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Single-shot three-dimensional reconstruction based on structured light line pattern

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A B S T R A C T

Reconstruction of the object by single-shot is of great importance in many applications, in which the object is moving or its shape is non-rigid and changes irregularly. In this paper, we propose a single-shot structured light 3D imaging technique that calculates the phase map from the distorted line pattern. This technique makes use of the image processing techniques to segment and cluster the projected structured light line pattern from one single captured image. The coordinates of the clustered lines are extracted to form a low-resolution phase matrix which is then transformed to full-resolution phase map by spline interpolation. The 3D shape of the object is computed from the full-resolution phase map and the 2D camera coordinates. Experimental results show that the proposed method was able to reconstruct the three-dimensional shape of the object robustly from one single image.

1. Introduction

In recent years, non-contact three-dimensional surface imaging technology advances rapidly and greatly with the stimulation of market demands in industry and scientific research. Based on the surface characteristics of the object, the non-contact three-dimensional surface imaging techniques could be divided into two categories: techniques to measure the specular surfaces [1–5] and techniques to measure the diffuse surfaces [6–18]. No matter for the specular surfaces or the diffuse surfaces, the robust measurement with one-shot is very challenging, however, it is highly desired especially when the measured surfaces are dynamic and deformable. As a result, many one-shot methods have been proposed for specular surface measurement [1–5] and diffuse surface measurement [11–18]. Each proposed method has its own merits or limitations and its application is also limited. Thus, a more versatile and robust one-shot 3D imaging method is always welcome in this research filed.

For the diffuse surface three-dimensional measurement, phase shift profilometry is among the most popular ones due to its relatively higher measurement accuracy and measurement efficiency compared to other non-contact three-dimensional surface imaging techniques. However, traditional phase shift profilometry requires at least three patterns to calculate the phase map for the coordinate computation. Consequently, phase shift profilometry has limited applications in measuring the shapes of moving objects or deformable objects. Despite the limitations, pioneering researchers had tried to measure the 3D shapes of the moving objects by utilizing the phase shift method [11–15]. Lau et al tried to measure the 3D shape of the moving object by projecting multiple phase patterns with time-synchronized illumination [11]. Zhang and Yau obtained the absolute coordinate measurement in real time by the phase-shifting method with an encoded marker [12]. Guan et al modulated three phase patterns into one composite pattern and achieved one-shot projection of the composite pattern to measure the 3D shape of the object [13]. Later, Yue et al modulated five phase patterns into one composite pattern and achieved one-shot projection of the composite pattern to measure the 3D shape of the object [14]. Chen et al also achieved one-shot reconstruction of color surface with the phase-shifting method by employing the Hue Saturation Intensity (HSI) color model [15]. Besides the phase-shifting based methods, different methods had also been exploited to measure the three-dimensional shapes of the moving objects [16–19]. Takeda et al achieved single shot 3D reconstruction by multiplexing in the frequency domain [16]. Davis et al invented the space-time stereo to measure the 3D shape by triangulation [17]. Koninckx and Van Gool realized one-shot 3D measurement by projecting a binary fringe pattern that is continuously adaptive to the scene [18]. Chen et al achieved one-shot 3D reconstruction by coded structured light [19]. These research results and methods are significant in the development of the three-dimensional surface imaging technology. However, they might have their own insurmountable drawbacks during applications. Consequently, there are few three-dimensional surface imaging products that are capable of reconstructing the object robustly by one-shot in market.

In this paper, we propose a one-shot 3D shape measurement method based on the projected line pattern that has been used successfully in

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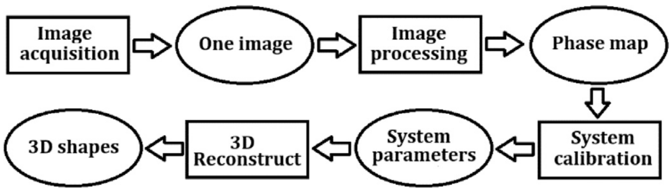

Fig. 1. Flowchart of the proposed method.

weld pool measurement [20]. To make use of more lines for higher resolution measurement, we produce the line pattern by a projector instead of the laser generator [20]. The bright lines in the line pattern are parallel before they are projected onto the surface of the object and become distorted by the surface of the object after they hit on the object. The three-dimensional information of the object is computed based on the distortions of the bright lines. To calculate the distortions of the bright lines accurately, robust image processing algorithms are essential. We utilize the image processing methods proposed in the past research [21–22] to segment and cluster the bright lines from the captured image. After clustering, the skeleton of each clustered line is obtained and then smoothed by spline fitting. The y coordinates of the points on the smoothed skeleton are used directly to form a low-resolution phase matrix which is transformed to the full-resolution phase map by spline interpolation. The 3D shape of the object is computed from the phase map and the camera coordinates. Experimental results indicate that the proposed method is competitive compared to state of the art three-dimensional surface imaging methods.

