Measurement 45 (2012) 101–108

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A flexible phase-shifting method with absolute phase marker retrieval

Haihua Cui *, Wenhe Liao, Ning Dai, Xiaosheng Cheng

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics & Astronautic, 29 Yudao Street, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 4 March 2011
Received in revised form 30 May 2011
Accepted 18 September 2011
Available online 28 September 2011

Keywords:
Phase-shifting
Absolute phase marker
Phase measurement
3D shape measurement

ABSTRACT

The phase-shifting algorithm is an important and widely employed technology in optical 3D shape measurement. An additional absolute phase marker map is necessary to acquire the absolute phase with traditional phase-shifting algorithm, which not only has a low efficiency but also may not meet certain special requirements of the practical application. In this study, a flexible phase-shifting method, which does not need the additional absolute phase marker map, was developed. A newly designed absolute phase marker was embedded into one of the phase fringe images, and this was retrieved according to its mathematical model; then, the primary phase inside and outside the absolute phase marker region was computed with different methods. Results of experiments show that the retrieval of the marker is easy and flexible, and the phase computation with this novel method is accurate and robust.

1. Introduction

Structured 3D shape-measurement techniques have been widely applied in various fields, such as in manufacturing, healthcare, computer science, family safety, and digital entertainment [1]. With advancements in technology, higher efficiency of 3D measurement constitutes a new requirement for most applications for measurement. Therefore, a new area of focus for research involves the reduction of numbers of the projected coding fringe image and improvement of the coding efficiency. A variety of techniques have been developed, including the three-step phase-shifting method [2,3], four-step phase-shifting method [4], single color phase-shifting method [5], trapezoidal phase-shifting method [6], Fourier phase method [7], area-encoded algorithm [8], defocused binary pattern algorithm [9] and so on. The four-step phase-shifting method is a widely studied and frequently employed method because of its high stability and superiority. However, it needs an additional absolute phase marker map to solve the complete phase map, and this not only reduces the efficiency of the phase-shifting algorithm but also cannot fulfill certain special needs in practical application.

It is well known that the phase-shifting algorithm based on space is a relative phase solution. The computed phase is a relative value that is based on the pixel phase of its neighbor [10]. The acquired phase needs to be transformed into an absolute phase value for the 3D measurement [5]. The addition of an additional absolute phase marker map is a common method [5]. In case of an inability to embed the absolute phase map into a coded fringe image, the number of projected fringe images can be reduced and the efficiency of the phase-shifting method can be improved. Several researchers have undertaken in-depth studies of this problem, and to the general need is to identify a flexible method that cannot only embed the absolute phase marker but also can acquire the accurate absolute phase without affecting the marker pattern. Zhang and Yau [5] developed a method which embeds a tiny cross marker into sinusoidal fringes. The marker is detected automatically based on the gamma map. However, this method is, in general, difficult, especially when the image is blurred and very sensitive to image noise. Guo and Huang [11] have also developed a method for absolute phase retrieval. A cross-shaped marker is set and detected based on edge detection in image-processing technology.

* Corresponding author. Tel.: +86 2584895881; fax: +86 2584891701.
E-mail address: cuihh816@gmail.com (H. Cui).

0263-2241/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.measurement.2011.09.014

This method is sensitive to the object's surface reflectivity, and this significantly limits the application of the method. For the same purpose, Su [8] developed a structured pattern in which the sinusoidal fringes are encoded with both binary stripes and colorful grids. The accuracy of the edge detection is also important to this pattern. Su and Zhang [7] also developed a method to embed a special absolute phase marker into sinusoidal gratings. The mark is detected based on the principle that the orientation of the Fourier spectra of the mark is perpendicular to that of the sinusoidal fringe. This method is novel, but it cannot be universally applied. In addition, the detection accuracy of the mark with Fourier transformation is limited. Gai and Da [12] added a strip marker in the projecting fringe, and then detected the strip marker to obtain the absolute phase based on stripe modulation. Although this method can solve the problem as stated by the author, the modulation with three fringes and the marker is very sensitive to the quality of the image.

