A Method for Surface Topography Measurement using a New Focus Measurement 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-measurement 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.

Key words: surface topography measurement, focus variation, focus-measurement 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-measurement function[5][6][7].

Existing focused-measurement functions can be generally divided into 3 categories by different transform domains: functions in spatial domain, frequency domain and wavelet domain[8][9]. Commonly used functions in spatial domains mainly involve Gray Level Variance (GLV) proposed by Krotkov in 1988, Tenengrad Method (TEN)[10] and Sum Modified Laplacian (SML) proposed by Nakagava in 1994. Existing wavelet-domain 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[11]. However, the existing algorithms are not optimal in extracting high-frequency details due to its limited direction selectivity.

In this paper, a new method based on dual-tree complex wavelet transform is proposed. A new focus-measurement function is constructed based on dual-tree wavelet transform considering its better direction selectivity[12][13]. To our knowledge, this is the first demonstration of the application of a dual-tree wavelet transform based focus-measurement function in surface topography measurement.

The rest of the paper is organized as follows. In Section 2, the traditional methods are reviewed and the newly proposed focus-measurement 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 optical system with a small depth of field. It depends largely on the model of focused and defocused imaging. After 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 each of them goes through a process of being defocused, focused and again defocused. For each pixel in the same location of the sequence image, focus measurement is implemented to find out the serial number of the best focused image. Then the depth of each pixel can be estimated.

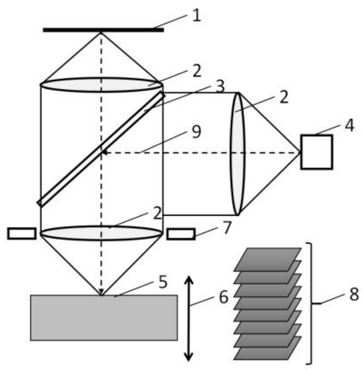

Fig.1 (1)CCD (2)lens (3)light splitter (4)light source (5) sample (6)motor (7)ring illuminator (optional) (8)sequence image (9)ray of light

3 Focus Measurement function

The essential step of Focus Variation Method is to find out the serial number of the image with its best degree of focus. To serve this purpose, an effective focus-measurement 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, one-layer orthogonal wavelet decomposition is preferred here 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

Fig.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:

$$f = |horizontal| + |vertical| + |diagonal| \qquad (3)$$

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

$$f = |horizontal|^2 + |vertical|^2 + |diagonal|^2 \qquad (4)$$

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 3 limited directions, in which case it fails to distill information in some ridges and edges. These factors will limit the effectiveness of the focus-measurement function.

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

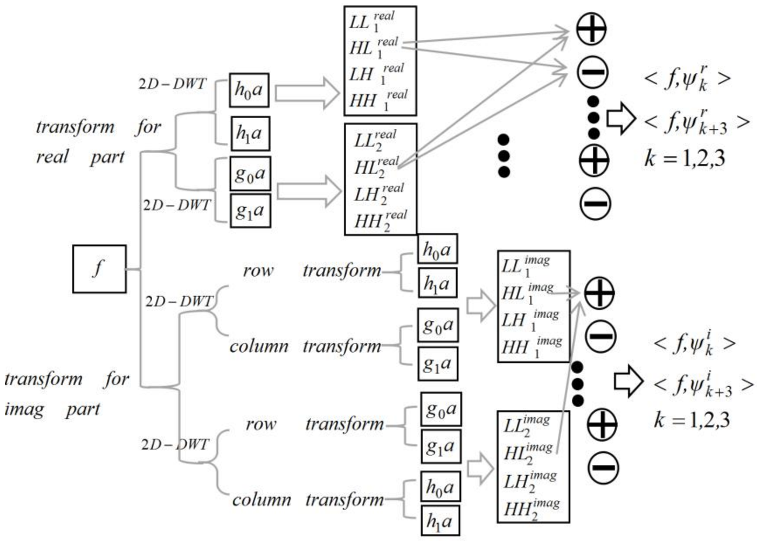

Fig.3 the realization of one-layer DTCWT

The final DTCWT coefficients are the sum of the corresponding real and image part.

$$< f,\psi_l^c > = < f,\psi_l^r > + j < f,\psi_l^i > \qquad (5)$$

After a one-layer DTCWT, information can be distinguished in 4 distinct directions involving the horizontal, vertical, 45° and-45° direction. The newly proposed focus-measurement function is obtained by squaring the sum of the absolute value of coefficients in 4 directions.

$$f = (|horizontal| + |vertical| + |diagonal45| + |diagonal - 45|)^2 \qquad (6)$$

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 the combined advantage of sharpness and speed.

