joint area of the reference and input images, the point search is terminated. A global affine transformation is fitted between the matching control points by a weighted least squares method in which the effect of abnormal control point pairs is minimized. The alignment accuracy achieved depends both on the accuracy of image registration and on the accuracy of transformation fitting [7]. If the transformation is correct and thus describes the warping required to convert the images into the same coordinates, the error can be satisfactorily approximated by the transformation fitting error. Our experiments, covering 89 pair-wise registrations of multimodal surface topography measurements of paper and board, imply that affine transformation is very suitable for our application. The transformation fitting error has remained below 0.1 pixels in the experiments.

2.2. Image Alignment

The transformation estimated at the registration phase is finally applied to the input image. This provides the geometrical alignment of the reference and input images. The coordinates of the input image are first warped to overlay them with those of the reference image. The input image must then be interpolated to evaluate the pixel values at the warped non-integer coordinates. Fig. 2 shows examples of the aligned surface topography maps of a cardboard sample. They have been selected from three different measurements that will be described in Section 3.

When the images to be aligned have different spatial resolutions, interpolation requires particular attention. When possible, it is advisable to select the reference image to be the one with the lower resolution. This minimizes the amount of artificial interpolated data in the result. We will analyze the effects of interpolation in Section 4.

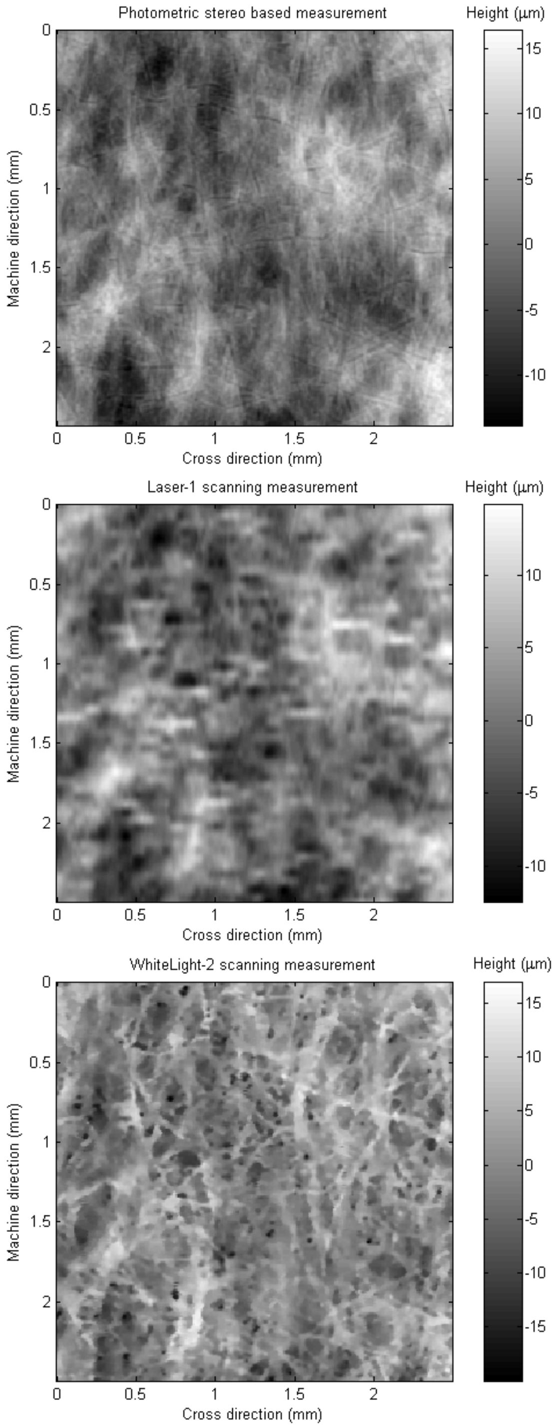

Fig. 2. Examples of aligned surface topography maps measured with different devices: Photometric stereo based device (top), Laser-1 scanner (middle) and WhiteLight-2 scanner (bottom). A small area has been selected from the total aligned map to show fine details.

3. MEASUREMENT DATA

The image data analyzed in this presentation is from five surface topography measurement devices. One of them, the photometric stereo based device, produces the topography map a couple of orders of magnitude faster than the other devices. It is also the only indirect method applied since it recovers the surface topography map from digital photographic images. The other four measurement devices are optical profilometers that produce the surface height values by direct scanning, using either red laser light or white light. The two laser scanners (Laser-1 and Laser-2) differ from each other in the z-directional resolution and measuring range. The two scanners that apply white light are equipped with different scanning sensors: the z-directional measuring range of the first sensor (later referred to as WhiteLight-1) is ten times larger than that of the second (WhiteLight-2). Table 1 summarizes the main properties of the images acquired by each device.

