Three-dimensional Imaging Confocal profiler without in-plane scanning

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ABSTRACT

Most 3D metrological microscopes used today require a scanning through the optical axis, which is time consuming. The common techniques are Coherence Scanning Interferometry (CSI), Imaging Confocal Microscopy (ICM), and Focus Variation (FV). If one technique is good for smooth surfaces, it is not for rough ones, while the good for rough is too noisy for smooth ones. Additionally, high local slopes are also dependent on the scattering properties of the surface, making the Numerical Aperture of the objective the most important property of the microscope. Imaging Confocal Microscopy is the best compromise in terms of surface application range (from smooth to rough), high local slopes on shiny surfaces, highest numerical aperture and highest possible magnification. Unfortunately, any kind of Confocal microscope today (laser scan, disc scan or microdisplay scan) requires an in-plane scanning to build up the confocal image in addition to the vertical scan, increasing the total measuring time in comparison to CSI and FV. This is against the needs of quality control in production environments, where scanning speed must be as short as possible.

In this paper, we use a Microdisplay Scanning Microscope for obtaining the confocal image only relying on a single image per plane. We use a structured illumination to project a desired pattern onto the surface with a very well-defined frequency and direction. By means of the Hilbert transform, we digitally shift the projected pattern one or many times to recover the bright field and the optical sectioned images. This new method reduces significantly the measurement time, simplifies the overall cost of the system and eliminates the maintenance of scanning devices, while maintaining the optical sectioning properties of each plane. We also studied the performance of the resulting topography in terms of system noise, accuracy, repeatability and fidelity of the surface using different methods to obtain the confocal image. Finally, we also compared the results with true confocal results and with other techniques that require a single image per plane, such as Active illumination Focus Variation (AiFV).

Keywords: Focus Variation, Confocal, Three dimensional measurements, Optical inspection

1. INTRODUCTION

Confocal microscopes are widely used for areal measurements thanks to its good height resolution and the capability to measure high local slopes. Other technologies such as Coherence Scanning Interferometry (CSI) and Focus Variation (FV)[1] are also widely used for the measurement of technical surfaces. Each technology has its own advantages and disadvantages. For instance, Interferometry provides the highest vertical resolution independently of the numerical aperture of the objective, but it has the drawback of being highly sensitive to vibrations and requires a dense Z scan to extract the areal information. Focus Variation has the benefit of being very robust for the measurement of rough surfaces, but it requires high numerical aperture to achieve high vertical resolution. For low magnification objectives, Focus Variation is more suitable to measure the form and waviness components of a surface more than its texture, due to its limited lateral resolution.

For high precision manufacturing processes, such as high-speed milling, electro-discharge machining, or laser processing, it is preferable to use imaging confocal microscopes for the three-dimensional assessment of surfaces instead of interferometry and Focus Variation. The reason is its robustness against environmental disturbances, machine vibrations, fast changing temperatures, combinations of different materials, while maintaining high lateral resolution. Its high dynamic range makes it more suitable to measure anything from nanometer level smooth surfaces up to rough materials such the ones found in additive manufacturing. Nevertheless, confocal microscopes pose a technological limitation because of the need to scan the signal through the three-dimensional space: they require in-plane scanning to recover the optically sectioned image and a second scanning process along the optical axis to recover the axial response. There have been many approaches to speed-up both scanning methods, but all of them require bulky optical and mechanical components that make confocal microscopes expensive for quality control of in-line processes, were additionally, space need to implement

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measurement instruments is typically limited. There are mainly three different technologies to perform the in-plane scanning according to the ISO25178-607. The three types of imaging confocal microscopes are laser scanning, disc scanning, and microdisplay scanning. The first two types use mechanical movements arranged with optical components to scan the light source, while the third one uses electro-optical components to perform a similar in-plane scanning.