3.Experiment to compare performances of functions

The experimental verification of the focus-measurement function requires a sequence of images with different degree of focus. However, noise and unknown disturbance always exist 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. The defocusing degradation of image can be explained by a disc blur model:

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

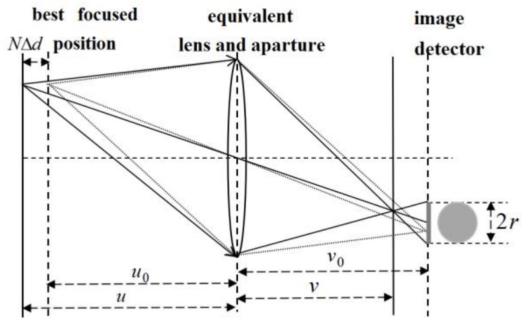

Fig.4 The mathematical model of image defocus in Focus Variation

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

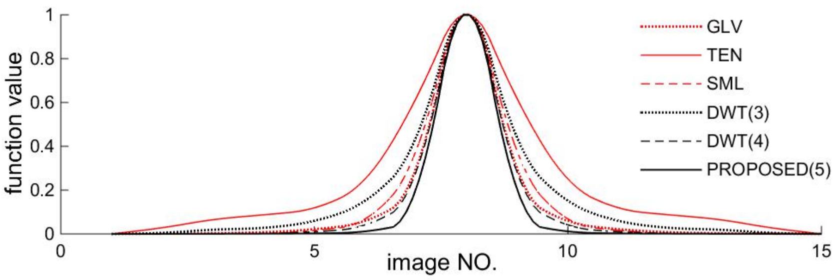

Fig.5 Performances of different functions.

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.

4. Experiment on MEMS micro resonator structure

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

In our experiment, 25 images were acquired by setting $\Delta d = 400nm$ on an optical system with:

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

Table.1 Configuration of the focus variation system we built

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 $qshift\_a$. 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.

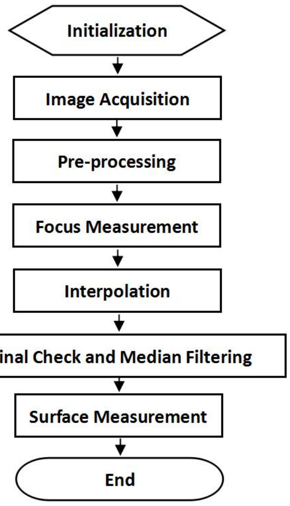

Fig.6 Main procedures

The Results of the experiment are shown in Fig.7

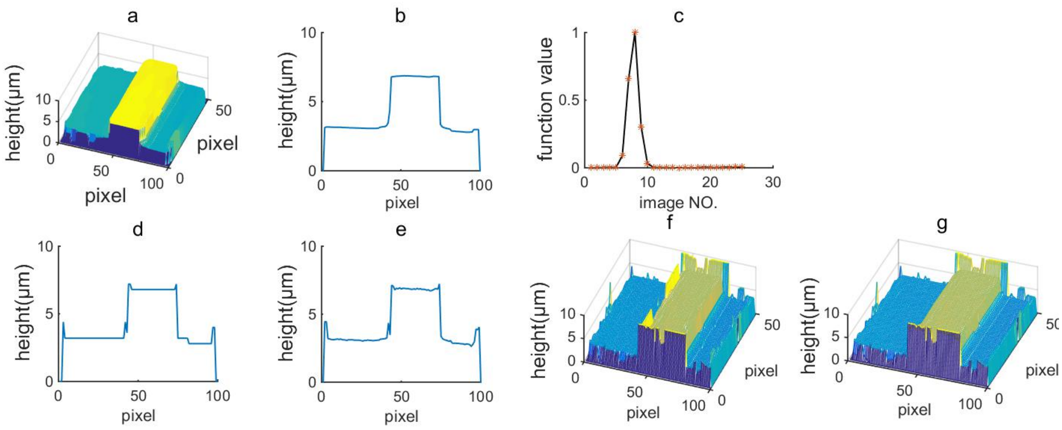

Fig.7 a. The final depth map b. The final sectional view c. The focus-measurement curve of pixel (20,20) d. Sectional view before interpolation e. Sectional view after interpolation f. Depth map before the final check g. Depth map after the final check

The measuring results of the step height were:

1st measurement	3.8948
2nd measurement	3.9127
3rd measurement	3.9197
4th measurement	3.9051
5th measurement	3.8750
Average height	3.9015
Standard deviation	0.0175

Table.2 Height of the step on the sample(μm)

For reference, the sample was also tested by a Sensofar 3D optical profilometer which gave the average height 3.9086μm and standard deviation 0.0011. Therefore, the results shows that the proposed method has good performance in restoring surface topography and robustness against noise.

5. 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.8 suggests that the new function is usable and shows the best result with a very narrow peak which indicates better sharpness. Meanwhile, the image processing method shows good accuracy in restoring surface topography.

While it is hard to draw definitive conclusions about its optimum, the proposed function shows obvious improvement than traditional algorithms in focus measurement. And to our knowledge, this is the first demonstration of the application of a DTCWT-based focus-measurement function in surface topography measurement. The method provides desired properties in measuring cutting tool edges. 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.

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