Table 1. Properties of surface topography images acquired by each measurement method.

Measurement device	Image size, *x* by *y* (mm)	Resolution, [*x*, *y*] (points / mm)
Photometric stereo	15 by 15	[137, 137]
Laser-1 scanning	15 by 15	[100, 20]
Laser-2 scanning	16 by 16	[100, 20]
WhiteLight-1 scanning	16 by 16	[100, 100]
WhiteLight-2 scanning	16 by 16	[100, 100]

The different devices have been used to measure the surface topography of coated and uncoated paper and cardboard samples. This article presents the analysis results for an uncoated cardboard sample.

4. ANALYSIS AND RESULTS

A multivariate image is constructed by stacking the aligned maps on top of each other. Each measured map thus becomes a variable in the three-way array. In this section, statistical analysis tools will be applied to the multivariate surface topography image to infer about the inter-relationships between the measurements. Subsection 4.1 will analyze the information obtained by combining all the five different topography measurements of the same surface. Principal component regression will be applied to reveal the specific features of each measurement device. In subsection 4.2, the differences and similarities of the measurement devices will be examined through comparing their frequency responses.

4.1. Principal Component Regression

Principal component analysis (PCA) is a multivariate statistical analysis method that decomposes the original set of variables into orthogonal and – when normally distributed – statistically independent linear combinations [4]. These linear combinations, i.e., principal components, are organized so that the first component explains the largest part of the total variability of the original data, the second component explains the second largest part, and so on.

We have evaluated the principal components of the multivariate image consisting of the five aligned surface topography maps of an uncoated cardboard sample. Prior to PCA each measurement (i.e. variable) has been normalized to have zero mean and a standard deviation equal to unity. This gives all variables equal opportunities to contribute to the model. To see the small-scale specialties of each measurement, we have chosen a 2.5 mm by 2.5 mm area from the multivariate image for the analysis. The resulting loading vectors, **p**, of each principal component are shown in Table 2. These values express the weight of each variable in the principal component scores.

Table 2. Principal component loading values for the five measurements.

Variable	p1	p2	p3	p4	p5
Photometric stereo	0.45	0.59	-0.12	-0.10	-0.65
Laser-1 scanning	0.46	0.42	-0.25	-0.02	0.74
Laser-2 scanning	0.43	-0.10	0.87	-0.19	0.08
WhiteLight-1 scanning	0.43	-0.59	-0.40	-0.55	-0.08
WhiteLight-2 scanning	0.46	-0.34	-0.09	0.81	-0.10

The first principal component is interpreted as the noise-free estimate of the measured quantity given all the measurements. As shown in Table 2, the loading values for the first principal component are almost equal. The first loading vector, **p1**, has also been calculated for the total common area (13 mm by 12 mm) of the aligned measurements and the result is practically equal to that presented in Table 2. This is a very significant result. It means that the true surface topography of the cardboard sample can be best estimated by computing the point-wise mean of the measured topography maps. The mean image on the small observation area is presented in Fig. 3. The result also implies that all the measurement devices applied in this research are equally accurate. Based on the eigenvalues of the correlation matrix of the original variables, the first principal component explains approximately 80 % of the total variability of the multivariate data.

Although certain deductions about principal components 2-5 can be made from the loading values presented in Table 2, the interpretation is not as straightforward as that of the first component. Instead of PCA, we have concentrated on regression analysis to examine the differences between the measurement devices. The basis of our regression analysis is the result obtained above by PCA: the mean of

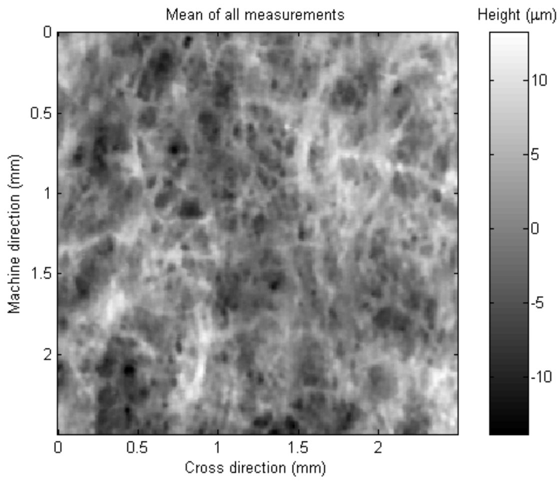

Fig. 3. Mean of all surface topography measurements of the cardboard sample on the selected 2.5 mm by 2.5 mm area.

the five measurements presents the surface topography variations detected by the five devices together. It can thus be expected that the mean of four measurements also describes the true surface topography, but less accurately. By evaluating the difference between the latter mean and the measurement that is left out of the mean calculation, we can reveal the errors and peculiarities characteristic of that measurement.

