Surface height retrieval based on fringe shifting of color-encoded structured light pattern

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A new method of fringe shifting for color structured pattern projection is presented for three-dimensional (3D) surface height measurement. Temporal encoding of color stripes is combined with locally spatial shifting of multiple fringes to realize image acquisition with a small number of pattern projections. Object topography is retrieved with high resolution by decoding the code word of each fringe with the help of the redundant information provided by the shifting patterns and the encoding patterns in their temporal and spatial neighborhoods. An application to evaluate the shape of a buckled tube demonstrates the effectiveness of the method. © 2008 Optical Society of America

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Projecting light patterns onto an object surface provides shape information through phase modulation of the light structure. Various methods to design the structured patterns have been proposed, and different ways to retrieve three-dimensional (3D) object topography have been developed [1]. The laser scan technique [2], for instance, which projects a laser stripe onto the object surface to result in a corresponding shift of those distorted by the object surface. In this optical measurement system, the triangle \( \triangle ABC \) is used to illuminate the specimen with the structured patterns in an inclined direction, and a digital camera (Canon EOS 350D; resolution, 3456 \( \times \) 2304) is placed at \( O_p \) to capture the patterns in the normal direction to a reference plane. The use of the system is initialized from a reference plane by projecting patterns on it before recording the undistorted fringes in comparison with those distorted by the object surface. In this optical geometry, the triangle \( \triangle ABC \) is similar to \( \triangle O_pO_2C \), and the surface height \( h \) produces a movement of the point \( B \) on the reference plane to the point \( C \) on the object surface to result in a corresponding shift \( d \).
The total length of the code word being encoded is

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fringe shifting is realized by three shifting patterns and two encoding patterns using three colors encoded by a three-order De Bruijn sequence with six symbols to codify the patterns. Totally, 450 color fringes are encoded by the codes of six colors, red, yellow, green, cyan, blue, and magenta, with each fringe occupying one pixel of the projector in width, including two black pixels between any adjacent color fringes in the shifting patterns. Thus five patterns \( m+b = 3+2 \), three shifting patterns, and two encoding patterns are produced to codify \( 36 (3(3-1)^{b-1} \times 3) \) fringes in total. In our practical test to measure the buckling shape of a rectangular tube under compression, as shown in Fig. 3(a), we use a three-order De Bruijn sequence with six symbols to codify the patterns. Totally, 450 color fringes are encoded by the codes of six colors, red, yellow, green, cyan, blue, and magenta, with each fringe occupying one pixel of the projector in width, including two black pixels between any adjacent color fringes in the shifting patterns, to form five patterns projecting onto the whole specimen surface. For the patterns captured by the camera during projections, two main steps are carried out in the image processing to identify both the locations and the code words of the color fringes so as to obtain the surface height map.

1. Segmenting the shifting patterns and locating the fringe centers. To obtain the positions of the color fringes, segmentation is first performed by binarizing the second derivative of the value channel of the captured image [8]. The center location of the color fringe can be detected in the segmented region with subpixel accuracy by using a normalized centroid algorithm given by center=\[ \frac{\sum_{i}^{N} I(i) \times x(i)}{\sum_{i}^{N} I(i)} \], where \( I \) is the intensity function of the segmented region, \( x \) is the coordinate function, \( i \) is

\[ (S1(k),S2(k),\ldots,Sm-1(k)) \]

\[ = (S0(k+1),S1(k+1),\ldots,Sm-2(k+1)), \]

\[ \text{where } S(k) = s_k. \text{ Moreover, because the adjacent symbols are different in the designed sequence, another restriction has been included given by} \]

\[ S0(k) \neq S1(k), S1(k) \neq S2(k), \ldots, Sm-2(k) \neq Sm-1(k). \]