Structured Illumination Microscopy (SIM)[2] is another optical sectioning method that provides similar images to those of confocal microscopes. The optical sectioning capability of SIM is almost the same as a confocal microscope when they are used for three-dimensional measurement of surfaces. On SIM, a periodic sinusoidal pattern is placed on the field diaphragm position of the microscope, which is imaged on to the surface. Those parts of the surface within the focal region of the objective preserve high contrast of the original pattern, while decreasing the contrast for those out of focus. By phase shifting the original pattern at three different phases equally spaced over 2π, it is possible to recover the contrast modulation of the pattern with a very simple calculation. Although SIM is in principle simpler than confocal scanning microscopes, the associated hardware to shift the pattern must be very precise to avoid image harmonics, and thus it is not so different from scanning complexity with other confocal configurations. The main advantage of SIM is its scanning speed with modern high-speed cameras. To avoid phase shifting the illumination pattern mechanically, Wicker[3] proposed a single-shot optical sectioning method by splitting the three phases of the original pattern on three different polarizations and using three cameras with properly aligned polarizers.

Chromatic confocal microscopy is a very well known technique for single point height measurement. Zint[4] developed a system using a set of pinholes equally spaced on a matrix and imaged onto the surface with a hyperchromate objective. The pinholes are imaged with a spectral separation unit extending the spectrum for every point along a camera's set of. The design is single-shot and is capable of achieving hundreds of 3D frames/second, although the measured region contains only 1000 points and the numerical aperture is very low.

A simpler implementation of Structured Illumination Microscopy is described by Schwertner[5]. In this publication, a sinusoidal pattern is illuminated in transmission and reflection, and two images are recorded. The fact that the sinusoidal pattern is shifted by π, makes it impossible a priori to recover the optical section with a simple calculation. It requires a calibration process to calculate the phase of the pattern for every pixel, and the calculation of the gradient along the pattern direction. Other non-moving techniques involve the use of the Hilbert transform. Patorski[6] used two images, a sinusoidal pattern and a bright field to compute a $\pi/2$ shift of the original pattern with the use of the Hilbert-Huang transform. Hoffman [7] used the same idea to avoid scattering problems for in-vivo imaging, where contrast of the pattern through scattering media decreases, and the phase shift is no longer trustable. Hoffman used a single image and recovered the bright field image by blocking the main frequency of the pattern in the Fourier space.

In this paper we focus on the design of a compact optical profiler for in-line inspection. The main driver of the design is to have as small as possible of a footprint, while at the same time being able to provide three-dimensional measurements with a technique based on optical sectioning microscopy. In section 2 we will explain how we decided to implement a very compact 0.25X field lens with two field diaphragms: one providing a bright field image and the second one with the option to incorporate a glass pattern. We decided to choose a sinusoidal pattern and we used the spiral phase quadrature transform to digitally shift the pattern and thus recover the optical section. Section 3 focuses on the comparison between the method described in 2 and a confocal microscope, and finally present our conclusions in section 4.

2. METHODS

In this paper we propose two different methods to obtain an optically sectioned image without the need of in-plane scanning. This will be used for increasing the speed of confocal measurements as the number of images acquired at each plane will be reduced.

In our proposed methods, we used a periodic pattern only in one direction, similar to the ones used for Structured Illumination Microscopy (SIM). In these microscopes, a sinusoidal pattern is placed on the field diaphragm position and optically or mechanically shifted several times to recover the optical section. Our approach uses a Ronchi grating in order to keep the cost of the system as low as possible. For every image pixel, the intensity can be approximated as

$$I_{ij} = A_{ij} + B_{ij} * \cos\left(\frac{2\pi}{p} x_{ij} + \phi_{ij}\right) \quad (1)$$

where A_{ij} is the non-structured image (DC component), B_{ij} the amplitude contrast of the structuring pattern multiplied by the intensity distribution of the surface, p the period of the grating and ϕ_{ij} its phase. The non-structured DC components can be recovered from a bright field image, and thus we can write

$$I'_{ij} = I_{ij} - A_{ij} = B_{ij} * \cos\left(\frac{2\pi}{p} x_{ij} + \phi_{ij}\right) \quad (2)$$

