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Letter

A convenient look-up-table based method for the compensation of non-linear error in digital fringe projection

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HIGHLIGHTS

- The theoretical analysis of the nonlinear errors in digital fringe projection is deduced.
- The LUT is made from measured phase map without extra calibration experiment.
- The process of algorithm is convenient to be applied in real-time digital fringe projection.

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ABSTRACT

Although the structured light system that uses digital fringe projection has been widely implemented in three-dimensional surface profile measurement, the measurement system is susceptible to non-linear error. In this work, we propose a convenient look-up-table-based (LUT-based) method to compensate for the non-linear error in captured fringe patterns. Without extra calibration, this LUT-based method completely utilizes the captured fringe pattern by recording the full-field differences. Then, a phase compensation map is established to revise the measured phase. Experimental results demonstrate that this method works effectively.

Advanced composite materials are becoming more and more widely used in the aerospace field in equipment such as radar antenna arrays and airfoils. Since these structures work in different types of specialized conditions, an increasing demand exists for their deformation details with respect to their location in large areas, on a small scale, and with the need for high precision. In recent decades, these requirements have prompted the rapid development of optical non-contact three-dimensional (3D) surface profile methods [1–8]. Of these methods, digital fringe projection (DFP), which uses phase extraction and image processing, has been extensively investigated and is considered to be one of the most effective techniques for 3D shape measurement. Figure 1 shows a schematic diagram of a typical DFP-based measurement system [9–11].

A digital projector is used to project a simulated fringe pattern on the measured surface; then, the reflected light, whose intensity is modulated by the shape of the measured surface, is captured by a digital charge-coupled device (CCD) camera. In our measurement system, we employ a phase-shifting technique to calculate the phase as

$$\varphi = \arctan\left(-\frac{\sum I_i \cdot \sin a_i}{\sum I_i \cdot \cos a_i}\right), \quad (1)$$

where I_i is the light intensity of the captured image, i denotes the image sequence number, and a_i is the phase shift. Here, the non-linear error plays a key role in affecting the DFP. Digital devices, such as complementary metal–oxide semiconductor (CMOS) cameras, CCD cameras, and digital projectors, are manufactured to be non-linear to achieve a better visual effect; thus, the phase error is often introduced during the deformation from the ideal sinusoidal to non-sinusoidal fringe patterns. In optical measurement, digital devices are becoming indispensable. As such, the non-linear error is inevitable in most measurement results.

Various efforts have been made to diminish this non-linear error. Pan et al. reported that the phase error originated from the non-sinusoidal waveforms and suggested that a Fourier series could be used to decompose the captured images in different-order harmonics, and then, an iterative phase compensation algorithm be applied to compensate for the non-linear error [5]. Hoang et al. first used a universal phase-shifting technique

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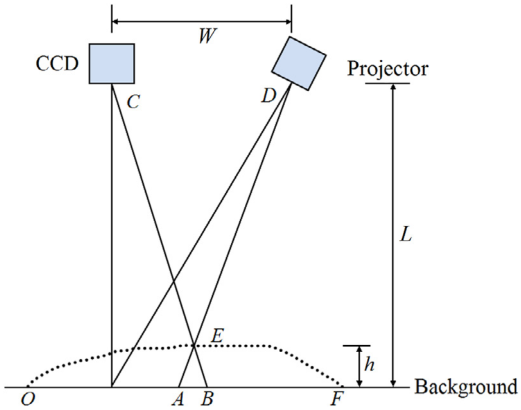

Fig. 1. Schematic diagram of DFP measurement system.

to detect the gamma value and then pre-encoded the measurement setup. Using the new light intensity, an accurate measurement result could be achieved [7]. Other researchers have also conducted work related to the calibration of gamma non-linearity [12–14]. Surrel believed the error could be alleviated by a number of phase-shifting fringe patterns [15]. To diminish the phase error in DFP, Huang et al. proposed a new phase-shifting algorithm (double three-step algorithm) [16], and both the theoretical and experimental results showed that the algorithm could work effectively. A method based on amplitude modulation was proposed by Gai and Da [17], which can identify the fringe order by the fringe pattern's amplitude, and reasonable results were obtained. Zhang and Huang proposed a method based on three-step phase shifting to compensate for the measured phase, and its key step was to establish an error compensation table called a look-up-table (LUT) [6]. This method has proven to be generic for the arbitrary step phase-shifting technique, and an easier-operating LUT-based method in DFP measurement could be proposed, wherein a uniform flat surface board is used to calibrate the non-linear error rather than conducting a pre-calibration of the monotonic gamma values of the projector [18]. Some other related works may also be found in Refs. [19–23]. For example, Schwider et al. mathematically discussed the historical development of different algorithms for error-compensating phase-shifting [22]. Zhou et al. claimed that errors arose from both non-linear gamma values and the ratio of the intensity modulation; thus, ambient light was considered in their compensation method [23].

