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Surface contouring by optical edge projection based on a continuous wavelet transform

Chenggen Quan, Hong Miao, and Yu Fu

A novel optical edge projection method for surface contouring of an object with low reflectivity is presented. A structured light edge is projected onto a dark surface, and the image is captured by a CCD camera. The surface profile of the object is then evaluated by an active triangular projection technique, and a whole-field three-dimensional contour of the object is obtained by scanning the optical edge over the entire object surface. An edge detection method based on a continuous wavelet transform (CWT) is employed to determine the location of the optical edge. The method of optical edge detection is described, and characteristic details of gray-level distribution along the edge are analyzed. It is shown that the proposed wavelet edge detection method is not dependent on any threshold values; hence the true edge position can be determined without subjective selection. A black low-reflectivity object surface made from woven carbon fiber is measured, and the experimental results show that the profile of a woven carbon fiber can be obtained by the proposed method. © 2006 Optical Society of America

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1. Introduction

A number of optical techniques for obtaining topographic information are available. Optical techniques are noncontact and nondestructive and are desirable for vibration analysis, quality control, and contour mapping. Moiré,^{1,2} holography,³ Fourier transform,^{4,5} phase measuring profilometry,^{6,7} and shearography^{8,9} are common optical methods for surface contouring. In recent years, phase shifting fringe projection^{10,11} has become the predominant method for surface profile measurement and has been extended to measurement of microcomponents.

In surface profile measurement, a structured light is projected onto the surface of an object and the projected fringe pattern is perturbed by the object's profile. By processing the perturbed fringe patterns, one can obtain a surface profile. Conventional phase shifting fringe projection produces good results when the surface of the object has good reflectivity. How-

ever, if the surface has low reflectivity, such as a woven carbon fiber, a large error will result from the low image intensity.

In this paper we propose a novel optical edge projection method to overcome the problem of low reflectivity of the object's surface. A structured light edge is projected onto an object, and the distorted optical edge is captured by a CCD camera. By extracting the optical edge shadow and comparing it with a reference line, one can obtain the height of the object's surface along the edge by using a triangulation technique. We obtain a whole-field three-dimensional (3D) profile of the object by scanning the optical edge over the entire surface of the object. The accuracy of the proposed method is dependent on the optical edge detection algorithm. In our previous work^{12,13} an edge detection method based on a threshold value estimated from a gray-level histogram and a Canny¹⁴ edge detection method were used to determine the 3D surface profile. In this study the gray-level distribution of the projected optical edge is analyzed in detail by use of a continuous wavelet transform (CWT), and the optical edge position is determined by the gray-level distribution. Unlike the previously reported method, this method is independent of any threshold value, and a precise optical edge position can be obtained.

2. Theoretical Analysis

Figure 1 shows a schematic of the optical arrangement of the projection and imaging system. An opti-

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Fig. 1. Schematic of the optical arrangement.

cal edge is projected onto a specimen at a right angle. The image of the edge is located along point A, and O is the corresponding point on a reference line. When the object is viewed at an angle θ with respect to the normal direction, a distorted image AC is observed. The height $h(x, y)$ of point A can be calculated directly from simple geometry.

As shown in Fig. 1, the height of the specimen's surface, $h(x, y)$, can be expressed by

$$h(x, y) = AC / \sin \theta, \quad (1)$$

where AC indicates the projected optical edge; the length of AC is calculated from the reference line and is in units of pixels. The actual values of AC are determined from a calibrated reference line. Figure 2 shows the specimen with the projected optical edge and the reference line along with the distorted optical edge.

To obtain a precise measurement of surface profile, one must determine the projected optical edge with a high degree of accuracy. Hence a suitable edge extraction method is needed in the proposed system. Many edge detection methods have been developed, most of which need to set one or two threshold values to allow the edge position to be determined. In such cases, the

Fig. 2. (a) Woven carbon fiber, (b) optical edge with three test areas marked, (c) distorted edge and reference line.

final edge position may vary when different threshold values are chosen. Normally, the value of the threshold is often estimated subjectively according to a study of the edge signal; thus the true edge position can hardly be determined if the edge itself is complex. Figure 3 shows the optical edge details that correspond to three small areas (areas A, B, and C) marked in Fig. 2(b), where Figs. 3(a1), 3(b1), and 3(c1) show the 3D information on the edge and Figs. 3(a2), 3(b2), and 3(c2) show the respective gray-value histograms of the selected areas. It can be seen that the edge has a width of several pixels and that the gray-level distribution is not the same in different areas along the line of the distorted optical edge. To extract the true edge position, one should consider an objective edge detection method without a threshold as a feasible solution.