In order to calculate the optically sectioned image it is necessary to recover the amplitude contrast B_{ij}, that is easily recovered with a $\pi/2$ shifted image

$$I''_{ij} = G(I') = B_{ij} * \sin\left(\frac{2\pi}{p} x_{ij} + \phi_{ij}\right) \quad (3)$$

with G being any operator that shifts the frequency components of the image by $\pi/2$. Finally, we have

$$B_{ij} = \sqrt{I'^2 + I''^2} \quad (4)$$

There are several approaches for the G operator. The most straightforward approach is to consider the image as a series of profiles consisting on each image column, if the sinusoid is projected in the vertical direction, or each image row if the sinusoid is horizontal. Then we apply to each profile the Hilbert Transform to each profile, which causes an exact phase shift of $\pi/2$ to any profile. The shifted image is then recovered by simply substituting each column or row by the shifted profile. This approach does not consider the phase gradient of the image, inducing some error in samples that have a privileged direction. Additionally, it is not computationally efficient since it needs as many Fast Fourier Transform (FFT) as image columns/rows, instead of just performing a bidimensional FFT.

The Hilbert-Huang transform is an extension of the Hilbert transform that decomposes the original signal in various intrinsic mode functions. This decomposition allows to remove the high oscillation mode, which is usually associated to noise, but has the inconvenience of being computationally expensive [8].

The main limitation of the Hilbert Transform applied to images is how to extend the signum function into a two-dimensional function. Several attempts to solve this issue have been proposed with different approaches but they suffer from being anisotropic solutions, which do not work for all cases. Only the spiral phase quadrature transform, (Larkin, 2001 [9], Figure 1), solves the problem of the directional discontinuity of the signum function. The solution is to use a pure spiral phase function in the Fourier space, defined as:

$$S(u,v) = \frac{u + iv}{\sqrt{u^2 + v^2}} \quad (5)$$

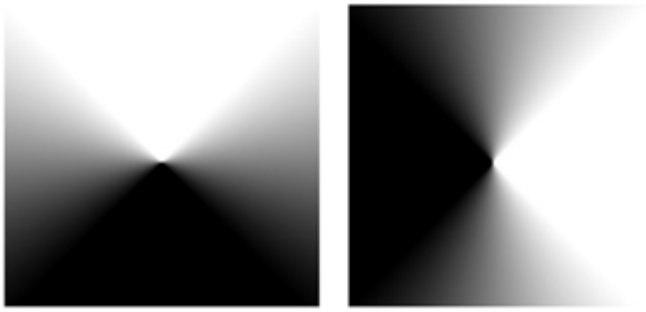

Figure 1. Pure spiral phase function in the spatial frequency domain. Real part (left) and imaginary part (right). Scale is -1 to 1.

We propose two different methods to recover the optically sectioned image depending on the procedure to remove the image DC component. The first method consists of acquiring two images: the structured illuminated image and a brightfield image, which represents the DC component at each pixel. Therefore, the brightfield image is subtracted from the structured illumination to obtain I'. Then the spiral phase quadrature transform is applied to obtain I'' and finally Eq. 4 is applied to recover the optically sectioned image B.