In the principal component regression analysis we have taken one surface topography map at a time and computed the least-squares regression coefficient to predict this map with the mean of the four remaining maps. Since the only explanatory variable in this regression problem is the mean value, the predictions of the different maps are very similar to each other. The correlation coefficients between the measurements and their predictions vary from 0.76 to 0.84. The most informative results of the regression analysis are the difference images calculated by subtracting the prediction from the original 2D measurement. Fig. 4 shows this image for the photometric stereo based measurement device. This example has been selected because it reveals the most significant detail among all the devices when compared to the original measurement images. The photometric stereo based system is also the only indirect method applied to the surface topography measurement.

The photometric stereo method seems to discern the fibrous structure of the sample surface with a higher precision than the other methods. However, it has been observed that the measurements acquired by the photometric stereo device tend to present the fibers as impressions rather than elevations, as also depicted by Fig. 2. The locations and orientations of the fibers can thus be deduced from this measurement but the surface height values at these locations are misleading. The WhiteLight-2 profilometer seems to locate the pores on the sample surface particularly well (see Fig. 2). The other white light based profilometer applies a coarser scanning sensor and hence detects less detail than WhiteLight-2. The laser profilometer measurements produce the least structured difference images when compared to the mean of the other measurements. The most discernible features in these images are the slight cross-directional errors of Laser-1 measurement which are also shown in the middle part of Fig. 2

4.2. Spectral Analysis

The spectra of the surface topography measurements provide information about the bandwidths of the signal and of the measurement devices. We have concluded, by looking at the large scale samples of the measured topography maps, that the WhiteLight-2 device has the widest bandwidth of the compared methods. It can thus be used as a reference to assess the loss of information at the interpolation that is applied in image alignment. We have computed the 2D spectra [8] with the fast Fourier transform (FFT) based 2D Welch method for the original and aligned surface topography measurements. Fig. 5 presents the 2D spectra for the case where the WhiteLight-2 measurement has been aligned with the photometric stereo based measurement. The corresponding cross-directional 1D spectra are presented in Fig. 6. These pictures clearly show that the alignment affects the spectrum only slightly in comparison to the difference of the spectra of the measurement methods. It is also obvious from the spectra that the photometric stereo based measurement does not contain the high-frequency components of the surface topography features. This will affect the parameters calculated based on this measurement.

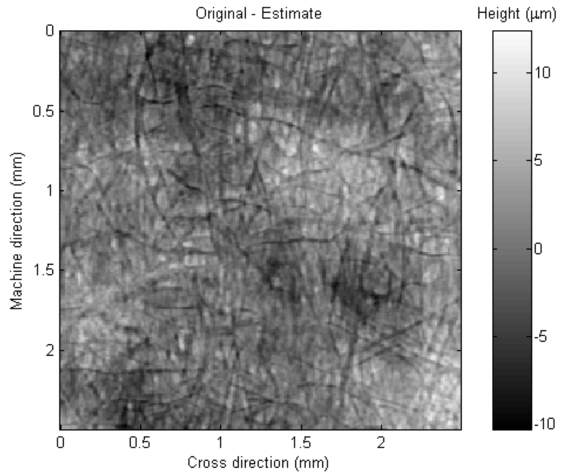

Fig. 4. Difference between the original topography measurement and its regression-based estimate for the photometric stereo method on the same area as the images presented in Figures 2 and 3.

Spectral analysis is important because most parameters describing surface roughness are related to the spectrum and can in fact be computed from the spectrum. Multivariate spectral analysis can be performed on the spectra of the aligned maps to further infer about the differences of the measurement methods. This will be one of the subjects of our future work.

5. CONCLUSIONS

In this work we have introduced a new image registration procedure and indicated its feasibility in multivariate image analysis. The focus in our work has not been on inventing completely new image registration methods but to build a robust automatic registration procedure for randomly textured data using the methods that best suit the application. The developed image registration method has proved itself quite robust in several practical examples. It tends to achieve a satisfactory registration result whenever the initial search parameters entered to the algorithm are reasonable enough.

We have applied multivariate statistical analysis to the aligned surface topography maps measured from paper and cardboard and shown some of the results for an uncoated cardboard sample. The objectives of the analysis have been two-fold.