2. The proposed method

The proposed method could be summarized by the flowchart in Fig. 1. Firstly, the line pattern is projected onto the calibration grid and one image was captured. After image processing, the phase map is obtained. With the phase map and the known coordinates of the calibration grid, the system is calibrated to get the system parameters. After system calibration, the grid is replaced with the object that needs to be reconstructed. The object is reconstructed from one single image with one-shot projection of the same line pattern.

The designed line pattern is formulated as follows.

$$I = 1 + \cos(2\pi k y / N_1) \tag{1}$$

where k is the number of the produced bright lines in the line pattern. y is the vertical coordinate of the projector and N_1 is the resolution of the projector in the vertical direction.

The segmentation approach proposed in [22] contains five parts: difference operation, spline fitting, gradient feature detection, threshold selection and filtering noise blobs because the quality of the captured laser line images is extremely low. In this research work, the quality of the captured images is much higher than that of [21–22]. Hence, we simplify the previously proposed segmentation approach and only select the gradient feature detection and the threshold selection to segment the bright lines for computation efficiency. The gradient detection filter is formulated as follow.

$$K_g = R(VH, \theta) \tag{2}$$

where

$$V = \left[-k; v_1; v_2; \ldots; v_{N-1}; k\right] \tag{3}$$

$$H = \left[h_0, h_1, \ldots, h_{N-1}, h_N\right] \tag{4}$$

$$h_i = w_h(i); i = 0, \ldots, N \tag{5}$$

$$v_i = w_v(i); i = 1, \ldots, N-1 \tag{6}$$

where N equals the width of the laser line and it determines the size of the kernel. k is a constant. w_h and w_v are two weighting functions. As can be seen, the product VH is a $(N+1) \times (N+1)$ matrix. $R(VH, \theta)$ is to rotate the matrix VH by θ degrees in the counterclockwise direction around its center point. θ is orthogonal to the line direction and is chosen as 90° in this research.

After gradient feature detection, we get the gradient feature image, $g(x, y)$. We then calculate a global threshold for the gradient feature image. The threshold selection method comprises of the following steps. Firstly, the gray scale of the gradient feature image is rearranged in the interval [0, 255]. Its histogram distribution is normalized. Then, the normalized histogram distribution is smoothed by a low-pass discrete Fourier transformation (DFT) filter. Two slopes, the slope on the left $s_2(i)$ and the slope on the right $s_2(i)$, are computed for each sampled point on the smoothed histogram distribution by fitting a line with the least squares model. The slope difference, $s(i)$, at point (i) is computed as:

$$s(i) = s_2(i) - s_1(i) \tag{7}$$

The continuous function of the above discrete function, $s(i)$ is the slope difference distribution, $s(x)$. To find the candidate threshold points, we set the derivative of $s(x)$ to zero.

$$\frac{ds(x)}{dx} = 0 \tag{8}$$

The solutions of the above equation correspond to the valleys of the slope difference distribution. The solution that corresponds to the valley with the maximum absolute value is chosen as the optimum threshold in this specific application. The segmentation is the most essential part of image processing because it is challenging and its accuracy determines the final 3D reconstruction accuracy. We show the captured calibration grid image in Fig. 2(a) and show the segmentation result by the simplified segmentation approach in Fig. 2(b). As can be seen, all the lines are segmented accurately. To demonstrate the effectiveness of the gradient detection filter, we show the segmentation result by applying the threshold selection on the original image directly in Fig. 2(c). It is seen that the whole center part is segmented from the background because of the uneven grayscale distribution caused by the projected light. Thus, the effectiveness of the gradient detection filter in removing the uneven background is verified further in this research work. After segmentation, the lines need to be clustered automatically and we propose a top to bottom clustering method in this paper.

Step 1: The segmented lines in the segmentation image are labeled automatically to form a labeled image.

Step 2: The topmost point (x_{top}, y_{top}) is detected by finding the minimum y value of all the segmented lines in the segmentation image. The labeled line with the topmost point (x_{top}, y_{top}) in the labeled image is selected and numbered as i. The segmentation image is then updated by removing the numbered topmost line with a subtraction operation.

Step 3: The topmost point (x_{top}, y_{top}) in updated segmentation image is detected by finding the minimum y value of all the segmented lines. The labeled line with the topmost point (x_{top}, y_{top}) in the labeled image is selected and numbered as $i + 1$. The segmentation image is then updated by removing the numbered topmost line with a subtraction operation.

Step 4: Repeat Step 3 until all the lines in the segmentation image are numbered. $i = 1$ in this study. Fig. 2(d) shows the clustering result by this proposed top to bottom clustering method.

In this paper, we propose a novel phase map calculation method. For the traditional phase shift profilometry [10], at least three images are required to obtain the closed form solution for the phase map. As a result, the traditional phase shift profilometry is not suitable for on-line 3D measurement or deformable object reconstruction. In this paper, we calculate the phase map from the clustered lines as follows.