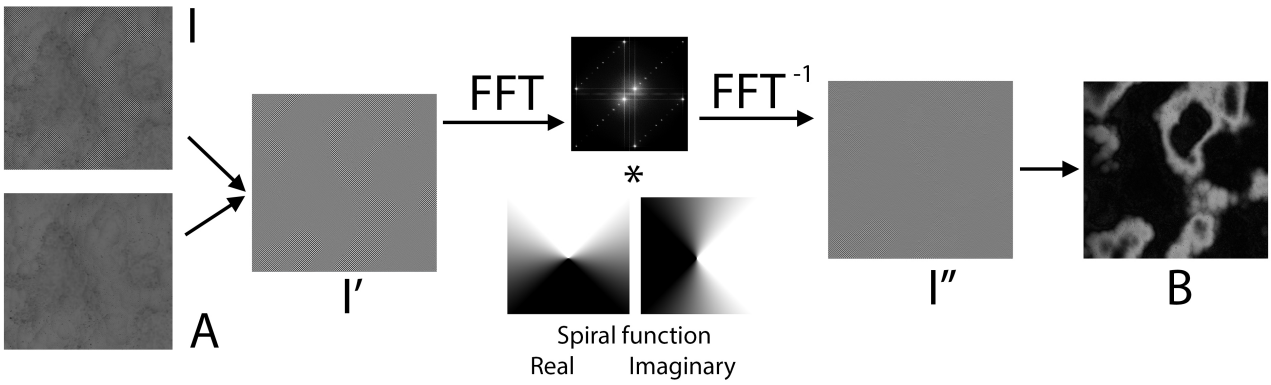

Figure 2. Diagram of the two-image method for optical sectioning.

This method requires projecting the Ronchi pattern into the sample and uniformly illuminating the sample to recover the brightfield image. This causes more complexity on the system set-up or obligates the presence of a microdisplay component, which significantly increases microscope costs.

Alternatively, we propose another method that only requires the structured illuminated image. In this method, the DC component is eliminated by removing the carrier frequency in the Fourier domain. Once the artificially obtained brightfield image is calculated, we apply the same procedure as of the two-image method to recover the optically sectioned image.

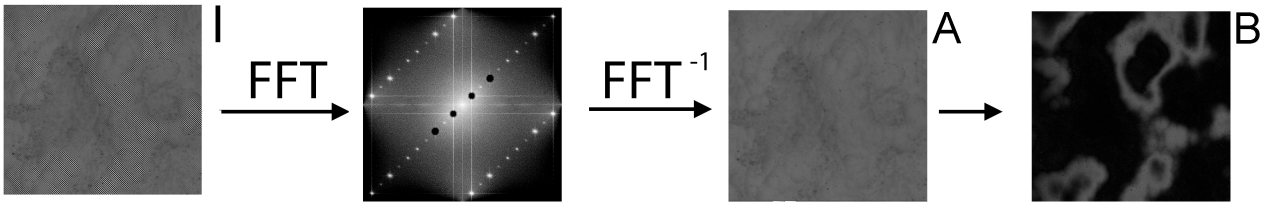

Figure 3. Diagram of the one-image method for optical sectioning.

For continuous samples this method is sufficiently valid, but for samples that present discontinuities, the frequency removal for the extraction of the DC component causes the appearance of artifacts in the sectioned image. Nevertheless, this method allows an improvement of the acquisition speed by a factor of 3 respect to a traditional Structured Imaging Microscopy, since it no longer needs to acquire three images per plane. On the other hand, it is necessary to perform four FFT, forward and backward for removing the DC component and forward and backward to apply the spiral phase quadrature transform.

Instead, the two-image method only increases the acquisition speed by a factor of 1.5, but with the benefit that artifacts arising from surfaces with discontinuities are less visible and significant.

Figure 4 shows the result of applying the two and one image acquisition method (left and middle) in comparison to the optically sectioning capability of active illumination focus variation (right). The one image method shows a residual frequency pattern along the same direction of structured illumination. The strong blur of the AiFV is due to the focus operator, a Sum of Modified Laplacian on this case, with a summing window of 11x11 pixels.

