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Adaptive projection intensity adjustment for avoiding saturation in three-dimensional shape measurement

Chao Chen [a], Nan Gao [a], Xiangjun Wang [b], Zonghua Zhang [a,c,*]

[a] School of Mechanical Engineering, Hebei University of Technology, 300130 Tianjin, China
[b] State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072, China
[c] Centre for Precision Technologies, University of Huddersfield, Huddersfield, HD1 3DH, UK

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ABSTRACT

Phase-based fringe projection methods have been commonly used for three-dimensional (3D) measurements. However, image saturation results in incorrect intensities in captured fringe pattern images, leading to phase and measurement errors. Existing solutions are complex. This paper proposes an adaptive projection intensity adjustment method to avoid image saturation and maintain good fringe modulation in measuring objects with a high range of surface reflectivities. The adapted fringe patterns are created using only one prior step of fringe-pattern projection and image capture. First, a set of phase-shifted fringe patterns with maximum projection intensity value of 255 and a uniform gray level pattern are projected onto the surface of an object. The patterns are reflected from and deformed by the object surface and captured by a digital camera. The best projection intensities corresponding to each saturated-pixel clusters are determined by fitting a polynomial function to transform captured intensities to projected intensities. Subsequently, the adapted fringe patterns are constructed using the best projection intensities at projector pixel coordinate. Finally, the adapted fringe patterns are projected for phase recovery and 3D shape calculation. The experimental results demonstrate that the proposed method achieves high measurement accuracy even for objects with a high range of surface reflectivities.

1. Introduction

Phase-based fringe projection techniques have been widely investigated in academia and used in industrial fields because of the advantages in their full-field inspection, non-contact operation, lost cost, high accuracy, and fast data processing [1,2]. Typically, phase-shifted fringe patterns are projected onto an object. The fringe patterns are deformed on reflecting from the object's surface and captured by a camera at an oblique angle. The absolute phase map calculated from the deformed fringe patterns can be applied for establishing correspondence between a projector pixel coordinate and a camera pixel coordinate in a structured light system [3,4]. Alternatively, a three-dimensional (3D) image of the object can be constructed according to the relationship between the absolute phase information and depth information in a calibrated system [5]. However, image saturation is an intractable issue for fringe projection when incoming intensity exceeds the maximum number of gray levels of the camera sensor (255 for an 8-bit camera). The captured intensity value is subjected to this maximum number, causing improper intensities values in the captured fringe patterns, and ultimately bringing about phase information and inspection errors. To overcome this problem, many solutions have been proposed.

For image saturation caused by specular light reflections, composite images without saturation are generated from images captured using multiple camera viewpoints [6], multiple projector directions [7] or modified projectors [8] to measure previously saturated image regions. These methods can avoid local saturation. However, they require complex hardware and/or registration to merge multiple surface images captured using different methods. Another method can overcome image saturation by acquiring further fringe patterns and computing the phase at the same point selecting the unsaturated fringe patterns points [9,10]. However, the measurement precision of this method is limited because phase shifts which are eventually used for calculating phase information may be non-optimal.

Image saturation can be caused by broad reflectivity variation [11]. To address this, Zhang et al. [12] presented a high dynamic range imaging technique by capturing sets of phase-shifted images at different camera exposure times. They constructed composite phase-shifted images by

* Corresponding author at: School of Mechanical Engineering, Hebei University of Technology, 300130 Tianjin, China.
E-mail address: zhzhang@hebut.edu.cn (Z. Zhang).

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selecting the highest unsaturated intensities from the images at each pixel. This technique avoids saturation and improves dynamic range of measurement, but adjustment of exposure time is not quantified. Waddington and Kofman [13] proposed to solve the image saturation problem, by diminishingly changing the projected intensity. They projected fringe patterns at multiple maximum input gray levels (MIGL), aiming to fuse composite fringe-pattern images. Subsequently, Jiang et al. [14] provided a 3D scanning method combining these strategies, adjusting the projected light intensity and the camera exposure time simultaneously. A lot of exposures are applied to acquire good fringe modulation in fringe patterns. Therefore, these techniques could be time consuming. Feng et al. [15] presented a generic high-dynamic-range image projection technique in which the exposure time is predicted and polarizers are introduced to remove high intensities. These reduced intensities may lead to low signal-to-noise ratios (SNRs) for captured phase-shifted images. Although all of these techniques work well for a large range of surface reflectivities, they have two disadvantages. One is that multiple sets of fringe patterns at different maximum gray levels or exposure time must be repeatedly acquired while the process of fringe-pattern projection and image capture is complex. The other is that composite phase-shifted images cannot maintain the good fringe modulation over the measured surface, leading to decreased accuracy.

An alternative technique for overcoming image saturation is to reduce the number of images. Chen and Zhang [16] proposed combining a phase-shifting algorithm and several saturated fringe patterns. The method does not require any changes to the measurement conditions (e.g. camera exposure, projection fringe contrast), does not need any special hardware (e.g. polarization filter), or pre-knowledge of the measured object. The method adopts saturated fringes obtained from a fixed exposure time to measure a shiny object, greatly decreasing the required number of fringe patterns. However, fringe pattern number is proportional to the period of the fringe pattern. Thus to use fewer fringe patterns, the fringe pitch must be reduced, potentially increasing the difficulty in phase unwrapping if too-narrow fringes are used [17]. Li and Kofman [18] altered the local MIGL in projected fringe patterns based on the local reflectivity of an object surface. This is better than uniform reduction of the MIGL for saturated regions. Lin [19,20] proposed an adaptive modification of the illumination intensity of the projected fringe patterns to avoid image saturation. The advantage of this method is that it can illuminate locally on a pixel-to-pixel basis, by projecting adaptive patterns, rather than adjusting the camera exposure time, which is global. However, one common drawback of this method is that computing the optimal projection intensities is time-consuming procedure. Moreover, the method of generating the adapted fringe patterns uses at least two prior steps of fringe-pattern projection and image capture.

