Optics and Lasers in Engineering 107 (2018) 28–37

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Absolute phase retrieval methods for digital fringe projection profilometry: A review

Song Zhang

School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, USA

ARTICLE INFO

Keywords:
Phase unwrapping
3D shape measurement
Structured light
Fringe projection
Absolute phase

ABSTRACT

This paper provides a review for absolute phase recovery methods that are applicable for digital fringe projection (DFP) systems. Specifically, we present two conventional absolute phase unwrapping methods: multi-frequency or -wavelength phase-shifting methods, and hybrid binary coding and phase-shifting methods; and also introduce some non-conventional methods that are specific for DFP systems: multiview geometry methods with additional camera(s) or projector(s), DFP system geometric constraint-based phase unwrapping method, and pre-knowledge (e.g., computer-aided-design, CAD, model) based phase unwrapping method. This paper also briefly overviews hybrid methods including phase coding, composite, and pre-defined markers based absolute phase unwrapping methods. This paper explains the principle behind each individual absolute phase unwrapping method; and finally offers some practical tips to handle common phase unwrapping artifact issues.

1. Introduction

Three-dimensional (3D) optical shape measurement becomes increasing important due to the ever-growing analytic capabilities of personal computers and nowadays even mobile devices. As a non-contact and remote sensing means, the real-time 3D optical shape measurement techniques have the great potential to be an integrated part of intelligent systems (e.g., machines, robots) [1], as well as to be a novel sensing means for human–machine or human–computer interactions [2].

Digital fringe projection (DFP) based 3D optical shape measurement techniques draw significant interests in various fields because of the flexibility of fringe generation nature, relatively inexpensive and easy setup, and the facilitation by affordable digital-light-processing (DLP) developmental kits [3]. For all DFP-based 3D shape measurement techniques, phase unwrapping is critical since only wrapped phase ranging from $-\pi$ to $+\pi$ can be obtained through analyzing fringe pattern(s) either using a phase-shifting algorithm [4] or a Fourier transform method [5,6]. To unwrap phase, 2π discontinuous locations have to be identified and removed by adding or subtracting multiple integer numbers of 2π. The number of 2π to be added to a point (x, y) is often called fringe order $k(x, y)$. Essentially, phase unwrapping is to determine $k(x, y)$ for each point such that the wrapped phase can be properly unwrapped.

Although numerous phase unwrapping algorithms have been developed, conventional phase unwrapping methods can be classified into two categories: spatial phase unwrapping and temporal phase unwrapping. The former methods unwrap the phase by referring phase values of other points on the same phase map through a local or global optimization. The book edited by Ghiglia and Pritt [7] summarized a number of spatial phase unwrapping methods. Due to the existence of noise, surface reflectivity variations, and other factors, spatial phase unwrapping can be very challenging. Despite recent advancements, robustly unwrapping the entire phase map is still very challenging if the phase data is very noisy. One of the most popular, robust and efficient spatial phase unwrapping methods is to use a quality map to guide the unwrapping path. The basic idea of quality-guided phase unwrapping is that higher quality phase points are unwrapped before lower quality phase points such that the error will not propagate to a lot of points. Su and Chen [8] reviewed a number of robust quality-guided phase unwrapping algorithms, and Zhao et al. [9] compared different strategies of generating a quality map for robust phase unwrapping. Regardless the robustness of a spatial phase unwrapping algorithm, it is fundamentally limited by the surface *smooth* assumption: the object surface has to be smooth to at least one unwrapping path such that the object surface geometry will not introduce more than π phase changes between two successive points. In general, spatial phase unwrapping only provides a relative phase map for a smoothly connected patch. In other words, the recovered shape from a spatially unwrapped phase map is relative to a 3D point on the surface. The absolute position between different smooth patches cannot be recovered.

Temporal phase unwrapping, in contrast, determines fringe order $k(x, y)$ per point based on analyzing additionally acquired information at a temporally different time. In this method, fringe order is determined

---

E-mail address: szhang15@purdue.edu

https://doi.org/10.1016/j.optlaseng.2018.03.003
Received 29 January 2018; Received in revised form 1 March 2018; Accepted 5 March 2018

from additionally acquired information without requiring the knowledge of phase values of other points on the phase map, and thus a temporal phase unwrapping method typically yields the absolute fringe order and the unwrapped phase is absolute. Conventional temporal phase unwrapping methods (e.g., two and multi-wavelength phase-shifting algorithms [10,11]) originated from laser interferometry can be directly applied to DFP profilometry. For a noise-free system, a two-wavelength phase-shifting algorithm theoretically works well, yet a practical measurement system always has noise and thus multi-wavelength phase-shifting algorithm is typically required for absolute phase recovery. Creath [12] analyzed the noise impact of two-wavelength phase-shifting methods; Towers et al. [13] proposed the strategies to select optimal wavelengths to minimize the noise influence; and recently Zuo et al. [14] thoroughly studied the problems associated with implementing such temporal phase unwrapping methods to DFP systems.

Unlike laser interferometry where only sinusoidal fringe patterns can be generated, DFP system can generate different forms of structured patterns, enabling a lot more methods for absolute phase unwrapping. For example, fringe order can be directly encoded into a sequence of binary [15,16] or ternary [17] coded patterns, a single statistical pattern [18,19], a single stair image [20], as well as other forms [21–29]. These enriched temporal phase unwrapping methods offer one to select the most suitable phase unwrapping approach for a specific application.