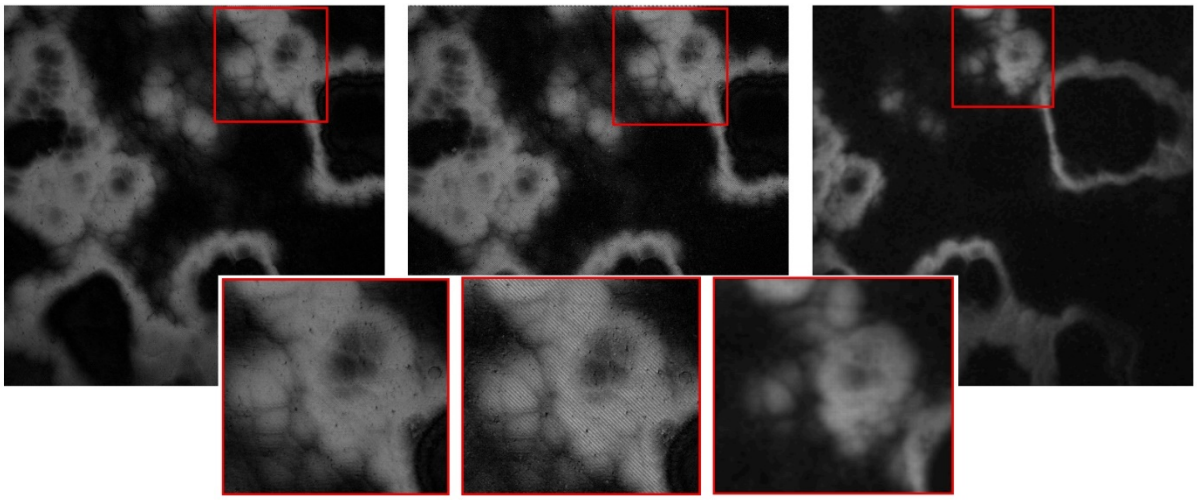

Figure 4. Optically sectioned image of AIR B40 roughness standard with the two-image method (left), one-image method (centre) and active illumination focus variation (right).

The final aim of this research is to develop an optical profiler that is able to measure with the confocal technique without in-plane scanning. We present a dual illumination system that allows to measure with both methods described above. One illumination channel will uniformly illuminate the full scene to acquire the brightfield image, while the other incorporates a glass texturized with any kind of pattern to be projected onto the sample.

The pattern is placed in the field diaphragm position of the microscope and due to its location, the pattern is diffraction limited to the surface under inspection and to the imaging camera simultaneously. Those regions of the surface that lie within the depth of focus of the objective will create a very sharp image of the pattern onto the camera, while the other regions will be out of focus and thus the pattern will be blurred.

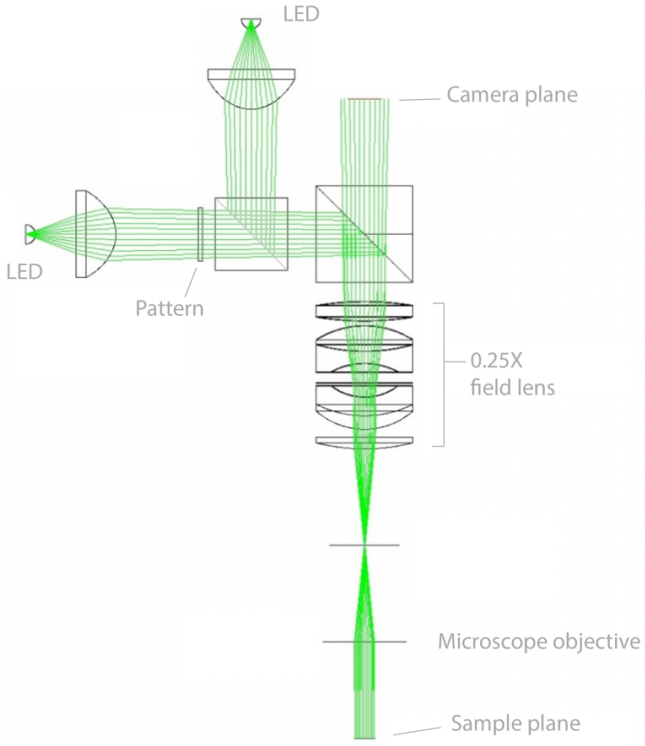

Figure 5. Optical layout of the developed system.

The configuration of this system not only allows to measure with confocal but with other technologies as well. If the microscope objective is changed for an interferometric objective the measurement can be done with Coherence Scanning Interferometry with the brightfield illumination channel. If the pattern used for texturing the sample is a high contrast checkerboard as the one used by Bermudez[10] the system will be able to measure with Active Illumination Focus Variation (AiFV). The AiFV approach works very well for nearly any kind of surface, with the drawback of a loss of lateral resolution.