The wavelet transform,¹⁵ which has proved to be a useful mathematic tool, can be employed in this application. The CWT of a signal $s(t)$ is defined as its inner product with a family of wavelet functions $\psi_{a,b}(t)$:

$$W_s(a, b) = \int_{-\infty}^{+\infty} s(t) \psi_{a,b}^*(t) dt, \quad (2)$$

where

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right), \quad b \in R, \quad a > 0, \quad (3)$$

where $\psi(t)$ is known as the mother wavelet, $\psi_{a,b}(t)$ are basis functions of the transform, known as daughter wavelets, a is the scaling factor related to the frequency, b is the time shift, and $*$ denotes a complex conjugate. The factor $1/\sqrt{a}$ in Eq. (3) is used to keep the energy of $\psi_{a,b}(t)$ constant during dilation and translation.

Signal $s(t)$ can be recovered from wavelet coefficients $W_s(a, b)$ by an inverse wavelet transform given by¹⁵

$$s(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_0^{+\infty} W_s(a, b) \psi\left(\frac{t-b}{a}\right) \frac{da}{a^2} db, \quad (4)$$

where the constant C_ψ is given by

$$C_\psi = \int_{-\infty}^{+\infty} \frac{|\hat{\psi}(\omega)|^2}{\omega} d\omega < +\infty \quad (5)$$

and $\hat{\psi}(\omega)$ denotes the Fourier transform of $\psi(t)$. Mother wavelet function $\psi(t)$ is a zero-mean wiggle (real or complex), localized in both time and frequency, and it satisfies the admissibility condition expressed by expression (5).

From Eqs. (2) and (3) we can rewrite the CWT as follows:

Fig. 3. Gray-level distributions and histograms of three test areas on the optical edge marked in Fig. 2(b).

$$W_s(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} s(t) \psi_{a,b} \left(\frac{t-b}{a} \right) dt. \quad (6)$$

With a certain a and b , Eq. (6) can be considered a correlation process between the signal and a daughter wavelet function. A series of correlation coefficients can be obtained within the range of the signal when time-shift factor b varies. The higher the coefficient is, the greater the similarity between the signal and the daughter wavelet is. If we could find a suitable wavelet that can describe the special characteristic of the signal, the precise position of the

parts that have the special characteristic in the signal would be determined from the correlation coefficients by wavelet transform. Meanwhile, the wavelet function will be dilated (or compressed) with different scaling factors a . Therefore the results obtained under the aforementioned circumstances are the coefficients produced at different scales by different sections of the signal. The coefficients constitute the results of a regression of the original signal performed on differently scaled wavelets.

Kaspersen *et al.*¹⁶ employed a Mexican-hat wavelet to detect the edge of an ultrasound image and obtained promising results. In the proposed method,

Fig. 4. Gray-level distribution of the cross section of an optical edge.

the object to be analyzed is a black-to-white optical edge (as shown in Fig. 3); the signal to be analyzed by the CWT is its gray-level distribution (as shown in Fig. 4), and the special characteristic is a step transition of gray level from black to white. In such a case, the first-order Gaussian wavelet (as shown in Fig. 5) is employed because the wavelet is suitable for describing the step's special characteristic. When the edge signal is analyzed by this wavelet, a maximum value will appear in a correlation coefficients matrix. This maximum value indicates that, at a certain resolution and in a certain position, the edge signal is most similar to the daughter wavelet. From the resolution, the edge profile can then be deduced, and the true optical edge location can be determined from the edge position. Figure 6(a) shows a 3D plot of the wavelet transform coefficients, and one of the cross sections for a given scale is shown in Fig. 6(b).

