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Review

Phase shifting algorithms for fringe projection profilometry: A review

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ABSTRACT

The principle of structured light and triangulation is used in a wide range of 3D optical metrology applications, such as mechanical engineering, industrial monitoring, computer vision, and biomedicine. Among a multitude of techniques based on this principle, phase shifting profilometry (PSP) plays a dominant role due to its high attainable measurement accuracy, spatial resolution, and data density. Over the past few decades, many PSP algorithms have been proposed in the literature in order to achieve higher measurement accuracy, lower pattern count, and/or better robustness to different error sources. Besides, many unconventional PSP codification techniques address the problem of absolute phase recovery with few projected patterns, allowing for high-efficiency measurement of objects containing isolated regions or surface discontinuities. In this paper, we present an overview of these state-of-the-art phase shifting algorithms for implementing 3D surface profilometry. Typical error sources in phase measurement for a phase shifting system are discussed, and corresponding solutions are reviewed. The advantages and drawbacks of different PSP algorithms are also summarized to provide a useful guide to the selection of the most appropriate phase shifting technique for a particular application.

1. Introduction

The physical world we live in is three dimensional (3D). The 3D acquisition and information processing technology reflects the ability of human beings to cognize and grasp the objective world, so to some extent it is an important symbol of human wisdom. Conventional cameras and imaging detectors can only acquire 2D intensity information of the scene but cannot record 3D shape and depth information. Although humans can perceive the depth based on the binocular stereopsis formed by the eyes, they cannot accurately quantify the 3D geometry of objects. To address this issue, 3D shape measurement technologies have been developed to quantitatively obtain 3D geometric information so as to provide a data basis for clearer understanding and better comprehension of the state and function of real-world objects.

The rapid development of modern information technology has promoted the gradual maturity of the 3D shape measurement technology, which has penetrated into almost all fields around us with different styles and characteristics. In industrial design, the reverse engineering based on 3D shape measurement can rapidly create the accurate and digitalized 3D CAD models of the existing products, significantly shortening the development cycle and facilitating the further engineering processes [1]. In the field of intelligent manufacturing, the 3D sensing technology allows machines to perceive the 3D world, enabling a new starting point for manufacturing automation, intelligence, and re-creation [2]. In the field of virtual reality, a large number of digitized 3D scenes and models have been extensively used in national defense, simulated training, scientific experiments, and 3D animation [3]. In the field of cultural heritage preservation, 3D shape measurement technology has become an essential tool for the non-contact and non-destructive documentation of cultural heritage and its long term preservation [4]. In medical plastic surgery, 3D shape measurement technology has been widely used in facial soft-tissue repairing, surgical examination, and dentures customization [5]. And other applications exist in a variety of fields including manufacturing inspection, biomedicine, architecture, security, and human-computer interaction [6].

3D shape measurement techniques can be classified into two different categories, contact and non-contact [7]. Contact methods measure and reconstruct 3D geometry by probing the 3D surface through physical touch. An example of such a technique is the coordinate measurement machine (CMM) that can measure 3D geometry through a precise carriage system or articulated probe arm [8]. While this type of measurement can achieve high accuracy, it is typically limited to low measurement efficiency, since the system uses a physical probe that needs to touch the object surface point-wisely. Furthermore, due to the neces-

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sity of physical contact, it is undesirable for the measurement of soft or deformable objects. In order to solve the problems associated with contact-based techniques, a number of non-contact 3D shape measurement methods have been developed and are now increasingly being used in different fields. Optical methods lead the way in this category with the advances of high-performance light source and imaging devices. Various optical metrology approaches for 3D shape measurement have been developed, such as optical interferometry [9–11], time-of-flight (TOF) technique [12,13], stereo vision [14,15], shape from focus [16–18], and structured light (SL) [19–22]. These methods are based on different principles of optical measurement and have specific measurement sensitivity, spatial/temporal resolution, and measurement range. Readers interested in the basic principle, properties, and application ranges of these optical 3D shape measurement methods can refer to the review articles by Chen et al. [23] or Blais et al. [24].

The following of this paper is focused on the SL technique. SL is a very popular non-contact 3D shape measurement technique with the advantages in terms of simple hardware configuration, high measurement accuracy, high point density, high speed, and low cost. It has found extensive applications in industry and scientific researches. In essence, SL methods can be regarded as a modification of stereo vision. One of the cameras is replaced by a light source which projects the light patterns onto the scene. Since the object surfaces are covered with artificial features created by projected light patterns, the correspondence problem in the (passive) stereo vision for texture-less objects can be easily overcome. A typical 3D shape measurement system based on SL consists of one projection unit and one or more cameras. During the measurement, light patterns with known structures are projected sequentially onto the object being measured. Meantime, images of the object under the light projections are captured by the camera(s). By utilizing triangulation method between the camera and the projector (or between two cameras) and knowledge on the light patterns, the 3D shape of the object can be reconstructed from the captured images based on the pre-calibrated geometric parameters of the SL system. New researchers in this area are recommended to first read the tutorial by Geng et al. [22].

