A Method for Surface Topography Measurement using a New Focus Function based on Dual-tree Complex Wavelet Transform

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ABSTRACT

Surface topography measurement is an important tool widely used in many fields to determine the characteristics and functionality of a part or material. Among existing methods for this purpose, the focus variation method has proved high performance particularly in large slope scenarios. However, its performance depends largely on the effectiveness of focus function. This paper presents a method for surface topography measurement using a new focus measurement function based on dual-tree complex wavelet transform. Experiments are conducted on simulated defocused images to prove its high performance in comparison with other traditional approaches. The results showed that the new algorithm has better unimodality and sharpness. The method was also verified by measuring a MEMS micro resonator structure.

Keywords: surface topography measurement, focus variation, focus function, dual-tree complex wavelet transform

1. INTRODUCTION

Focus variation method[1][2], as a new optical approach for surface topography, has attracted widespread interest in fields such as ultraprecision machining, tool detection, electronic industry, material science and biomedicine[3][4]. Particularly in large slope scenarios, focus variation method has proved to have higher performance. However, as focus variation method works by finding out the best focused position of each pixel, its overall performance depends largely on the effectiveness of the focus function[5][6][7].

Existing focus functions can be generally divided into three categories by different transform domains: functions in spatial domain, frequency domain and wavelet domain[8]. Commonly used functions in spatial domains mainly involve Gray Level Variance (GLV) proposed by Krotkov in 1988, Tenengrad Method (TEN)[9] and Sum Modified Laplacian (SML) proposed by Nakagava in 1994. Algorithms based on frequency domain and wavelet domain takes many forms. They majority of them rely on measurements of high-frequency components after transform. Existing wavelet-based functions are mainly based on traditional wavelet transform, which becomes popular in recent studies due to its benefits in providing both positional information and frequency information[10]. However, the existing algorithms are not optimal in extracting high-frequency details due to its limited direction selectivity.

This paper presents an alternative focus function based on dual-tree complex wavelet transform (DCDWT). Theoretically, DTCWT enables an observation of variation from 6 distinct directions and a resulting better extraction of detail information than traditional algorithms do[11][12]. Thus the newly proposed function takes advantage of the superior direction selectivity to better evaluate the focusing degree of images. Also, the proposed function used in surface topography measurement is a new application of DTCWT.

The rest of the paper is organized as follows. In Section 2, the traditional methods are reviewed and the newly proposed focus function is introduced. In Section 3, experiments are conducted using image defocused simulation to prove the higher performance of the newly proposed focus measurement function. In Section 4, the method is applied in measuring a MEMS micro resonator structure. Finally, some conclusions are made in Section 5.

2. PRINCIPLE OF MEASUREMENT

Focus variation method is based on a combination of vertical scanning and an optical system with a small depth of field. The principle of measurement depends largely on the model of focused and defocused imaging. As is illustrated in Fig. 1, when the objective lens scans vertically with a certain step distance Δd and takes a picture at every step, the system acquires a sequence of images. Points on the sample surface are scanned and imaged on CCD. Each of them goes through a process of being defocused, focused and again defocused. For each pixel on the same location of the sequence image, effective focus measurement is implemented on its neighborhood to precisely evaluate its degree of focus. By comparing the values from different images, we can obtain the serial number of the best focused image of the measured pixel and roughly estimate the depth of the corresponding point on sample surface. Further, one can also adopt interpolation to get depth map with higher accuracy.

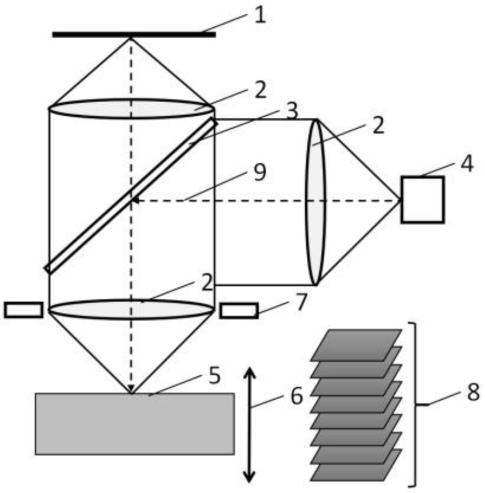


Figure 1. (1)CCD (2)lens (3)light splitter (4)light source (5) sample (6)motor (7)ring illuminator (optional) (8)sequence image (9)ray of light

3. FOCUS MEASUREMENT FUNCTION

The essential step of focus variation method is to find out the best focused position of from the image sequence. To serve this purpose, an effective focus function is needed to accurately evaluate the focusing or defocusing level of every pixel.

