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Phase error analysis and compensation considering ambient light for phase measuring profilometry

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ABSTRACT

The accuracy of phase measuring profilometry (PMP) system based on phase-shifting method is susceptible to gamma non-linearity of the projector–camera pair and uncertain ambient light inevitably. Although many researches on gamma model and phase error compensation methods have been implemented, the effect of ambient light is not explicit all along. In this paper, we perform theoretical analysis and experiments of phase error compensation taking account of both gamma non-linearity and uncertain ambient light. First of all, a mathematical phase error model is proposed to illustrate the reason of phase error generation in detail. We propose that the phase error is related not only to the gamma non-linearity of the projector–camera pair, but also to the ratio of intensity modulation to average intensity in the fringe patterns captured by the camera which is affected by the ambient light. Subsequently, an accurate phase error compensation algorithm is proposed based on the mathematical model, where the relationship between phase error and ambient light is illustrated. Experimental results with four-step phase-shifting PMP system show that the proposed algorithm can alleviate the phase error effectively even though the ambient light is considered.

1. Introduction

Phase-shifting based phase-measuring profilometry (PMP) is one of the most widely used approaches in non-contact 3D shape measurements for its fast speed, high reliability and high accuracy, including biomedical applications [1], human body shape measurement [2], reverse engineering [3], and quality control [4]. For phase-shifting methods, the ideal sinusoidal waveforms are commonly employed for non-ambiguous 3D reconstruction. A series of sinusoidal fringe patterns are projected onto the object surface and captured by the camera, where the phase is modulated by the object height distribution. Then, the phase distribution is calculated by analysis of the images. Thus the object shape is measured or reconstructed through phase unwrapping methods and system calibration techniques.

In practice, there are many error sources that lead to the deviation of the fringe patterns captured by the camera from ideal ones and introduce additional phase error inevitably. Generally, the nonlinear response of gamma distortion in the projector–camera pair and uncertain ambient light are considered as the dominant error sources. To improve the accuracy of PMP system, many researches have been extensively proposed on addressing the effects of gamma distortion and improving gamma model. However, up to date, the effect of ambient light is still not explicit, and most of the experiments are performed in low-illumination or dark rooms [5]. Zhang and Yau analyzed the camera image generation procedure and utilized a lookup table (LUT) to alleviate the phase error [6]. Since the nonlinearity of camera is ignored in their derivation, the ambient light is considered as an independent factor. Chen et al. proposed a phase error compensation method by using smoothing spline approximation (SSA) [7], whereas the procedure of their work is time-consuming. Pan et al. proposed an iterative method and simplified phase error to one-order [8]. This phase error model is too simple to compensate the phase error accurately. Hoang et al. presented an advanced technique which can retrieve phase from multiple optical interferograms containing intensity nonlinearity and arbitrary phase shifts [9].

Recently, the gamma model was a popular researching field. Liu et al. developed a mathematical gamma model to predict the distortion effects and established a model of the harmonic coefficients about the gamma value [10]. They considered nonlinear response of both camera and projector as a combined gamma value for the projector–camera pair. Hoang et al. proposed a gamma correction method by applying a gamma pre-encoding process [11]. Li et al. incorporated the projector defocus into Liu's model and proposed a more accurate method to calibrate system gamma value [12]. Zhang et al. improved Liu's [10] and Li's [12] work and established a universal gamma model [13]. They employed gamma pre-encoding method to eliminate

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the phase error. Since the ambient light intensity is not considered in Liu's work [10], the effect of ambient light is neglected spontaneously in the subsequent gamma correction model [13]. Zhang and Yau proposed a method to measure objects with a high variation range of surface reflectivity, by taking a sequence of fringe images with different exposures [14]. Their approach may be useful for high dynamic range scanning, but it still requires a dark environment. Waddington et al. did some research to diminish the RMS errors for variable ambient illuminance [15,16]. Their work presented a method by adjusting the maximum input gray level to an optimal trade-off point. However, their method is short of mathematical gamma model with ambient light.

Considering the technical insufficiency of these protocols, in this paper, we performed theoretical analysis to phase error model taking account of both gamma non-linearity and ambient light. It is noteworthy that, a detailed mathematical gamma model to establish the relationship between the phase error and ambient light is proposed. Consequently, several experiments are implemented to demonstrate our model, in which the phase error is accurately compensated even in uncertain ambient lighting conditions.

2. Phase error analysis

2.1. Phase error model for PMP

Mathematically, the ideal intensity of the fringe pattern in a PMP system regardless of gamma nonlinearity is expressed as

$$I_{n,p} = A^p + B^p \cos(\phi^p + \delta_n) \tag{1}$$

where A^p and B^p are user defined constants, δ_n is $2\pi n/N$ that represents the phase-shifting value, n is the index and N is the phase-shifting total amount, $\phi^p = 2\pi fx$ is user defined phase information, f is the frequency, and x is the row coordinate of a pixel in projector. Although gamma distortion brings high-order harmonic inevitably in all PMP system and un-negligible ambient light brings additional phase error, the captured fringe pattern is still in the form of sinusoidal waveform generally when the gamma value and ambient light meet specific demands [8]. Therefore, the intensity of the captured fringe pattern could be expressed as

$$I^{\gamma}_{n,c} = \alpha[M + N \cos(\phi + \delta_n)]^{\gamma} \tag{2}$$

where the term α is a modulation constant controlling the intensity range, γ is the combined gamma value for the projector–camera pair, ϕ is the phase information corresponding to the desired object, M and N are normalized average intensity and intensity modulation respectively, which are related to the factors including reflectivity, uncertain ambient light, sensitive constant of the camera and gamma value of the projector. When the ambient light is not considered, the term M and N are equal to their initial values (0.5, in general) [10]. However, M and N may often vary as the ambient light exists in any case. Thus the actual phase derived from Eq. (2) should contain inevitable phase error related to the factors above.