The aforementioned temporal phase unwrapping methods can all work on a single-projector and single-camera DFP system by acquiring additional information (i.e. images). For high-speed applications, it is not desirable to capture additional images since it slows down the entire measurement process. Recently, because of the reduced costs of hardware (e.g., cameras) and the desired high measurement speeds, researchers have developed alternative absolute phase unwrapping methods [30–37] by integrating more hardware components (e.g., a camera or a projector) into the measurement system. Different from a stereo-view system with a single camera and a single projector, these systems typically construct a multiview system that consists of more than two different perspectives. Such a system is over-constrained for 3D reconstruction, providing the opportunity to directly use wrapped phase for absolute 3D shape measurement. Therefore, the additional hardware-based phase unwrapping method has emerged as one of the important absolute phase unwrapping methods. Instead of capturing additional images, this type of phase unwrapping method determines absolute fringe order using the additional geometric constraints available to the hardware system, the wrapped phase constraint, and/or the existing stereo-vision approaches. Since no additional images are required, these absolute phase unwrapping methods do not belong to the conventional temporal phase unwrapping category yet still obtain absolute phase maps. Furthermore, because no additional image acquisition is required, they are more suitable for high-speed applications than the conventional temporal phase unwrapping methods.

In addition to the aforementioned absolute phase unwrapping methods, there are also other absolute fringe order determination methods that were recently developed based on the available information obtained elsewhere. For example, nowadays, most fabricated parts have computer-aided design (CAD) models, and the CAD model can also be used to determine absolute fringe order $k(x, y)$ by sampling the CAD from the same perspective of the camera of the DFP system [38]. We call this type of method *pre-knowledge-based phase unwrapping*. Since the calibrated DFP system provides the geometric relationship between (x, y, z) coordinates and the phase on the projector, An et al. [39] developed the geometric-constraint based phase unwrapping method for the single camera and single projector DFP system, and Jiang et al. [40] extended the depth range of An's method. These methods do not belong to the conventional temporal phase unwrapping category since they do not require temporally acquired information for absolute fringe order determination. Different from the multiview methods, these methods can be applied to a standard single-camera and single-projector DFP system, making them more valuable to high-speed applications at reduced complexity and cost of the hardware system.

This paper reviews conventional and recently emerged absolute phase recovery methods that are applicable to DFP systems. We will thoroughly explain two conventional absolute fringe order determination methods: different frequency phase shifting and binary coding; and discuss some newly emerged major absolute phase recovery methods for DFP systems including multiview geometry-based method by additional more hardware components (e.g., the second camera), the inherent geometric constraint-based method, and pre-knowledge-based method. We will also introduce other methods including hybrid methods such as phase coding, random pattern encoding, as well as the use of pre-defined markers. The principle behind each individual methods will be explained. Furthermore, due to noise and sampling, all absolute phase unwrapping methods create artifacts (i.e., points that are incorrectly unwrapped), they have to be properly handled for practical accurate measurements. This paper will offer some tips on handling those artifacts. Finally, we will cast our perspectives on their difficulty level for implementation.

Section 2 explains principles of each phase unwrapping method. Section 3 discusses some methods to handle phase unwrapping artifacts, and Section 4 summarizes this paper.

2. Principles

2.1. Basics of absolute phase unwrapping

The general sinusoidal fringe pattern can be mathematically represented as

$$I_i(x, y) = I'(x, y) + I''(x, y)\cos(\phi(x, y) + \delta_i), \tag{1}$$

where $I'(x, y)$ is the average intensity, $I''(x, y)$ is the intensity modulation, $\phi(x, y)$ is the phase, and δ_i is the phase shift. To recover phase $\phi(x, y)$, a Fourier transform [5,6] or a phase-shifting method [4] can be employed. Essentially, these algorithms use an arctangent function to compute phase value pixel by pixel. Due to the use of an arctangent function, the resultant phase value ranges from $-\pi$ to $+\pi$, or 0 to 2π with 2π modulus; and the phase obtained at this stage is often called wrapped phase. The wrapped phase has to be unwrapped before being converted to 3D coordinates pixel by pixel. Phase unwrapping is to determine 2π discontinuous locations, find the integer number of 2π's that a point should be added, and then remove 2π discontinuities by adding the desired number of 2π to the wrapped phase, $\phi(x, y)$. Mathematically, the relationship between wrapped phase $\phi(x, y)$ and unwrapped phase, $\Phi(x, y)$ can be described as

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

Here $k(x, y)$ is an integer number that is often regarded as *fringe order*. If fringe order $k(x, y)$ can be uniquely determined for each point that is consistent with a pre-defined value, then the unwrapped phase $\Phi(x, y)$ is regarded as *absolute* phase.

As discussed in Section 1, spatial phase unwrapping determines fringe order $k(x, y)$ that is typically relative to one point on the phase, and thus cannot give absolute phase. In contrast, the absolute phase unwrapping determines absolute fringe order $k(x, y)$ by referring to information acquired from somewhere else (e.g., additional images) and thus yields absolute phase.

The remaining sections discuss some of the major absolute fringe order $k(x, y)$ determination methods that can be applicable to the DFP systems. We will explain the basic principles of some well-known conventional methods (e.g., temporal phase unwrapping), and some non-conventional methods.

2.2. Binary coding method

The most straightforward method is to directly encode the fringe order $k(x, y)$ into a sequence of binary structured patterns. And the method