Firstly, the comparison of surface topography measurements has aimed at evaluating the information captured by the alternative measurement methods. Principal component analysis has indicated that, given the multivariate 2D measurement, the best estimate of the true surface topography map is obtained by computing the mean

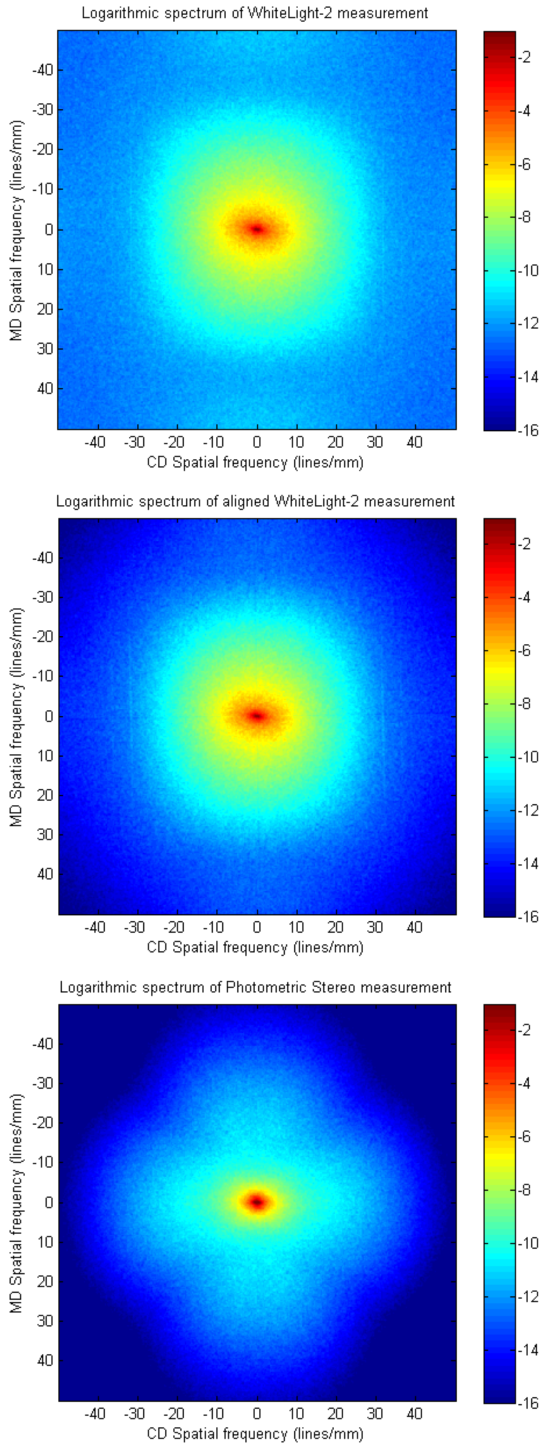

Fig. 5. Logarithmic 2D power spectra of the original WhiteLight-2 (top) and photometric stereo based measurement (bottom). The middle spectrum is from the WhiteLight-2 measurement aligned with the photometric stereo measurement.

of the aligned measurements at each point. This result is also a strong indication of the success of our image registration procedure. Regression analysis has revealed the specific information captured by each individual measurement system. Spectral analysis has also been used to examine the differences and similarities of the measurements.

Secondly, we have analyzed the correspondence between a fast but indirect 2D profile measurement method and slow scanning methods that are available as reference. The

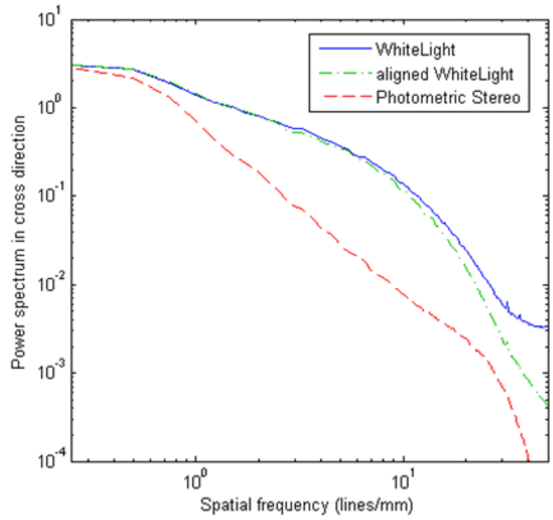

Fig. 6. Comparison of the cross-directional spectra of original and aligned WhiteLight-2 and photometric stereo based measurements.

objective has been to assess the accuracy of the surface topography measurement produced by the fast method and to compare it with the information gathered by the reference devices. The analysis has shown that the bandwidth of the fast measurement does not compare to that of the highest resolution reference measurement. However, the fast device has been found to expose the fibrous structure of the sample surface with considerably higher accuracy than the other devices.

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