Optik 124 (2013) 887–891

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

An on-line phase measuring profilometry: Processed modulation using for pixel matching

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ARTICLE INFO

Article history:
Received 2 October 2011
Accepted 3 February 2012

Keywords:
On-line PMP
Pixel matching
Modulation
Delamination
Binarization

ABSTRACT

An novel on-line phase measuring profilometry (PMP) is proposed, which is more helpful and accurate than the dynamic Fourier-transform profilometry (FTP) in solving the problem where the object motion is along a straight line. It can be used for industrial on-line 3-D shape inspection. In PMP, the phase shifting technique is adopted and the phase calculation from N frames deformed patterns to wrapped phase is a point-to-point performance. The movement of the object results in the displacement of images in deformed pattern, so pixel matching is carried out to modify the positions of images to meet the PMP. Modulation represents the contour of the object, which is used to guide the pixel matching in this paper. Delamination and binarization of the modulation patterns further improve the pixel matching's accuracy and speed. Experiments verify the feasibility and effectiveness of the proposed method.

1. Introduction

Because of non-contacting, whole-field analysis, high resolution, automatic measurement, fringe projection technique such as phase-measuring profilometry (PMP) and Fourier-transform profilometry (FTP) has a huge potential for applications in many areas, including industrial manufacturing, on-line inspection, reverse engineering, computer graphics, plastic surgery, security checks, and etc. [1]. A structured pattern is projected onto the object surface, and the deformed fringe pattern whose phase is modulated by the object height is recorded by a CCD, the phase distribution is calculated by analyzing the deformed pattern, fianlly, the 3-D height distribution of object is gained through using the relationship of phase-to-height mapping. Nowdays, the great advances in optics, optoelectronics and computer technique make it much easier to realize the measurment systems [1,2].

A variety of optical 3-D shape measurement methods have been proposed to deal with the dynamic or motional objects. Su et al. measured and displayed the process of the eddy generating and deepening using FTP [3,4]. Zhang described a high-resolution, real-time 3-D shape measurement system, which based on a digital fringe projection and phase-shifting technique [5,6], and he had successfully measured the facial expression changes of a smiling person. Yoneyama et al. proposed a new phase-measuring suface profiling technique of a moving object without phase-shifting device [7].

Although FTP is convenient in dynamic 3-D measurment for only one deformed pattern, PMP guarantees the higher accuracy of measurement result because the phase calcualtion is a point-to-point performance [8,9]. Huang and Zhang's system using for dynamic 3-D measurement are based on PMP, but both of them adoped rapid phase-shifting technique [5,10]. An economical and simple on-line 3-D inspection system based on PMP for measuring the object in linear motion is proposed in this paper, which does not project the phase-shifting frings in a high switching speed. In the proposed system, the projecter's switching speed is unrestricted and the CCD's capture speed must synchronizes with the switching speed. The positions of moving object's images in different deformed patterns are different, so pixel matching [11,12] must be implemented between the deformed pattens to modify the positions of the images in deformed patterns. The pixel matching process is not easy, because the image of objcet is covered by the fringes and the deformed pattens lack the distinct characteristics. If the contour of object can be extracted from the deformed pattern by using of some digital imaging processing technique, the pixel matching would complete rapidly.

Aiming at the above questions, a novel method for pixel matching based on delamination and binarization of modulation is proposed in this paper. Modulation [13,14] represents the contour of the object, which can be acted as a mark to carry out pixel matching. And modulation can be obtained by using method of Fourier tansform analysis easily. In order to make further improvement in the accuracy and speed of pixel matching and measurement, this paper also mentioned that the modulation distribution is processed by delamination and binarization techniques. By setting a threshold value of the modulation information, the abrupt change

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0030-4026/$ – see front matter
doi:10.1016/j.ijleo.2012.02.026

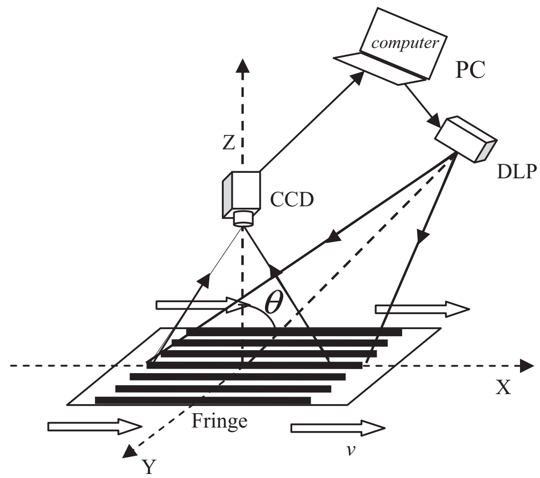

Fig. 1. Online 3-D inspection system.

values of modulation in the shadow area are evaded; By cutting out a reliable area with distinct characteristics which can exactly describe the contour of object, the area without distinct characteristics on the reference plane are filtered. Then the reliable area are converted into a binary image, which are used as a pixel matching template. Through the above pre-processing, the pixel matching accuracy and speed can be improved significantly. This method successfully extends the suitability of on-line 3-D inspection based on PMP.

