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Optical edge-projection method for three-dimensional profilometry

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A novel optical edge-projection method is proposed for surface contouring of an object with low reflectivity. A structured light edge is projected onto a dark surface, and the image is captured by a CCD camera. The object contour is evaluated with an active triangular projection algorithm, and one obtains a whole-field three-dimensional contour of the object by scanning the optical edge over the entire object surface. The proposed method is applied to a black nonreflective object made from woven carbon fiber and is also applied to measure the profile of a small object (a coin). The results show that an accurate profile of the specimen can be obtained. © 2005 Optical Society of America

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Optical techniques are widely used to determine three-dimensional (3D) profiles in many engineering fields. Generally these techniques are noncontact and nondestructive and are useful for vibration analysis, quality control, and contour mapping. Common optical methods for contouring include moiré,¹ holographic,² Fourier-transform,^{3,4} phase measuring,^{5,6} and shearography methods.⁷ In recent years, phase-shifting fringe projection^{8,9} has become the predominant method of surface contouring and has been extended to measurement of microcomponents. When a structured light is projected onto the surface of an object, the projected fringe pattern is perturbed by the profile of the test surface, thereby permitting direct derivation of the surface profile. The conventional phase-shifting fringe projection method produces good results when the surface of the object has good reflectivity. However, if a surface that has low reflectivity, such as a woven carbon fiber, is measured, large errors will result owing to the low intensity of the images captured.

We proposed a novel optical edge-projection method with which to measure the 3D profile of such a surface. A structured light edge is projected onto an object surface, 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 surface along the edge by using triangulation. One obtains a whole-field 3D profile of the object by scanning the optical edge over the entire object surface. The specimen is mounted onto a computer-controlled platform, and the optical edge scans the surface of the specimen when the platform is moved. The accuracy of the method is dependent on that of the optical edge-detection algorithm.

Figure 1 is a schematic of the layout of the projection-and-imaging system. An optical 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 system is viewed from another direction at angle θ , a

distorted image of edge AC can be observed. Height $h(x,y)$ of point A can be calculated directly from simple geometry. Height $h(x,y)$ of a point on the specimen's surface can be obtained from

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

where AC indicates the projected optical edge, whose length is calculated from the reference line in units of pixels. The actual values of AC are calculated from a calibrated reference line.

The main advantage of the proposed method is that, unlike the normal fringe projection method, it permits a surface with low reflectivity to be evaluated. Normally, it is difficult to measure the shape of the valley in a black specimen because of the specimen's low reflectivity and severely uneven surface. However, in this study the structured light projected onto the surface enabled the image to be separated

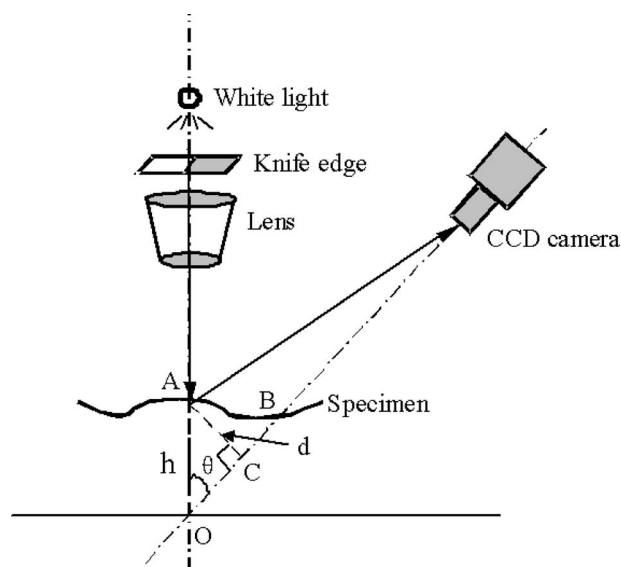


Fig. 1. Optical edge-projection setup.

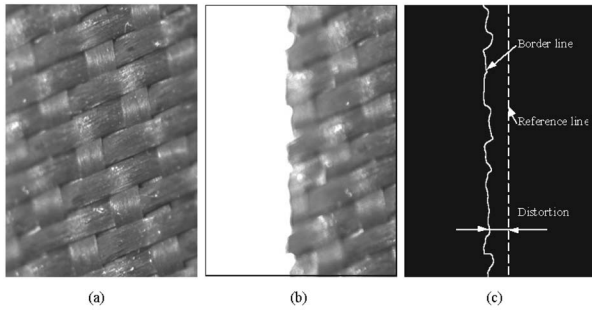


Fig. 2. (a) Woven carbon fiber specimen, (b) optical edge, (c) distortion.

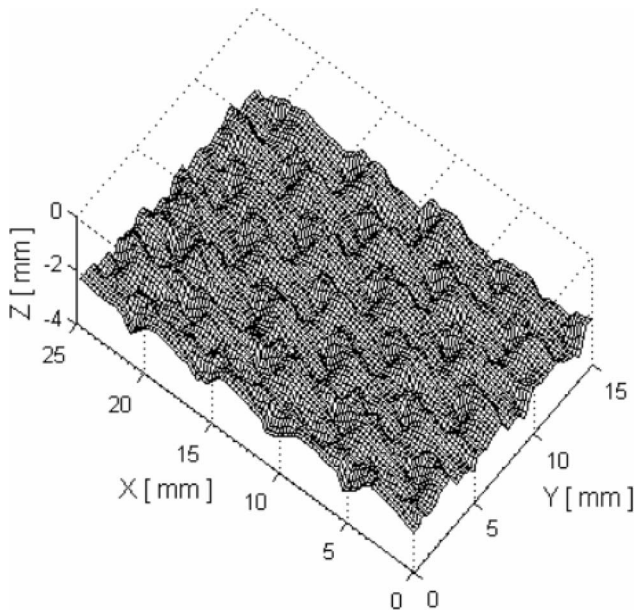


Fig. 3. Surface profile of the specimen.