3.1 Traditional algorithms

Commonly used traditional functions involve GLV, TEN, SML and DWT-based functions. In terms of DWT-based functions, we discuss the use of one-layer orthogonal wavelet decomposition since only a small neighborhood is selected when evaluating each pixel. After the transform, we can obtain one low-frequency sub-band LL, and 3 high-frequency ones HL, LH, HH which present detail information in the horizontal, vertical and diagonal direction, respectively.

LL1	HL1
LH1	HH1

Figure 2.The block diagram of one-layer DWT

Functions can be constructed by measuring and analyzing the high-frequency components.

One way is to summarize the absolute values of the high-frequency components:

$$f = |horizontal| + |vertical| + |diagonal| \tag{1}$$

Also it is popular to measure the high-frequency energy in the neighborhood:

$$f = |horizontal|^2 + |vertical|^2 + |diagonal|^2 \tag{2}$$

3.2 Proposed DTCWT-based function

Although the traditional wavelet transform can extract information at particular scales and directions, it still lacks directionality. DWT-based algorithms can only detect features in three limited directions, in which case it fails to distill information in some ridges and edges. These factors will limit the effectiveness of the focus function.

One solution is to use the dual-tree complex wavelet transform proposed by Nick G.Kingsbury in 2005. In this paper, we implement a one-layer DTCWT, as Fig. 3 shows, which can be described as two parallel transform: one results in the real part and the other results in the image part. Each transform also contains a parallel 2D-DWT.

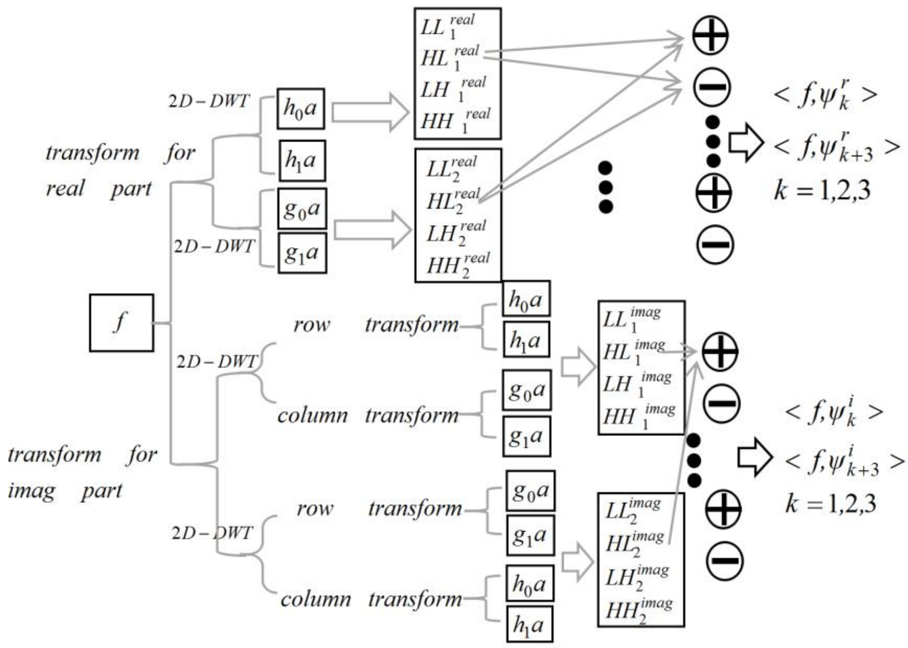


Figure 3. The realization of one-layer DTCWT in the proposed focus function

The final DTCWT coefficients are obtained by summing up the corresponding real and image part.

$$< f,\psi_l^c > = < f,\psi_l^r > + j < f,\psi_l^i > \tag{3}$$

After a one-layer DTCWT, information can be distinguished in four distinct directions involving the horizontal, vertical, 45°and-45°direction. The newly proposed focus function is obtained by squaring the sum of the absolute value of coefficients in four directions.

$$f = (|horizontal| + |vertical| + |diagonal45| + |diagonal-45|)^2 \tag{4}$$

Where in our function,

$$horizontal = < f,\psi_1^c > + < f,\psi_6^c > \qquad vertical = < f,\psi_3^c > + < f,\psi_4^c >,$$

$$diagonal45 = < f,\psi_2^c > \qquad diagonal-45 = < f,\psi_5^c >$$

According to our analysis and experiments, the proposed square form (the square of the sum of components) is better than other possible forms like the energy form (the sum of the square of components), cubic form and others, considering a trade-off between sharpness of the function and its computational complexity.