The versatility in use of the optical profiler contrasts with its small dimensions, as it is intended to be integrated in automated quality controls to provide fast and accurate 3D measurements of surfaces.

Figure 6. System dimensions compared to a 33 cl can.

3. RESULTS

To assess the performance of the described methods, different tests were performed. All measurements were made with a microdisplay confocal profiler to be able to compare the proposed methods with the active illumination focus variation technique (AiFV). The Ronchi pattern was projected so the lines have an angle of 135º with respect to the horizontal. We measured the system noise on a SiC mirror of λ/8 with different brightfield objectives from Nikon. The results are shown in the table below.

Table 1. System noise measured on a flat mirror with different methods.

Objective / Sq (nm)	Confocal	2 Image method	1 Image method
10X 0.3NA	20.4	15.4	13.2
20X 0.45NA	6.3	7.5	9.2
50X 0.8NA	1.9	2.2	2.3
150X 0.9NA	1.9	3.8	3.8

The system noise measurement with AiFV is not included in this table because the values are equivalent to confocal, but this technology has the drawback of losing high frequency information due to the image plane smoothing. In terms of system noise, we can conclude that our proposed methods are equivalent to confocal.

The suggested methods' performance was also tested on a rough sample shown in figure 7. We used the NPL AIR B40[11] roughness standard and we measured it with a Nikon 20X 0.45NA objective. The confocal topography is not shown due to its similarity to the proposed method results. Table 2 shows the result of the Height roughness values according to the

ISO25178-3[12] for the proposed methods in comparison to an Imaging Confocal Microscope and active illumination focus variation.

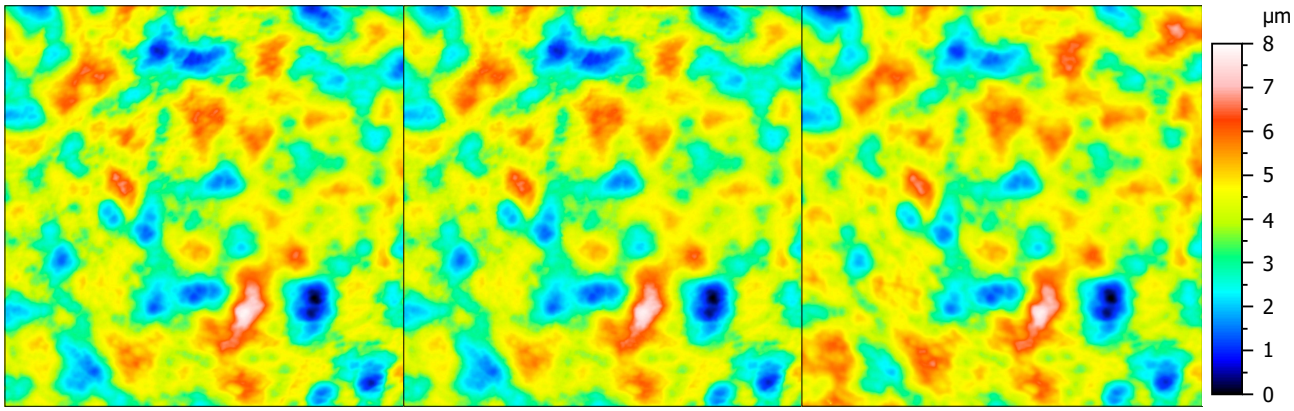

Figure 7. Topography of AIR B40 measured with the two-image method (left), one-image method (centre) and AiFV (right).

Table 2. Surface parameters according to the ISO 25178 of AIR B40 roughness standard.

Height value (µm)	Confocal	2 Image method	1 Image method	AiFV
Sq	1.080	1.082	1.068	1.081
Sa	0.847	0.845	0.834	0.846
Sz	7.823	7.794	7.677	7.673

For rough samples the proposed methods are visually equivalent. However, they present some small differences with respect to confocal when comparing the surface parameters, showing greater differences with the one-image method than the two-image method, although for most applications the performance is still valid.