Over the past few decades, 3D shape measurement techniques based on SL have been rapidly developed in both communities of computer vision and optical metrology, and there have been many technical review articles survey and summarize previously published studies from different perspectives [22,25–31]. In the computer vision community, SL technique is also called 3D scanning, and the SL pattern codification strategies are mainly based on discrete intensity-based approaches. They can be further classified into spatial codification approaches and temporal codification approaches. In spatial codification approaches, e.g. De Bruijn patterns [19,20,32], non-formal coding [33,34], and M-arrays [35], the codeword of a specific position is extracted from surrounding points. The key idea is to guarantee the uniqueness of the local codeword over the global range in the pattern. Temporal codification methods are based on the codeword created by the successive projection of patterns onto the object surface. Therefore, the codeword associated to an image pixel is not completely formed until all patterns have been projected. Examples of these temporal codification methods include the temporal binary code [36], temporal n-ary code [37], and gray code [38]. Besides, color patterns or color multiplexing SL approaches with red, green, and blue channels have been proposed to improve the coding efficiency and reduce the number of projected patterns [30,37,39,40]. For more details about the principle and practical performance of these SL codification schemes, readers can access the review articles by J. Salvi et al. [26,27].

In the field of optical metrology, the most commonly used type of SL pattern for 3D shape measurement is fringe patterns, particularly fringe patterns with sinusoidal intensity distributions. Besides, the codification schemes used are mainly focused on continuous phase-based approaches. These sinusoidal SL techniques are often referred as fringe projection profilometry (FPP). By projecting sinusoidal fringe patterns onto the object and capturing the corresponding deformed fringe patterns modulated by the object surfaces, the depth information is encoded into the phase of the fringe images. The recorded modulated fringe images are then processed by fringe analysis algorithms to extract the phase distribution, which is thereby used to recreate the surface of interest in 3D space based on geometrical relations of the triangulation optical arrangement. For a general overview of FPP, readers can refer to the review article by Gorthi and Rastogi [25]. Traditionally, the typical approach to FPP involves generating fringe images by using laser interferometry, physical grating, or slide projector. However, with more recent developments in the area of digital display, digital video projectors have been increasingly used as the projection units of FPP systems. In contrast to the traditional methods of generating fringe images, digital video projectors are able to accurately control various attributes of the projected fringe patterns at high speed in software, which ultimately facilitate the effective applications of FPP techniques. It should be also mentioned that another classic approach to generate sinusoidal fringe patterns is based on the moiré effect. The application of moiré fringes for surface topology, so-called moiré topography, was first investigated in the late 1960's [41,42], which can be implemented in one of two variations: shadow moiré [43,44] and projection moiré [43–45]. In shadow moiré approaches, a single grating is used to cast a shadow onto the surface to be profiled which is imaged through the same grating from an offset angle to create moiré fringes whose phases are proportional to depth [46,47]. In projection moiré approaches, grating lines are directly projected onto the object surface, and moiré fringes are resolved by applying another reference grating either optically or digitally [43–45,48], so projection moiré topography can be regarded as a predecessor of FPP.

Benefiting from the continuity and periodicity nature of sinusoidal patterns, the FPP generally provides 3D data with both high spatial resolution and high depth accuracy. Considering the means of phase demodulation, the most popular FPP approaches includes Fourier transform profilometry (FTP) and phase shifting profilometry (PSP). The FTP utilizes only a single high-frequency fringe pattern, and the phase is extracted by applying a properly designed band-pass filter in the frequency domain. More technical details about FTP approaches can be found in the review article by Su and Chen [49]. The single-shot nature of FTP makes it highly suitable for the 3D shape measurement of dynamic surfaces. The review article by Su and Zhang provides an overview of dynamic shape measurement based on FTP and its typical applications [28]. Besides, not just limited to FTP, the windowed Fourier transform (WFT) [10,50] and the wavelet transform (WT) [51] can also be used for the phase demodulation of single high-frequency fringe pattern. It has been found that the WFT can provide higher measurement accuracy even in the presence of intensity nonlinearity error and depth discontinuities. For relevant content, readers can refer to the comparison papers by Huang et al. [52] and Zhang et al. [53].

In contrast to FTP, the PSP generally requires more than one (normally at least three) phase-shifted fringe patterns to reconstruct the 3D shape of the object. PSP originally stems from the classical laser interferometry technique. Srinivasan et al. [54] first introduced the phase shifting algorithm into the field of FPP for high-accuracy 3D shape measurement in 1984. Shortly afterwards, the PSP technique was successfully applied to the complete 360° reconstruction of a general 3D diffuse object [55]. Since the mathematical representation of the deformed fringe image intensity distribution is similar to that encountered in conventional optical interferometry, the methods of phase shifting interferometry (PSI) [56,57], well known for their accuracy, can be directly used for the fringe analysis and phase demodulation in FPP. Compared to FTP, the multiple-shot PSP techniques are generally more robust and can achieve pixel-wise phase measurement with higher resolution and accuracy. Furthermore, the PSP measurement is quite robust to ambient illumination and varying surface reflectivity. However, the PSP techniques require more time to acquire the multiple fringe patterns, and the object should be kept stationary during the projection of multiple fringe patterns. Recently, with the rapid advances in high-frame-rate image sensors, high-speed digital projection technology, and high-performance processors, PSP techniques have been increasingly applied