4. EXPERIMENT TO COMPARE PERFORMANCES OF FUNCTIONS

The experimental verification of the focus function requires a sequence of images with different degree of focus. However, noise and unknown disturbance always exist in reality and can affect the evaluation. To get accurate assessment, one can use computer modelling to simulate defocused images.

According to geometrical optics, when the object lies at a distance $N\Delta d$ from the best focused position, the acquired image is blurred and an object point results in a circle of confusion, as is illustrated in Fig.4.

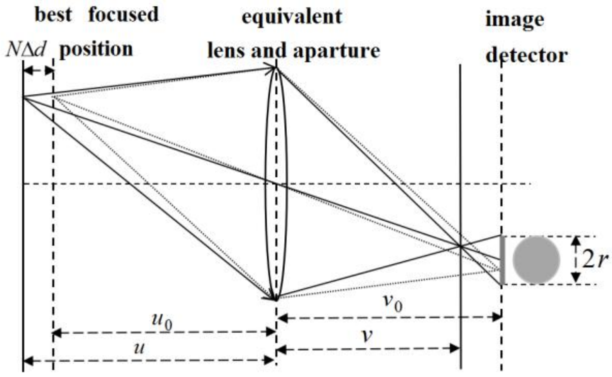


Figure 4. The mathematical model of image defocus in Focus Variation

The defocusing degradation of image can be explained by a disc blur model:

$$h(x,y)=\begin{cases}\dfrac{1}{\pi r^2} & x^2+y^2\le r^2\\ 0 & others\end{cases} \tag{5}$$

Here in this experiment, 15 images were simulated by setting f=4.5mm, D=6.5mm, u0=4.8mm, N=-7~+7,△d=500nm. The performance of focus functions are as follows.

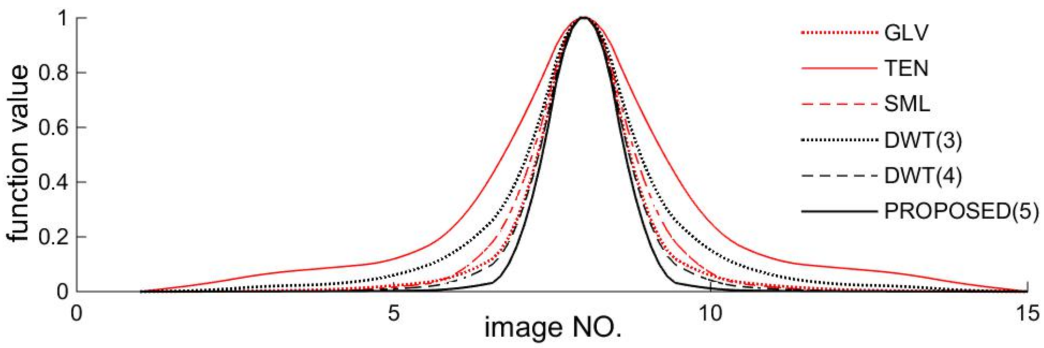


Figure 5. Performances of different functions

We compared the GLV, TEN, SML, two DWT-based functions (3)(4) and the proposed (5). Obviously, in Fig.5, the new function is usable and shows the best result with good unimodality and better sharpness than other algorithms.

5. EXPERIMENT ON MEMS MICRO RESONATOR STRUCTURE

We have built an optical system for focus variation measurement in our laboratory. The configuration of the system is shown in Table 1.

Table 1. Configuration of the focus variation system we built.

Section	Product Model
Light source	CCS HL V2-3M-RGB-3W CCS PJ-15-5-3CA (light controller)
Microscope	Nikon CM-70L
CCD	Basler A 102K

In this section, the proposed method is verified on our system by measuring a MEMS micro resonator structure. The main procedures are illustrated in Fig.6.