Figure 2 presents an example of the generated patterns to illustrate the above design scheme of structured light. Three symbols 1, 2, and 3 \( (\text{n}=3) \), representing the colors of red, green, and blue, respectively, form a three-order \( (m=3) \) De Bruijn sequence for color pattern generation. In the shifting patterns, there are two black pixels \( (b=2) \) between the adjacent color fringes. Thus five patterns \( m+b = 3+2 \), three shifting patterns, and two encoding patterns are produced to codify \( 36 (3(3-1)^{b-1} \times 3) \) fringes in total. In our practical test to measure the buckling shape of a rectangular tube under compression, as shown in Fig. 3(a), we use a three-order De Bruijn sequence with six symbols to codify the patterns. Totally, 450 color fringes are encoded by the codes of six colors, red, yellow, green, cyan, blue, and magenta, with each fringe occupying one pixel of the projector in width, including two black pixels between any adjacent color fringes in the shifting patterns, to form five patterns projecting onto the whole specimen surface. For the patterns captured by the camera during projections, two main steps are carried out in the image processing to identify both the locations and the code words of the color fringes so as to obtain the surface height map.

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the pixel index, \( t \) is a threshold (setting to 0.9 in our case), and \( I_{\text{in}}(i) = I(i)/\max(I(i)) \) is the normalized intensity function.

2. Recognizing the code words of color fringes and calculating the surface heights. Based on the segmented result, the code words of the color fringes are decoded by identifying their colors in the patterns through thresholding hue value of the images. To enhance the robustness of the color recognition operation, a mean value is calculated by averaging the hue values of the pixels around the center location of color fringe. Therefore, the mean hue values of the color fringes in both the shifting patterns and the corresponding encoding patterns are easily identified to determine the temporal code words. Errors in color recognition, however, may still exist owing to noise and color aberration in the images. In this case, the restrictions of Eqs. (3) and (4) included in the encoding scheme provide two criteria to check the identified code words so as to delete those falsely recognized. After obtaining the code words of every color fringe in the shifting patterns, whose spatial distributions are distorted by the object surface, the image shift \( d \) between the deformed pattern and the reference pattern is determined by matching the code words of the fringes, thus the surface height is calculated by Eq. (1).

To prove the validity of the proposed method, an experimental result is presented in Fig. 3 for the topographic measurement of a rectangular tube made of aluminum alloy, with a wall thickness of 1.5 mm in the hollow cross section of 76 mm \( \times \) 44 mm. Figure 3(a) gives a color fringe pattern projected onto the buckled wall of the tube loaded by axial compression, and Fig. 3(b) shows the plastic displacement of the wall surface as a height contour represented by gray levels. As the projected fringes at every point of the surface can be recognized by pattern decoding, the whole-field 3D map of the specimen can be obtained from image shift. Figure 3(c) gives a 3D plot of the buckled surface to show the local characteristics of the deformation field. In our experiment, the distance between the reference plane and the camera is \( H = 1.5 \) m, and the angle between the projecting and the receiving directions is 30°. With this system layout, the spatial resolution of surface sampling is about 0.1 mm in the y–z coordinates, the sensitivity is 0.18 mm/pixel, the accuracy is around 0.06 mm, and the available range of height measurement is 0–120 mm in the x direction, respectively. The shadow produced by inclined illumination seems to be not obvious for the buckled surface of the rectangular tube. For the object surface with big depth discontinuity, however, more projectors should be used to illuminate the object from different orientations so as to cover the shadow areas.

In conclusion, the proposed method of color-encoded structured light greatly reduces the number of projecting patterns, which can be decreased to five shots or even less (e.g., three shots) depending on the scene range of illumination and the resolution of sampling on the object surface. Therefore the technique can be applied to quasi-static or low-speed dynamic measurement of surface shape and deformation. With local shifting of multiple fringes to cover all illuminating pixels projecting onto the surface, the approach offers high spatial resolution of measurement, and the combination of time-multiplexing and spatial encoding of the structured patterns ensures the color fringes are recognizable without ambiguity to obtain 3D surface topography with high robustness.

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References