In this study, we developed a convenient way to realize the LUT-based phase compensation algorithm, which fully utilizes the data information in the measured phase map. The non-linear error is directly extracted from the phase map rather than calibrating a uniform flat surface board using a set of fringe images. Thus, we can easily realize this method through programming. The experimental results showed that errors were reduced by a factor of ten. This convenient method has good potential for real-time DFP measurement applications. We first describe our study of the characteristics in DFP images and then detail the procedure of constructing a phase compensation map. Next, we provide our experimental results, followed by a discussion of these results.

We performed a simple experiment to analyze the non-linear error, and the obtained results are illustrated in Fig. 2.

Figure 2(a) is an experimental fringe pattern captured by a CCD camera. The grayscale distribution of the red line (including several fringe periods) in Fig. 2(a) is shown in Fig. 2(b), which indicates that the grayscale distribution of the fringe pattern has become non-sinusoidal. The red and blue lines in Fig. 2(c) denote the ideal and real captured grayscales' responses to the projected grayscale of the red line in Fig. 2(a), respectively. In Fig. 2(d), the red and blue lines are the ideal linear and real measured phases calculated from the short green line (including one intact fringe period) in Fig. 2(a), respectively. This shows that the distribution of the measured phase in one intact fringe period was not linear. Therefore, the projection and capture procedures directly lead to unwanted grayscale changes in the captured fringe pattern, resulting in a non-linear distribution in the acquired phase. In the following, we provide a theoretical analysis.

Typically, we can express the captured image from a DFP as

$$I^{\gamma}_{\mathrm{n,c}} = \alpha M^{\gamma}[1 + p \cdot \cos(\phi + \delta_{\mathrm{n}})]^{\gamma}, \tag{2}$$

where α is the modulation constant that controls the intensity range, M is the average intensity that has been normalized, γ describes the non-linear error owing to the DFP system, $p = M/N$ is the ratio of the average intensity to the intensity modulation (N is the intensity modulation), ϕ is the phase to be measured, and δ_{n} is the phase shift. By applying $(1+x)^t = \sum_{m=0}^{\infty}[(t/m)x^m]$ (the binomial series), Eq. (2) can be expressed as

$$I^{\gamma}_{\mathrm{n,c}} = \alpha M^{\gamma} \sum_{m=0}^{\infty} \left[\binom{\gamma}{m} p^m \cdot \cos^m(\phi + \delta_{\mathrm{n}}) \right]. \tag{3}$$

Then, we use a cosine power function to expand Eq. (3) as

$$I^{\gamma}_{\mathrm{n,c}} = A + \sum_{k=1}^{\infty} B_k \cdot \cos[k(\phi + \delta_{\mathrm{n}})], \tag{4}$$

where $B_k = 2M^{\gamma} \sum_{m=0}^{\infty} b_{k,m}, A = 0.5B_0, b_{k,m} = (0.5p)^{2m+k} \binom{\gamma}{2m+k} \binom{2m+k}{m}$.

To accurately analyze the non-linear error, we only study the harmonic waves for $k \le 8$, because the harmonic wave with a higher order is small enough to be ignored. Four-step phase shifting is used in our system, and then, the non-linear error can be derived from Eq. (4) as

$$\Delta\phi = -\arctan \frac{q \cdot \sin 4\phi - r \cdot \sin 4\phi + s \cdot \sin 8\phi}{1 + q \cdot \cos 4\phi + r \cdot \cos 4\phi + s \cdot \sin 8\phi}, \tag{5}$$

where $q = B_3/B_1$, $r = B_5/B_1$, and $s = B_7/B_1$. Using Taylor expansion of Eq. (5), it could be derived as

$$\Delta\phi \approx (-q + r + rs) \cdot \sin 4\phi + \left(\frac{q^2}{2} - \frac{r^2}{2} - s \right) \cdot \sin 8\phi + qs \cdot \sin 12\phi + \frac{s^2}{2} \cdot \sin 16\phi. \tag{6}$$

Since we have $r \ll q$ and $s \ll q$, r and s can be ignored. The non-linear error can finally be described as

$$\Delta\phi \approx -q \cdot \sin 4\phi + \frac{q^2}{2} \cdot \sin 8\phi. \tag{7}$$

We can conclude from Eq. (7) that the non-linear error depends only on the ratio q and measured phase ϕ.

To realize the proposed LUT, two types of phases are introduced. One is the measured phase containing the error (blue line in Fig. 2(d)) owing to the phase-shifting technique. The other is the true phase that is defined to describe the phase in the sinusoidal fringe. The true phase (red line in Fig. 2(d)) can be calculated from the intact fringe patterns (distributed linearly in the intact fringe) being projected. During the digital image processing, a true phase $[-\pi, \pi]$ in each intact fringe is defined according to the number of pixels in the pitch. The true phase can be obtained only from the flat region where the phase is supposed to have a linear distribution, whereas the phase in the object region is not linear, since it contains shape information. The non-linear characteristics