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A layered modulation method for pixel matching in online phase measuring profilometry

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ABSTRACT

An online phase measuring profilometry with new layered modulation method for pixel matching is presented. In this method and in contrast with previous modulation matching methods, the captured images are enhanced by Retinex theory for better modulation distribution, and all different layer modulation masks are fully used to determine the displacement of a rectilinear moving object. High, medium and low modulation masks are obtained by performing binary segmentation with iterative Otsu method. The final shifting pixels are calculated based on centroid concept, and after that the aligned fringe patterns can be extracted from each frame. After performing Stoilov algorithm and a series of subsequent operations, the object profile on a translation stage is reconstructed. All procedures are carried out automatically, without setting specific parameters in advance. Numerical simulations are detailed and experimental results verify the validity and feasibility of the proposed approach.

1. Introduction

With the rapid development of modern industry, 3D inspection is widely used in manufacturing sector, such as machine vision, robot simulation, automated assembly and quality control. As the aim is to measure product profiles faster and more efficiently, non-contact optical techniques have been naturally investigated by both researchers and industry. There are several optical methods developed for 3D measurement, such as phase measuring profilometry (PMP) [1,2], Fourier transform profilometry (FTP) [3,4], Moire profilometry [5], and time of flight method (TOF) [6] etc. Wherein, PMP and FTP are all based on principle of structured light triangulation, and have shown to be robust and reliable among optical metrology techniques. In addition, their implements are relatively simple and low cost. So these methods have been widely adopted in industry nowadays.

FTP was initially proposed by Takeda. In this method, the 3D shape can be reconstructed with only one deformed fringe pattern. Despite the fact that it is a single frame and thus a very fast technique, it suffers from low accuracy and is not robust to high step samples. Therefore, other algorithms have been proposed to improve the performance of this method [7,8]. The frame requirement of PMP is more than a single, but it has shown a huge potential in high precision measurement. Indeed, this technique is based on point to point calculation and no phase error is introduced from discrete transform as compared with FTP. Traditionally, the structured light used in PMP is sinusoidal fringe. Comparing with other structured light patterns, such as gray code, sinusoidal fringe has better performance in phase unwrapping and experimental efficiency [9].

One of the important parts in online PMP is pixel matching. Due to the object is moving, its position in each frame is not the same. Thus classic PMP algorithms cannot be implemented directly. If the displacement of the object in each frame is known, the deformed fringe patterns can be realigned, so the case would be converted back to traditional static model. However, the object in captured image is covered with fringes, which makes difficult in target recognition. Fortunately, the object modulation can be used as matching material. Although the object is moving, the modulation as one inherent property adheres object surface and structure. Therefore, modulation can be used for displacement acquisition. Some researchers have discussed pixel matching methods related to modulation. Wu et al. proposed a matching method with traditional modulation correlation [10] and another filtered modulation method [11]. Peng et al. used shadows as low modulation to match pixels [12] and Chen et al. determined moving pixels using extra markers which are composed by four symmetric angles [13]. Besides, Wang et al. have proposed a model for rotating object [14].

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In this paper, a new layered modulation method for pixel matching is proposed. The images for modulation extraction are enhanced by Retinex theory, and as a result the contrast of fringes is improved significantly, which makes the obtained modulation have better distribution for segmentation operation. Then the object modulation is divided into multiple layers based on iterative Otsu method. Binarized mask of each modulation layer is used to perform normalized cross correlation with corresponding layer in another frame. The average displacement between two frames can be calculated by centroid concept. In the experiment, the object is placed on a translation stage with micrometer knob which could precisely simulate the uniform motion of a pipeline. Sinusoidal structured light is projected onto object, and the object moving direction is perpendicular to the fringe strips. But perpendicularity is not a critical factor, both shifting directions are taken into account. Finally, five equivalent phase shifting images can be extracted from original frames. After applying Stoilov algorithm and phase to height relation equation, the profile of the moving object is reconstructed.

2. Principle

Whether the object is moving is the major difference between online PMP and traditional PMP. If the online case can be converted to static model, thus classic PMP knowledge and formulas can be utilized again. Modulation provides a good way to accomplish this task. The detailed procedures are introduced and discussed in this chapter. And the highlights of the proposed method are shown in Fig. 1. A brief introduction for Retinex theory is described in Section 2.1. The basic principle of Stoilov algorithm and phase to height formula are illustrated in Section 2.2. The definition of modulation and spectrum selection choice is expressed in Section 2.3. The way how to layer modulation is introduced in Section 2.4. Normalized cross-correlation method and the shifting centroid concept are discussed in Section 2.5.

