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Digital fringe image gamma modeling and new algorithm for phase error compensation

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ABSTRACT

Sinusoidal phase error caused by gamma distortion is the dominant error source in phase measurement profilometry. Considering the gray saturation and defocus of captured image, we developed a new gamma model deduced from binomial and Fourier series expansion. The compensation model eliminates the phase error virtually and improves the applicability of gamma model error compensation. The experimental results show that the method is superior to traditional algorithms.

1. Introduction

Optical non-contact 3D shape measurement techniques are developed to obtain 3D contours. With recent advancement in digital display technology, 3D shape measurement based on digital projection units is rapidly expanding [1,2]. However, developing a system with an off-the-shelf projector, such as liquid crystal display and digital mirror device, for high-quality 3D shape measurement remains challenging. Ideally, the gray value of encoded fringe image captured by camera should meet sinusoidal characteristics, but in reality the grating image has distortions caused by manufacturing errors of projector models, projection adjustment, and commercial visualization linear gamma. The computed phase is also inaccurate with stripe images, which must be compensated to ensure the accuracy of 3D measurement.

The phase error factors include the following categories: saturation error, which refers to the error in which the input and output luminance of a projector no longer changes and remains in a value when brightness reaches a certain threshold (Fig. 1); quantization error, which includes intensity and spatial quantization errors in which the intensity data are continuous but the spatial data are discrete; and gamma nonlinear error, which refers to the nonlinear relationship between the input and output gray values of digital projector but with approximate exponential distribution, as shown in Fig. 2 [1]. One of the major issues in systems is the nonlinear response of the projection engines of projectors [1–4].

The literature on phase error is divided into three categories, namely, harmonic compensation methods [4], phase-shifting compensation methods [1–3,5,14], and gamma model compensation methods [6–18]. The gamma model compensation methods are currently a significant and challenging research focus. Literature [6] stated that nonlinear gamma introduced higher-order correlation coefficient of frequency domain and used a double coherent and multi-frequency analysis method to minimize the influence of the nonlinear gamma. Literature [8] used the lookup method to compensate the saturation error and obtain desired sinusoidal stripes and phases. The detailed analysis and experimental results demonstrate that the resolution matching between camera and projector influences the phase error. .Guo [9] used the normalized histogram method to calculate gamma value and compensate phase error. Huang [7] used a dual three-step phase-shifting method to compute the phase based on error distribution characteristics. Zhang [10] and Huang [11] proposed a lookup-table (LUT) compensation method in 2005. In this method, a series of gray image levels is used to calibrate a gamma nonlinear curve. The gamma curve is used to simulate projected structured light, and a phase–phase error LUT is then generated. The correspondence between phase and error is used to compensate the actual measured phase. Zhang and Yau [12] developed an improved algorithm, which reduced the error to 1/13 of uncompensated. Jia [13,14] proposed a method similar to the double-step phase-shifting method to remove the error caused by gamma. Zhongwei [16] improved measurement accuracy by 5.6 times with the LUT method proposed by Zhang [12]. Shaoyan [17] presented a

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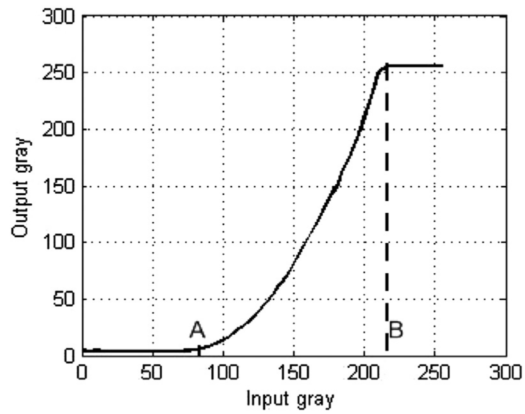

Fig. 1. Saturation error.

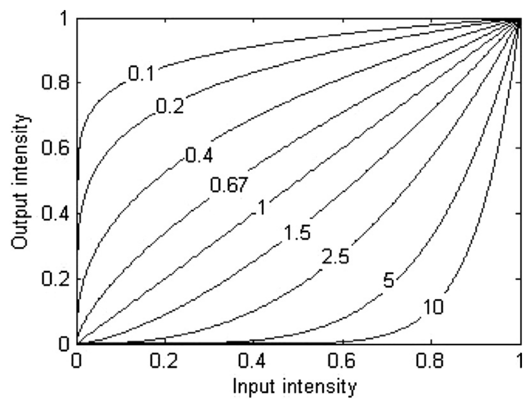

Fig. 2. Different gamma curve.

method that compensated the projected stripes instead of the phase, and adjusted the gray of the input-coded, structured light so that the captured stripe images would satisfy standard sinusoidal coding. The calibration procedure is highly complex. Bing [18] indicated that the distortion of projected sinusoidal coding stripes included only five time harmonics, derived an error mathematical model with Fourier series expansion, and established a more unified, automatic compensation method. Kai [20] also established a mathematical model of gamma with mathematical theory and developed two-phase error compensation methods with and without gamma calibration. The proposed method reduced the phase error to the original 1/33 and 1/60. A good result was achieved, but the error model did not consider the effect of actual ambient light. Zhongwei [21] introduced a defocus factor that considered the projector defocus based on the method of Liu [20] and achieved a more true gamma. The method considered the defocus effect but not the Gaussian function stripe width effect. Christopher [19] studied the effect of lighting and stripe gray gradation on measurement accuracy, and found that the measurement error maintained a certain range without saturation as well as provided suitable gray gradation and scope, which had experimental significance to error compensation.

The gray value of an image captured by a camera is affected by the reflectivity of the object, camera aperture, coding light cycle, Gaussian smoothing, and other factors. The Gaussian smoothing effect exists in the entire measurement process. Defocus exists in the depth direction of the camera, and the projected stripes are also smoothed by the Gaussian technique. Gaussian smoothing remains although the camera and projector are in a focused state. The projection optical Gaussian smoothing effect perpendicular to optical axis is the main cause of gamma error. The Gaussian smoothing effect can be reduced effectively with increasing coding light cycle, but the reduction causes the captured image to saturate. This paper presents a new gamma model to quantify the effect of Gaussian smoothing factor perpendicular to the optical axis plane of projection to gamma and prevent the gray saturation phenomenon.

2. Gamma model for phase measurement profilometry (PMP)

In various structured light illumination implementations, PMP is employed because of its robustness and depth accuracy. The gray value of image captured by camera generally has the following characteristics: the middle range of gray level (0–255) changes linearly, and both ends of the gray scale are relatively flat. The plot of the gray curve is shown in Fig. 1. The phenomenon is caused by the sensitivity of the camera and saturation. To eliminate or reduce this phenomenon, a pixel of the projected PMP pattern is changed into

$$I_n^p = A_p + B_p \cos\left(\phi - \frac{2\pi n}{N}\right) = 2A_p\left[0.5 + 0.5\frac{B_p}{A_p}\cos\left(\phi - \frac{2\pi n}{N}\right)\right], \quad (1)$$

where ϕ is the phase of the row coordinates of a pixel in the projector, I_n^p is the light intensity of the pixel, A_p and B_p are the user-defined constants, $A_p \neq B_p$ means that the gray value of the projected image is limited to a range of $\left(\left[A_P + B_P \quad A_P - B_P\right]\right)$, f is the frequency of sine