To resolve this problem, in this study, these authors propose a novel phase-shifting method. First, we designed a novel absolute phase marker and embedded the marker into one of the projecting fringes. Then, based on its mathematical model, the marker is detected accurately. Finally, the phase values of the marker's internal and external regions are solved, respectively, and the absolute phase map of the entire view is obtained. Compared with conventional methods, the present method has several advantages: (1) this method has high efficiency because it does not need the additional phase marker map; (2) the detection of the embedded marker is relatively easy; (3) the calculation of phases of the marker's internal and external regions is not sensitive to the edge of the marker region; and (4) the marker style in this novel method is unrestricted, and therefore, it can provide more ordered information for a still-connected surface or disconnected patches.

The remainder of this article is structured as follows: In Section 2, the principle of this new method is introduced; Section 3 describes the verification experiment; Section 4 provides discussion with regard to this method; and Section 5 presents a conclusive summarization of the findings in this work.

2. Principle

Structured light 3D measurement is a non-contact optical measurement method based on the active triangulation method. A projector projects high-robustness sinusoidal phase fringes, and then the object space is divided into numerous measurement regions with a unique phase-shifting code. The coordinates of the object can be computed by using the triangular geometric relation [1]. The specific schematic is shown in Fig. 1.

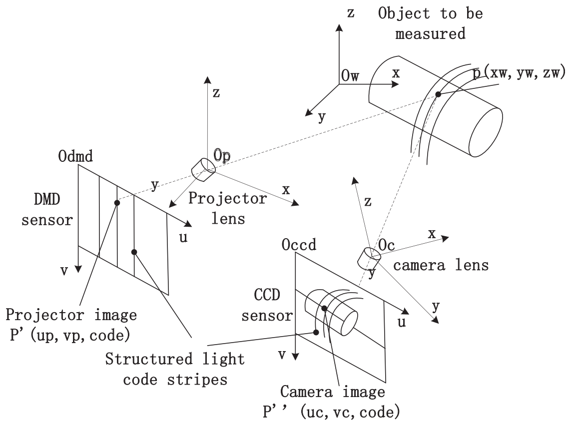

Fig. 1. The system structure of 3D measurement.

2.1. Traditional multi-step phase-shifting algorithm

The phase-shifting technology is a general technique employed to deal with the fringe image. It relies on the consecutive illumination of the test object with phase-shifting sinusoidal fringes and recording of the fringes by a charge-coupled device (CCD) camera at each illumination step. Several different phase-shifting algorithms have been developed previously. The general form of these algorithms is the least square algorithm. Let us assume that a total of N phase-shifted fringe images, each with a phase shift of $\phi_i (i = 1, 2, \ldots, N)$ are captured. Then, the intensity of the ith image can be represented as:

$$I_i(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \phi_i], \quad (i = 1,2,\ldots,N) \tag{1}$$

where $I_i(x,y)$ is the intensity value of pixel (x,y) in the ith fringe image, $I'(x,y)$ is the average intensity, $I''(x, y)$ is the intensity modulation and $\phi(x,y)$ is the primary phase which is to be determined. When the phase $\phi_i = \pi/2$ and $N = 4$, by applying the conventional four-step phase-shifting algorithm, the primary phase can be computed:

$$\phi(x,y) = \tan^{-1}\frac{I_4 - I_2}{I_1 - I_3} \tag{2}$$

It is well known that there are three unknowns in Eq. (1); therefore, the primary phase can also be obtained with three fringe images. By using the 2–4 fringe images of the four-step phase-shifting algorithm, the phase can be expressed as:

$$\phi(x,y) = \tan^{-1}\frac{I_4 - I_2}{I_2 + I_4 - 2I_3} \tag{3}$$

where $\phi(x, y)$ is called the primary or wrapped phase, which represents the discontinuous phase value that ranges in $(0, 2\pi]$. To obtain the continuous phase, the primary phase needs to be unwrapped with phase-unwrapping algorithms [10]. The unwrapped phase is a relative value; therefore, it cannot be applied for matching between the camera pixel and projector pixel, and, then, for computing 3D coordinates [5]. An absolute phase marker is required to mark the absolute order of the strips and to transform the relative phase to absolute phase.