2. Principle

Fig. 1 shows the layout of the on-line 3-D measurement system. The object which is kept on the production-line moves along with *X*. *N* frames phase-shifting sinusoidal grayscale fringe patterns whose derection are along the object motion are projected onto the object by the digital-light-processing (DLP) in a switching speed. A charge-coupled-device (CCD) whose optical axis is perpendicluar to the surface of production-line is used to capture the deformed patterns modulated by the object synchronously. In this measurement system, the phase shifting direction of the fringe patterns is along with *Y*. The captured images are then digitized by a frame grabber and their intensity $I_n(x,y)$ can be described as following:

$$I_n(x,y) = R_n(x,y)\{A(x,y) + B(x,y)\cdot\cos[\varphi_n(x,y) + (n-1)\cdot(2\pi/N)]\},\quad n = 1,2,3,\ldots\ldots N \tag{1}$$

where $R_n(x,y)$ is the surface reflectivity, $A(x,y)$ is the ambient light, $B(x,y)/A(x,y)$ is the fringe contrast, $\varphi_n(x,y)$ is the phase determined by the height of object and $2\pi/N$ is the phase-shifting step.

The motion of the inspected object relative to CCD results in the positions change of the images in different deformed patterns, so pixel matching must be carried out to guarantee the images of the object keeping in the same pixel position in different deformed patterns.

After pixel matching, a sequence of patterns with the same pixel coordinate of measured object can be cut down from the original captured patterns. And the intensity of the final patterns can be described as:

$$I'_n(x,y) = R(x,y)\{A(x,y) + B(x,y)\cdot\cos[\varphi(x,y) + (n-1)\cdot(2\pi/N)]\},\quad n = 1,2,3,\ldots\ldots N \tag{2}$$

where $R_n(x,y)$ is the surface reflectivity and $\varphi(x,y)$ is the phase determined by the height of object. Because the pixel coordinate values of the object's image in different deformed patterns are uniform after pixel matching, the the reflectivity and phase distridutions are uniform. So the subscript n can be removed. The phase distribution is calculated as following:

$$\varphi(x,y) = \arctan\left(\frac{\sum_{n=1}^{N} I'_n(x,y)\sin(2\pi n/N)}{\sum_{n=1}^{N} I'_n(x,y)\cos(2\pi n/N)}\right) \tag{3}$$

In order to simplify the calculation process, we suppose $N=5$ and the phase distribution can be described as:

$$\varphi(x,y) = \arctan\left(\frac{\sum_{n=1}^{5} I'_n(x,y)\sin(2\pi n/5)}{\sum_{n=1}^{5} I'_n(x,y)\cos(2\pi n/5)}\right) \tag{4}$$

From Eq. (4), the values of the phase $\varphi(x,y)$ are mathematically limited to the interval $[-\pi,\pi]$ corresponding to the principle value of arctan funtion. A phase-unwrapping algorithm is used to convert the sawtoothlike phase-wrapped image into a continuous phase map $\Psi(x,y)$. The height distribution $h(x,y)$ is restored by mapping the unwrapped phase $\Psi(x,y)$ into the height [15,16]:

$$\frac{1}{h(x,y)} = a(x,y) + b(x,y)\frac{1}{\Psi(x,y)} + c(x,y)\frac{1}{\Psi^2(x,y)} \tag{5}$$

where the parameters $a(x,y)$, $b(x,y)$ and $c(x,y)$ depend on system setup and need to be calibrated.

3. Pixel matching based on modulation

As mentioned above, pixel matching plays a key role in the on-line 3-D inspection with PMP. Therefore, the operation of pixel matching is considerable important, which just is the emphasis of this paper.

3.1. Extraction of modulation

Eq. (1) is Fourier transformed and the Fourier spectrum is described as following:

$$G_n(f_x,f_y) = P_n(f_x,f_y) + Q_n(f_x - f_1, f_y) + Q_n(f_x + f_1, f_y),\quad n = 1,2,3,\ldots \tag{6}$$

where $G_n(f_x,f_y)$, $P_n(f_x,f_y)$, $Q_n(f_x,f_y)$ represent the Fourier spectrum of $I_n(x,y)$, $R_n(x,y)\cdot A(x,y)$, $R_n(x,y)\cdot B(x,y)$, respectively. A suitable band-pass filter is used to filter only the +1 order term of the Fourier spectra and then inverse Fourier transform is carried out to deal with $Q_n(f_x - f_1, f_y)$:

$$g_n(x,y) = \int\int_{-\infty}^{+\infty} Q_n(f_x - f_1, f_y)\exp[i2\pi(f_x x + f_y y)]df_x df_y = \frac{1}{2}R_n(x,y)B(x,y)\exp\{i[\varphi_n(x,y) + (n-1)\cdot(2\pi/N)]\},\quad n=1,2,3\ldots \tag{7}$$

The distributions of modulation $M_n(x,y)$ are defined as the model of $g_n(x,y)$:

$$M_n(x,y) = \mathrm{abs}[g_n(x,y)] = \frac{1}{2}R_n(x,y)B(x,y),\quad n = 1,2,3,\ldots \tag{8}$$

Here the modulation information of deformed fringe patterns includes reflectivity distribution $R_n(x,y)$ and grating contrast distribution $B(x,y)$. $B(x,y)$ can be regarded as a constant if the projected grating is of good uniformity. The reflectivity of object and reference plane is different, so the modulation can distinguish the measured object from the reference plane easily. Therefore, we can use modulation of the object as a template to mark the movement of the object. Fig. 2(a) shows the measured object "Mickey", Fig. 2(b) and (d) shows the first and third deformed patterns and Fig. 2(c) and (e) shows the corresponding modulation distributions.