As stated in the previous section, the one-image method inherently removes some frequencies, therefore one needs to characterize the instrument transfer function (ITF). The ITF was evaluated by measuring with a Nikon 50X 0.8 NA objective, the Siemens Star standard, and the results were compared with the confocal method. As AiFV contains a spatial smoothing, the ITF cannot be well characterized with this procedure and the results are not comparable with the other techniques.

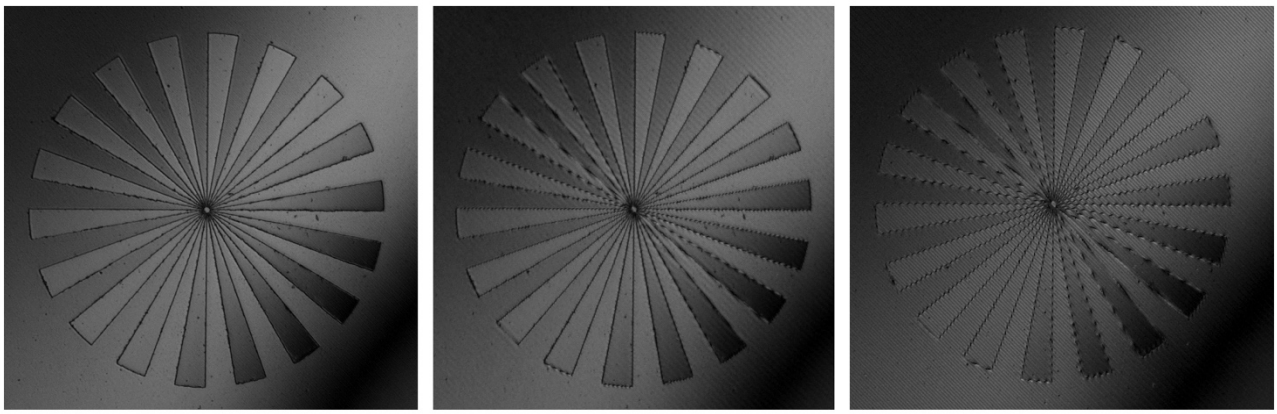

Figure 8. Optical sectioned image of the Siemens Star standard obtained with confocal (left), two-image method (centre) and one-image method (right).

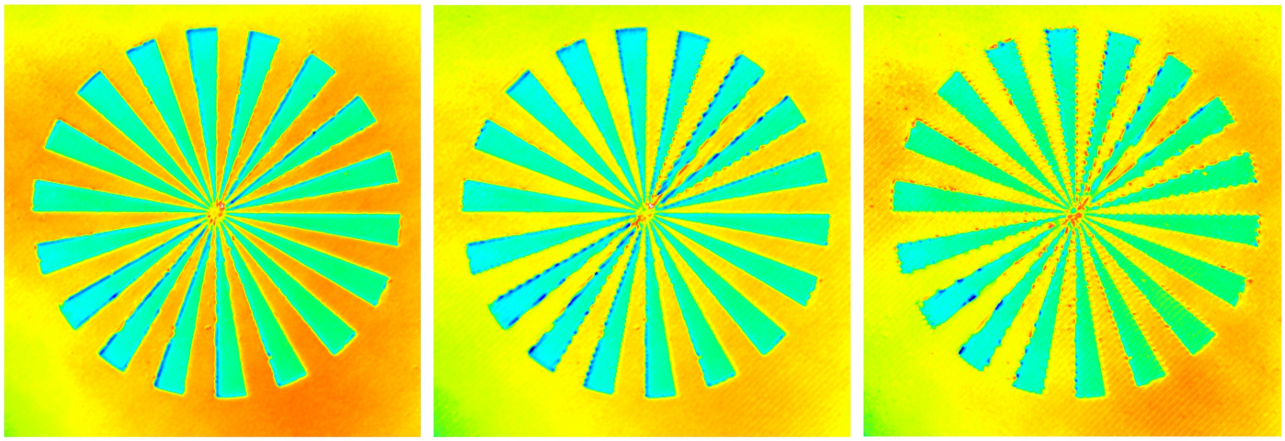

Figure 9. Siemens Star topography measured with confocal (left), two-image method (centre) and one-image method (right).