To reduce the number of projected and captured images and to maintain high measurement accuracy, an adaptive projection intensity adjustment method is proposed. The proposed method avoids image saturation and maintains high intensity modulation in measurements over a high range of surface reflectivities. This method decreases projected sets of fringe patterns by fitting a single polynomial function to transform captured intensities to projected intensities. The adapted fringe patterns are constructed using the best projection intensities at projector pixel coordinate system. The proposed method averts image saturation and possesses good fringe modulation, using only one prior step of fringe-pattern projection and image capture to construct the adapted fringe patterns. Twelve vertical and twelve horizontal sinusoidal fringe patterns along with a uniform gray level pattern are captured. The fringe patterns are used to map the camera pixel coordinate system to projector pixel coordinate system. The uniform gray level pattern is used to identify and cluster of saturated pixels.

The rest of the paper is organized as follows. In Section 2, the measurement principle of the proposed method is demonstrated in two aspects. In Section 3, the experimental setup and measurement procedure are detailed. The experimental results related to the proposed method are presented and a quantitative evaluation experiment illustrates accuracy of the proposed method. Finally, Section 4 concludes the paper.

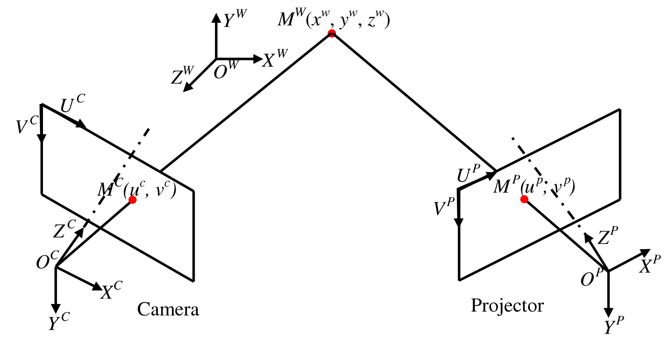

Fig. 1. The coordinate system of the phase-based fringe projection system.

2. Principle

Fig. 1 shows a coordinate system of the phase-based fringe projection system, where $(O^W; X^W, Y^W, Z^W)$ is the world coordinate system. $(O^P; X^P, Y^P, Z^P)$ and (U^P, V^P) are the projector coordinate system and its pixel coordinate system, respectively. $(O^C; X^C, Y^C, Z^C)$ and (U^C, V^C) denote the camera coordinate system and its pixel coordinate system, respectively. An arbitrary object point $M^W = (x^w, y^w, z^w)$ is projected from point $M^P = (u^p, v^p)$ in the projector image and captured at point $M^C = (u^c, v^c)$ in the camera image. The two points M^C and M^P are called a pair if they correspond to the same point M^W. Paired points have the same phase value. The correspondence relationship can be established from vertical and horizontal phase-shifted sinusoidal fringe patterns.

2.1. Absolute phase calculation and point correspondence

Four-step phase-shifting algorithm is adopted to retrieve the 3D shape of an object or to construct correspondence between the camera image and the projector image at each pixel. The intensities of the four fringe patterns $I_i(u^p, v^p)$ to be generated can be expressed as

$$I_i(\mu^p, v^p) = I_{\max}\left\{\frac{1}{2} + \frac{1}{2}\cos\left[\varphi(\mu^p, v^p) + i * \frac{\pi}{2}\right]\right\}, i = 0, 1, 2, 3 \tag{1}$$

where (u^p, v^p) is the projector pixel coordinate, $I_{\max}$ is the maximum projected light intensity. The wrapped phase $\varphi(u^c, v^c)$ can be accurately calculated as follows:

$$\varphi(u^c, v^c) = \arctan\frac{I_3(u^c, v^c) - I_1(u^c, v^c)}{I_0(u^c, v^c) - I_2(u^c, v^c)} \tag{2}$$

where (u^c, v^c) is the camera pixel coordinate. $I_i(u^c, v^c)$ represents the i th captured fringe pattern. $\varphi(u^c, v^c)$ provides the congruent phase value modulo 2π. The corresponding absolute phase can be computed from the wrapped phase using the phase unwrapping method.

The absolute phase value of a point $M^C = (u^c, v^c)$ in the camera image coordinate can be calculated by linear interpolation along the vertical and horizontal directions, denoted as $\varphi_v(u^c, v^c)$ and $\varphi_h(u^c, v^c)$, respectively. The pixel coordinates of the corresponding point $M^P = (u^p, v^p)$ in the projector image coordinate can be computed as follows:

$$\begin{aligned} u^p &= \frac{V\varphi_v(u^c, v^c)}{2\pi T} + \frac{V}{2} \\ v^p &= \frac{H\varphi_h(u^c, v^c)}{2\pi T} + \frac{H}{2} \end{aligned} \tag{3}$$

where V and H are the width and height of the projected fringe patterns. T is the largest integer number of the fringe cycle.

2.2. The adaptive fringe projection method

It is difficult to measure the 3D shape of objects containing regions with different surface reflectivities. If fringe images are projected at