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. It is to be noted that certain areas in the bright region, especially the top of the woven carbon fibers, have high intensity that is above the dynamic range of the camera. This, however, will not significantly affect the results, as only the intensity along the optical edge is of concern.

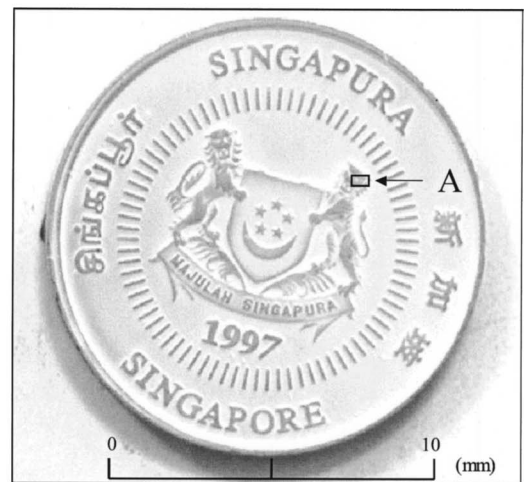
Two test specimens were used in this study. The first specimen consisted of a flat plate fabricated from a woven carbon fiber material. Figure 2(a) shows a section of the specimen, and Fig. 2(b) shows a projected optical edge. The surface has low reflectivity and is highly uneven because of its woven nature. Numerous valleys can be observed between the fibers. To view these valleys, a powerful 150 W dc white-light source is needed. The optical edge is projected at a right angle through a set of imaging lenses by an optical fiber and onto an area of 25 mm \times 15 mm. The distorted optical edge is captured by a CCD camera mounted at an angle to the light source.

A border line obtained by the Canny edge-detection method,¹⁰ together with a reference line, is shown in Fig. 2(c). The height distribution of the line is calculated from the relationship between the projected

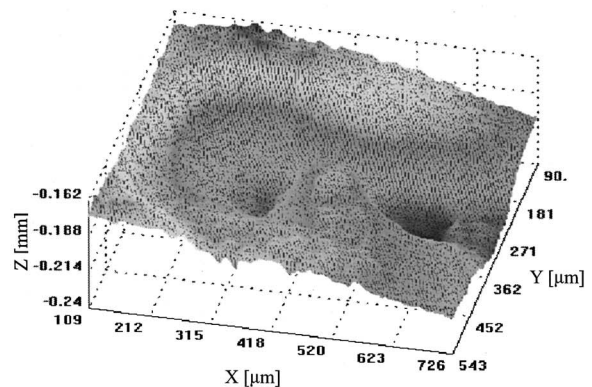
light and that of observation. Scanning the optical edge across the specimen surface yields a series of line profiles. The final profile of the specimen is calculated by linear interpolation. Figure 3 shows a 3D profile of the specimen. The fine structure of the woven fibers is clearly observable, and the shapes of the fibers with valleys between them is clearly identified.

When the proposed method is applied to a small component, a microscopic zoom lens with a long working distance and a high magnification is required. In this case, the effect of light diffraction at the projection edge can be amplified, and the optical edge will be blurred. To overcome this problem, a Canny edge detector¹⁰ designed specially for step edge extraction is used. In the Canny edge-detection algorithm, an image with an optical edge $f(x,y)$ is smoothed by convolution with a two-dimensional Gaussian function $G(x,y)$. Light diffraction, which occurs at the optical edge, will have the same convoluting effect that is required in the initial processing step of the Canny edge-detection method.

To verify the proposed method for profiling of a small object we used a test coin. A small image area (area A, 700 μ m \times 500 μ m) was studied [Fig. 4(a)], and the corresponding 3D profile of the eyeball (100 μ m in diameter) of an animal in the image is



(a)



(b)

Fig. 4. (a) Coin specimen, showing area of interest A, (b) height distribution of area A.

shown in Fig. 4(b). One can see that minute profile variations can be observed clearly.

In the proposed method, height information 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 one integral pixel; hence a resolution of one pixel is achievable. The resolution of the test object is also dependent on the optical magnification of the observation system. In the first experiment, the actual size of one pixel was $\sim 35\ \mu\text{m}$; hence a resolution of $35\ \mu\text{m}$ was achievable. In the second experiment the corresponding resolution was $0.7\ \mu\text{m}$.

In summary, we have presented a novel technique, termed an optical edge-projection method, with which to evaluate the profile of a highly nonreflective object. Experiments were carried out on a specimen fabricated from a woven black carbon fiber material, for which a normal fringe projection technique is not suitable. The proposed method can also be applied to measurement of the shape of a small object with an accuracy of the order of micrometers. The recording sensor determined the accuracy and resolution of the method, in this case one pixel; however, the resolution could be improved by the introduction of a sub-pixel edge-detection technique.

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