To analyze the relationship between phase error and uncertain ambient light, we rewrite Eq. (2) as

$$I^{\gamma}_{n,c} = \alpha M^{\gamma}[1 + p \cos(\phi + \delta_n)]^{\gamma} \tag{3}$$

where $p = N/M$ is the ratio of intensity modulation to average intensity. Subsequently, the binomial series $(1+x)^t = \sum_{m=0}^{\infty} [(t/m)x^m]$ is applied to Eq. (3) whether gamma value is an integer or not, so that it is expressed as

$$I^{\gamma}_{n,c} = \alpha M^{\gamma} \sum_{m=0}^{\infty} \left[\binom{\gamma}{m} p^m \cos^m(\phi + \delta_n) \right] \tag{4}$$

According to the cosine power formulas, Eq. (4) can be expressed as

$$I^{\gamma}_{n,c} = A + \sum_{k=1}^{\infty} \{B_k \cos[k(\phi + \delta_n)]\} \tag{5}$$

$$B_k = 2M^{\gamma} \sum_{m=0}^{\infty} b_{k,m} \text{ and } A = 0.5B_0 \tag{6}$$

In addition,

$$b_{k,m} = (0.5p)^{2m+k} \binom{\gamma}{2m+k} \binom{2m+k}{m} \tag{7}$$

where k is a non-negative integer.

According to the binomial series, $B_k = 0$ when $k > \gamma$ if γ is an integer and $\gamma \geq 1$. On the contrary, B_k is a summation of infinite series if γ is not an integer, and the value of B_k is not divergent [10]. Fig. 1 shows the absolute value of B_k when $M = 0.5$, $\gamma = 2.2$, and $p = 1$, 0.8, and 0.6.

As shown in Fig. 1, B_k decreases dramatically with the increase of k no matter what the value of p is. The uppermost line describes the situation regardless of the ambient light where p maintains its initial value of 1 that is defined in most PMP systems generally. Furthermore, there is a noticeable difference when p is varied corresponding to varied ambient light.

To analyze the phase error model accurately, the harmonic waves up to the eighth-order are considered. For the four-step phase-shifting method (i.e., $n = 1$–4), the phase error can be derived from Eq. (5) as

$$\Delta\phi \approx -\arctan\frac{q\sin4\phi - r\sin4\phi + s\sin8\phi}{1 + q\cos4\phi + r\cos4\phi + s\cos8\phi} \tag{8}$$

where q, r, and s is B_3/B_1, B_5/B_1, and B_7/B_1 respectively. Writing the Taylor expansion of Eq. (8) around $q, r, s = 0$ we obtain

$$\Delta\phi \approx (-q + r + rs)\sin4\phi + \left(\frac{q^2}{2} - \frac{r^2}{2} - s\right)\sin8\phi + qs\sin12\phi + \frac{s^2}{2}\sin16\phi \tag{9}$$

Since $r \ll q$, $s \ll q$, the phase error has a simplified form if r and s are ignored.

$$\Delta\phi \approx -q\sin4\phi + \frac{q^2}{2}\sin8\phi \tag{10}$$

By setting $d\Delta\phi/d\phi = 0$, the maximum phase error of the four-step phase-shifting method can be derived as

$$\Delta\phi_{\max} = \frac{1}{16}\sqrt{(w+3)^3(w-1)} \tag{11}$$

where $w = \sqrt{8q^2 + 1}$.

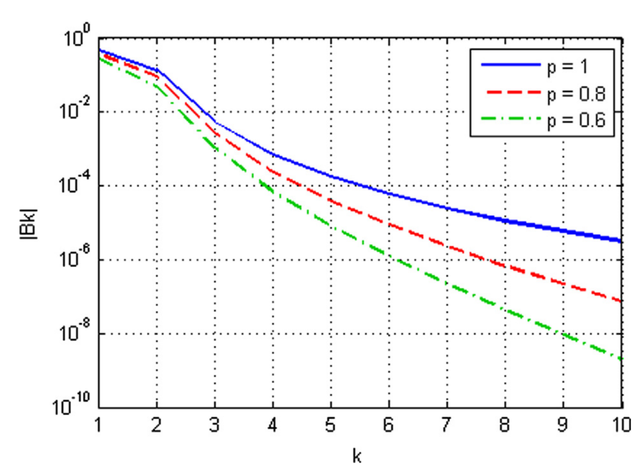

Fig. 1. The absolute values of B_k in different conditions.