Optik 162 (2018) 237–243

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Modified five-step phase-shift algorithm for 3D profile measurement

Jie Luo, Yu Wang, Xu Yang, Xiangcheng Chen*, Zihong Wu

School of Automation, Wuhan University of Technology, Wuhan, 430070, China

ARTICLE INFO

Article history:
Received 27 February 2017
Accepted 20 February 2018

Keywords:
Absolute phase measurement
Phase coding
Phase-shift
3D profile measurement
Phase unwrapping

ABSTRACT

A modified phase measurement profilometry based on five-step phase-shift algorithm, is proposed in this paper to achieve 3D profile measurement, which can not only accelerate the measurement speed, but also extend the measurement range in the same quantized level. A stair phase, used as codeword, is embedded into sinusoidal fringes, in which the sinusoidal component is used to guarantee the precision of the phase while the stair phase coding component is designed to identify the fringe orders. Fringe orders and wrapped phase distribution are calculated simultaneously, and thus absolute phase can be obtained without phase unwrapping processing, therefore, it has the potential merit of increasing the measurement speed. Moreover, this method can encode more fringe orders than composited two-frequency methods for the unwrapping processing of measurement phases map. Experiments demonstrate that this technique is robust and suitable for measuring complex objects or separated objects.

1. Introduction

The technology of optical 3D shape measurement, is widely used in many fields such as solid modeling, reverse engineering and biomedical engineering, for its high precision, non-touching, and non-damaging. Various optical techniques are used for 3D profile measurement, including light sectioning [1], time-of-flight [2], fringe projection [3], etc. Among the existing 3D shape measurement techniques, fringe projection profilometry has been increasingly used for its high precision, fast speed, full-field measurement capacity, and system simplicity.

3D sensing technology of fringe projection profilometry, actively projects some structured patterns encoded with codeword, onto the object surface, and recovers depth information by decoding the codeword. One of the most popular structured pattern is sinusoidal structured patterns, and different methods used to decode fringe patterns are called fringe pattern analysis techniques. Several algorithms have been proposed to analyze these fringe patterns, including Fourier transform profilometry [4,5], spatial phase detection algorithm [6], phase-shift algorithm [7], wavelet transform fringe analysis algorithm [8–11].

Because of speed and accuracy, phase-shift methods have become the most popular technology in optical metrology [12]. Wrapped phase are computed from several phase-shift patterns using arctangent function in the range of 0–2π. To eliminate the 2π discontinuity, phase unwrapping is necessary to obtain a smooth phase map of the object. Spatial and temporal methods, are the two mostly common methods used to realize phase unwrapping [13]. Spatial phase unwrapping

* Corresponding author.
E-mail address: chenxgcg@ustc.edu (X. Chen).

https://doi.org/10.1016/j.ijleo.2018.02.057
0030-4026/

approaches, utilizing the phase continuity and 2π jump to unwrap the phase, often fail because there are usually noises, shadows and discontinuities on a practical wrapped phase map. Different from the spatial phase unwrapping approaches, two different strategies are often employed in temporal phase unwrapping methods. The first one is combining the gray code and phase-shift method, such as gray-coding methods, binary coding methods, composite phase-shift algorithm, in which the gray code is used to obtain the period order in the entire image while phase-shift method is employed to specify the fine relative phase [7]. Zhang [14] proposed a composite phase-shift algorithm using three phased-shifted patterns and one stair pattern. Codeword work as varied intensities in this method rather than phase. Owing to the nonuniformity of surface reflectivity, each region, with different intensities on the stair image, are located by wrapped phase instead of reference stair pattern. To mitigate and reduce the influence of noise or interferences, Wang [15] proposed a phase-coding method for absolute phase measurement, which needed three extra patterns to mark the fringe order. On the basis of the above research, Zheng [16] proposed a phase-coding method for absolute phase which can generate more than 64 codewords by using six additional fringe images. There are also some methods based on the multiple-wavelength phase-shift method [17–21], in which the phase-shift patterns with no less than two different wavelengths are projected on to the measured object in sequence, so that it can unwrap phase pixel by pixel independently in the whole image. However, the common drawback of the above two strategies is the increased number of required patterns, which means that the measurement speed will be sacrificed.

To raise the measurement speed, many studies about the composited two-frequency methods used in phase-shift algorithm are proposed. Li [22] presented a method that merged two frequencies of fringe patterns on one grating, and using $2N\,(N = 3, 4, 5\ldots)$ phase shift method to calculate the high-frequency phase and low-frequency phase separately. Liu [18] proposed a dual-frequency pattern which combines a high-frequency sinusoid component with a unit-frequency sinusoid component, where the high-frequency component is used to generate robust phase information, and the unit-frequency component is used to reduce phase unwrapping ambiguities. In the above methods, there are problems of frequency aliasing which may reduce the phase quality. In order to guarantee the measurement accuracy, the amplitude of high frequency gratings is often larger than that of low-frequency gratings, which means if the value of high-frequency is more than five times of low-frequency, there might be errors in the process of phase unwrapping. Therefore, there is an urgent need to extend the number of the coded fringes when the composited patterns are used for 3D profile measurement.

In this paper, we propose a modified phase-coding method based on phase-shift algorithm, which can not only accelerate the measurement speed, but also extend the measurement range in the same quantized level. Sinusoidal fringes are applied for keeping the accuracy of the phase and phase-coding stair fringes are used as codewords for identifying the fringe orders. By integrating the sinusoidal component and phase-coding component into a single pattern, only five patterns are needed, and there are no additional codeword patterns.

The paper is organized as follows: Section 2 explains the principle theory of proposed method; Section 3 shows the experimental results; and finally Section 4 concludes this paper.

2. Theory

2.1. N-step phase-shift algorithm

Phase-shift methods are widely used in optical metrology for their speed and accuracy [12]. In general, for N-step phase-shift methods, the fringe images can be mathematically described as:

$$I_n(x, y) = A(x, y) + B(x, y)\cos\left(\phi - 2\pi n/N\right) \tag{1}$$

where $n = 1, \cdots, N$; $A(x, y)$ is the average intensity; $B(x, y)$ is the intensity modulation of the measurement fringe which is used to detect the object surface from the background, and $\phi(x, y)$ is the phase to be solved for. Through solving Eq. (1), we can obtain:

$$\phi(x, y) = \tan^{-1}\left[\frac{\sum_{n=1}^{N} I_n \sin\left(2\pi n/N\right)}{\sum_{n=1}^{N} I_n \cos\left(2\pi n/N\right)}\right] \tag{2}$$

The equation provides the wrapped phase ranging $[0,\ 2\pi)$ with 2π discontinuities. The 2π phase jumps can be removed to obtain a continuous phase map by adopting a phase unwrapping algorithm [23]. Specifically, the unwrapping is to determine fringe order, integer $k(x, y)$, so that:

$$\Phi(x, y) = \phi(x, y) + 2\pi k(x, y) \tag{3}$$

Here, $\Phi(x, y)$ is the unwrapped absolute phase. Robust phase unwrapping is usually very time-consuming because it involves a lot of computation as well as iterations. In this condition, many absolute phase measurement methods were proposed recently [14,15,24–27].