2.1. Retinex theory

Retinex is a representative computation theory based on color constancy. Its full name is retinal cortex theory, which was initially proposed by Land in early 1970s [15,16]. According to Retinex theory, the sensory surface color of object is closely related to the reflection property of object surface, but it has little relation with the spectral characteristics of the light entering human eyes. Based on Retinx image model:

$$I(x, y) = R(x, y)\cdot L(x, y) \tag{1}$$

where $I(x, y)$ is the intensity distribution of the image, $R(x, y)$ is the reflectance and $L(x, y)$ is the illumination, (x, y) denotes the pixel coordinate. $L(x, y)$ is determined by the illumination source, whereas $R(x, y)$ is determined by the characteristics of the object. Here, the illumination normalization can be achieved by estimating itself. Retinx theory mainly compensates the illumination impact on images. It is noticed that Eq. (1) has the same formulation

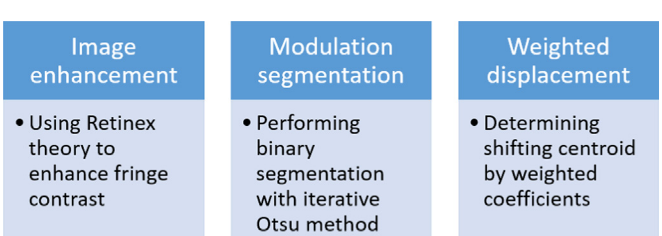

Fig. 1. Highlights of the proposed method.

as modulation formula Eq. (8), which implies the potential relationship between the two.

The color change caused by illumination is usually gentle, which is usually expressed as a smooth gradient of illumination, while the color change caused by surface variation is often a suddenness. By researching those two forms, it is able to make distinction between illumination change and surface change. When the surface color change caused by illumination is known, the constant color perception can be maintained. This theory is different from traditional image enhancement algorithms, such as linear and nonlinear transform, image sharpening, etc. The latter could only enhance one characteristic of image (e.g. dynamic range or image edge). While Retinex can achieve balance in three aspects, including dynamic range of gray compression, edge enhancement and color constancy.

Retinex theory can be used for adaptive enhancement on multiple types of images. In order to verify the feasibility of this method for fringe patterns, Frankle–McCann Retinex algorithm [17] is applied to test the effect of enhancement with sample images. Fig. 2 is the comparison before and after enhancing.

The left column of Fig. 2 shows the original images, while the right shows the enhanced ones by Retinex. It is obvious that the contrast of fringe patterns is greatly enhanced. Furthermore, the non-uniform illumination of background has also been eliminated, which all bring better performance in modulation segmentation.

2.2. Stoilov algorithm

The layout of the online PMP is shown in Fig. 3. In this model, the moving speed of the object is uniform, which means when the CCD captured interval is fixed, the displacement of the object between two adjacent frames should be the same. In other words, if the moving object is modulated by static sinusoidal fringe pattern, the equivalent phase shifting of each frame should be identical. Generally, Stoilov algorithm [18] just right can be applied in this case. Its formulation is a five equal step length phase shifting algorithm. When the phase-shift interval is $\pi/2$, it leads to the well-known five-bucket algorithm [19]. The requirement of Stoilov algorithm is only to ensure phase shifting of each frame is the same, without the exact phase shifting amount as a priori knowledge. The value of phase shifting is arbitrary, which makes measurement more convenient to operate.

In Stoilov algorithm, five frames are used to reconstruct phase, and fringe pattern intensity distribution can be expressed as follows:

$$I_n(x, y) = R_n(x, y)\left\{A(x, y) + B(x, y)\cos\left[\varphi_n(x, y) + (n-1)\varphi_\Delta\right]\right\},\quad n = 1, 2, 3, 4, 5 \tag{2}$$

where $R_n(x, y)$ is the reflectivity of the object, $A(x, y)$ is the background light intensity, $B(x, y)$ is the fringe contrast, $\varphi_n(x, y)$ is the phase in deformed fringe pattern which indicates the height of the object, φ_Δ is the unknown phase shifting value of each frame. According to the algorithm, the measured phase can be calculated as below:

$$\varphi = \arctan\left\{\frac{2\left[I_2'(x, y) - I_4'(x, y)\right]}{2I_3'(x, y) - I_1'(x, y) - I_5'(x, y)}\sin\varphi_\Delta\right\} \tag{3}$$

$$\sin\varphi_\Delta = \sqrt{1 - \left\{\frac{I_1'(x, y) - I_5'(x, y)}{2\left[I_2'(x, y) - I_4'(x, y)\right]}\right\}^2} \tag{4}$$

where $I_n'(x, y)$ $(n = 1, 2, \ldots, 5)$ are the aligned images from original $I_n(x, y)$ based on pixel matching results. Please note the φ here is