The optical sectioned images of the proposed methods present artifacts due to discontinuities on the surface. In these samples not all frequencies are shifted correctly and there is clearly a critical direction where the artifacts appear the most. This direction is parallel to the Ronchi lines projected onto the sample, but when calculating the full topography, the artifacts appear in the perpendicular direction. The artifacts emerging in the one-image method are higher than in the two-image method.

The presence of artifacts in the topography shows the limitation of measuring samples with discontinuities, making these methods not suitable for several applications, such as the semiconductor industry, where determining the height of abrupt features present in the sample is crucial.

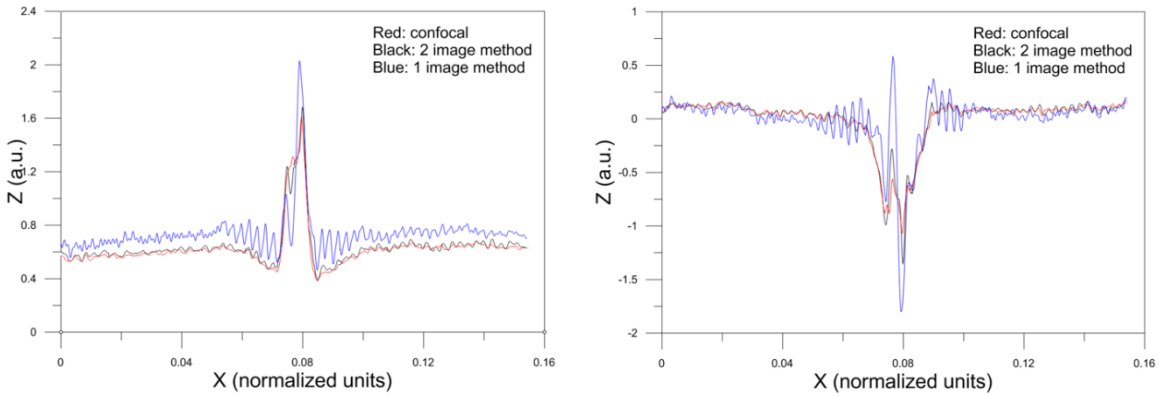

Figure 10. Cross profile of the Siemens Star standard. Valley to valley profile (left) and peak to peak profile (right).

The cross profile of the Siemens Star standard shows that the two-image method performance in terms of the ITF is nearly the same as the confocal performance, but the one-image method cannot correctly characterize high frequencies due to the frequency removal in the Fourier space when obtaining the brightfield image.

Further work on this research includes projecting Ronchi patterns in perpendicular directions to minimize the contribution of the critical direction.

4. CONCLUSIONS

We have presented the advantages and drawbacks of a scanning confocal microscope for three-dimensional imaging of technical surfaces. In general, scanning systems are bulky and expensive and most of them require some maintenance not suitable for non-stop operation. Available space and electrical environmental noise are common constraints found in manufacturing tools. We have proposed a non-scanning optical layout that provides optically sectioned images close to the ones from an imaging confocal microscope. The layout relies on a simple optical system with a 0.25X field lens, and two light sources, one through a glass pattern with a Ronchi grid on the field diaphragm position providing structured

illumination, and the other providing bright field illumination. We used the spiral phase quadrature transform to digitally shift the structured illumination by $\pi/2$ and thus retrieving the optical section. Two methods are proposed: the first one using two images (the structured illumination and the bright field), and a second one using only the structured image, and recovering the bright field by blocking the main frequency in the Fourier space. Both methods are able to measure smooth and rough continuous samples without discontinuities. A drawback of the proposed method is for those surfaces with steps, where both, the phase quadrature transform, and the frequency blocking method superimpose ripples on the sectioned images that are reflected as height variations on the three-dimensional measurements.

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