Fig. 5. Gaussian wavelet of order 1.

Fig. 6. (a) 3D map of the CWT coefficients, (b) position of the detected edge.

3. Experiment

Figure 7 shows the experimental setup. The specimen used in this study consists of a flat plate fabricated with a woven carbon fiber material, as shown in Fig. 2(a). The optical edge projection on the specimen is shown in Fig. 2(b). Figure 2(c) shows the distorted optical edge and reference line. The surface of the specimen has low reflectivity and is highly uneven owing to the woven structure. Numerous valleys can be observed between the fibers. To view these valleys we use a powerful white-light source. The optical edge is projected by a 150 W dc white-light source at a right angle by an optical fiber through a set of imaging lenses onto an area of 25 mm $\times$ 15 mm. The distorted optical edge is captured by a CCD camera at an angle with respect to the normal of the reference plane. The method works well on a dark object but has the shortcoming of requiring a scanning device. In this measurement system, the specimen is mounted onto a computer-controlled stage. As the stage is moved, the specimen's surface is scanned by the projected optical edge, and a series of line profiles can be obtained. The measuring time for one specimen takes approximately 1 or 2 min, depending on the dimensions of the specimen.

Fig. 7. Schematic of the experimental arrangement of the optical edge projection method.

4. Results and Discussion

Figure 8 shows a flow chart of the experimental procedures and the image processing algorithms used in the proposed method. A border line obtained by CWT edge detection together with a reference line is shown in Fig. 2(c). The height distribution of this line is calculated from the relationship between the projected light and that of the observation. Figure 9

Fig. 8. Flow chart showing experimental procedures and the image processing algorithm.

Fig. 9. 3D profile of the woven carbon fiber specimen.

shows a 3D plot of the surface contours of the specimen. The structures of the woven carbon fibers are clearly observed, and the shapes of fibers with valleys are all clearly identified.

Normally it is difficult to measure the shape of the valley in a black specimen because of the low reflectivity and large unevenness of the surface. However, in this study a special structured light projected onto the surface enables the image to be separated into two distinct regions. In the dark region, little or no information is obtained; in the bright region, precise details between fibers can be observed. Note that the bright region could be adjusted to have intensities above the dynamic range of the CCD camera. As a result, a sharp and clear optical shadow appears along the projected edge. Hence the variations in reflectivity of the object's surface will not significantly affect the measurements because only the intensities along the optical edge are significant.

Previously we used an edge detection method based on a threshold value estimated from a gray-level histogram.¹² In that work, we chose a threshold value by analysis of the histogram to determine the position of the optical edge. In fact, owing to the unevenness of the object's surface, the optical edge obtained was not uniform. From Fig. 3 it can be observed that the gray-value distributions and the histogram of one edge varied at different parts of the object. In this case, it was not ideal to choose one threshold in the histogram as the position of the optical edge. Different results may be obtained from different threshold values. This problem can be overcome by the proposed method based on the CWT. The proposed method determines the position of the edge by calculating the maximum correlation coefficient from a different scaling factor a without selection of threshold values. Furthermore, each point along the edge has its independent result, so the averaging effect can be avoided among different points. Hence, edge detection by use of the CWT has a higher accuracy than normal threshold methods.

Note that the resolution of the proposed method is lower than that of the phase shifting fringe projection method.¹⁰ In the proposed method, height informa-

tion is determined by comparison of the distortion of a border line with a reference line. The minimal difference between the border line and the reference line is 1 integral pixel, and hence a resolution of 1 pixel is achievable. Note that the physical resolution is also dependent on the optical magnification of the observation system. Subpixel resolution can be achieved by interpolation of the edge signal.

5. Concluding Remarks

We have presented a novel optical edge projection technique with which to obtain the profile of a low-reflectivity object. Experiments have been carried out on a specimen fabricated from a woven carbon fiber material for which a normal phase shifting fringe projection technique is not suitable. We employ an edge detection method based on a CWT to determine the position of the edge. The accuracy and resolution of the proposed method are determined by the resolution of the edge detection technique, which is 1 pixel in this case. The resolution, however, can be further improved by interpolation of the edge signal.

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