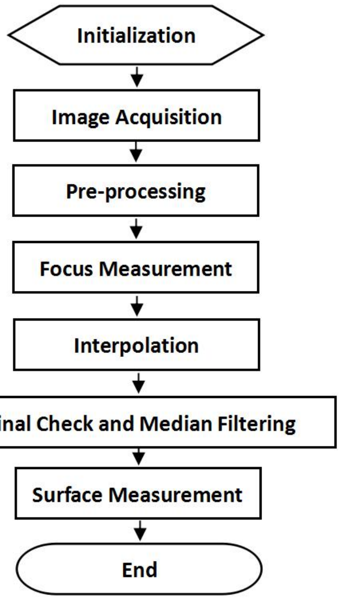
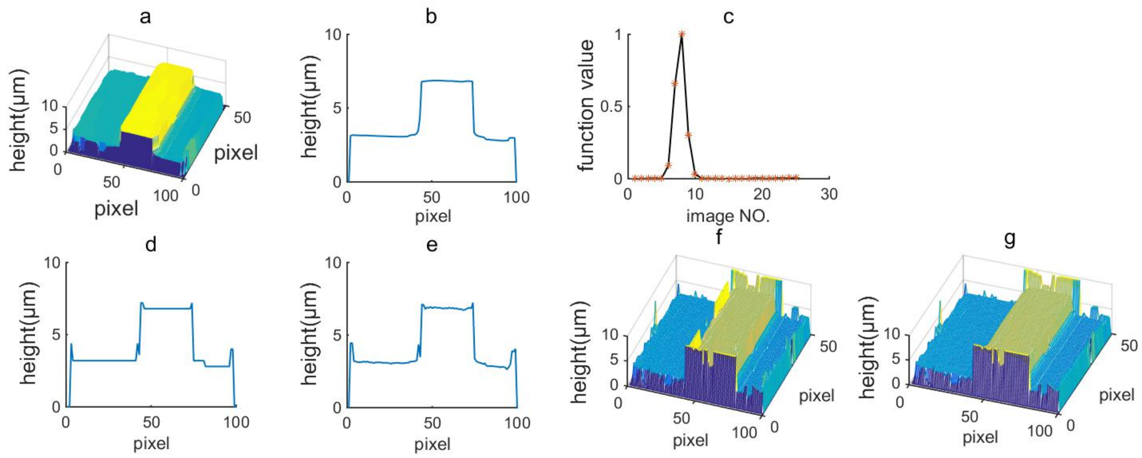


Figure 6. Main image-processing procedures of focus variation method for surface measurement.

In our experiment, twenty-five images were acquired by setting $\Delta d = 400nm$. As the first step of image processing, Gaussian filter was used to remove noise and reserve detail. The focus-measurement procedure was then implemented by setting window size 5×5 and using the filter group $qshift\_a$ for DTCWT. Next, Gaussian interpolation was adopted for higher resolution and precision. To reduce computational complexity, interpolation was implemented only on the three consecutive points centered by the maximum point of the focus-measurement curve. In the next step, we adopted a final check procedure based on Smallest Univalue Segment Assimilating Nucleus (SUSAN) operator to remove outliers. Finally, the step height on the sample was measured. The Results of the experiment are shown in Fig. 7:



(a) Final depth map (b)Final sectional view (c) Focus-measurement curve of pixel (20,20) (d) Sectional view before interpolation (e) Sectional view after interpolation (f) Depth map before the final check (g) Depth map after the final check

Figure 7. Results of experiment on MEMS structure.

The measuring results of the step height were shown in Table 2.

Table 2. Height of the step on the sample(μ m).

Number of measurement	**Height(μ m)**
1	3.8948
2	3.9127
3	3.9197
4	3.9051
5	3.8750
Average height	3.9015
Standard deviation	0.0175

For reference, the sample was also tested by a Sensofar 3D optical profilometer which gave the average height 3.9086μm and standard deviation 0.0011μm.

Therefore, the surface topography reconstruction result in Fig. 7 and depth measurement results in Table 2 show that the proposed method has good performance in restoring surface topography and good accuracy for surface measurement.

6. CONCLUSION

Our results provide evidence for the effectiveness of the new DTCWT-based function as well as the whole image-processing method. The result in Fig.5 suggests that the new function is usable and shows better result with a very narrow peak which indicates better sharpness than traditional ones. Meanwhile, experiment on MEMS shows that the image-processing procedures provide good accuracy in restoring and measuring surface topography.

The proposed function shows obvious improvement than traditional algorithms in focus measurement. We have implemented the functions in the focus-variation measuring system in our laboratory and in the process of applying it to large-sample measurement using image stitching.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of The National Key Research and Development Program of China (Grant No. 2017YFF0105905) and the 111 Project fund (Grant No. B07014).

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