Optics Communications 382 (2017) 18–27

Contents lists available at ScienceDirect

Optics Communications

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

Fast three-dimensional measurements for dynamic scenes with shiny surfaces

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ARTICLE INFO

Article history:
Received 20 May 2016
Received in revised form
20 July 2016
Accepted 21 July 2016

Keywords:
Fast three-dimensional measurements
Shiny surfaces
Fringe projection
Dynamic scenes
Stereo
Digital speckle

ABSTRACT

This paper presents a novel fringe projection technique for fast three-dimensional (3-D) shape measurements of moving highly reflective objects. By combining the standard three-step phase-shifting fringe patterns with a digital speckle image, dynamic 3-D reconstructions of shiny surfaces can be efficiently achieved with only four projected patterns. The phase measurement is performed by three-step phase-shifting algorithm as it uses the theoretical minimum number of fringe patterns for phase-shifting profilometry. To avoid the camera saturation, a dual-camera fringe projection system is built to measure shiny objects from two different directions. The erroneous phase obtained from a saturated pixel is corrected by the phase of its corresponding pixel in the other view which is free from the saturation problem. To achieve high measurement accuracy, the corresponding high light intensity areas in cameras are found by sub-pixel matches of the speckle pattern in either view. Benefited from the trifocal tensor constraint, the corresponding points in the two wrapped phase maps can be directly established, and thus, the difficulties in determining the correct fringe order for the discontinuous or isolated surfaces can be effectively bypassed. Experimental results indicate that the proposed method is able to successfully measure highly reflective surfaces for both stationary and dynamic scenes.

1. Introduction

Fast three-dimensional (3-D) shape measurement is playing an increasingly important role nowadays in many fields including online inspection, rapid inverse engineering, medical sciences and home entertainments. Traditionally, a coordinate measuring machine is often used to inspect contours of objects due to its advantage of high precision. However, its measurement speed is very slow because of the requirement of surface-contacts. In contrast, the image-based optical 3-D measurement is more efficient and free from physical contacts [1,2]. Generally, optical 3-D shape measurements can be classified into passive methods and active methods. To obtain reconstructions of high accuracy, the latter that actively illuminate the measured object with pre-designed light signals are more appealing. Among the active means, fringe projection is one of the most widely used techniques because of its superiorities of high resolution, precision and full-field measurement.

To achieve fast measurements with the fringe projection, some researchers employed Fourier transform profilometry (FTP) [3–6], by which only one fringe pattern is used for 3-D measurements. It can be found that this method is particularly suitable for fast measurements since its sensitivity to object movements has been reduced to the minimum (a single shot). Conventionally, however, this technique is usually adopted for a continuous surface, e.g. a single object without large depth variation. This is because the phase information is solved by a frequency-domain filtering with FTP, the problem of frequency overlap may emerge when a measured surface is of large variation of slope. Owing to rapid developments of digital light projecting and capturing devices, many researchers begin to use the phase shifting profilometry (PSP) by which multiple fringe patterns are utilized [7–12]. As the capturing speed of cameras is increased, the moving process can be assumed as a quasi-static process, which makes the implementations of the multi-pattern strategy possible. More importantly, PSP has advantages of higher precision, resolution and being insensitive to ambient light over FTP. Based on PSP, Wang and Zhang [13] proposed a nine-pattern method to measure moving objects. Then, to reduce the number of used patterns Zuo et al. [14] developed a

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http://dx.doi.org/10.1016/j.optcom.2016.07.057
0030-4018/

fringe projection system by employing five images to reconstruct 3-D shapes of fast rotating blades. Further, Weise et al. [15] and Zhong et al. [16] presented techniques by which only the three fringe patterns were utilized for unambiguous 3-D depth measurements. In their methods, the phase unwrapping was conducted relied on relations resulted from the multi-view geometry. Recently, Feng et al. [17] proposed an approach where only two patterns were used. One of the images is a speckle pattern and the other one is a composite pattern fused by the digital speckles and a fringe pattern. The speckles are used to unambiguously unwrap the phase obtained from the fringe image. For the mentioned methods, although they would show good performance for fast measurements of dynamic scenes, it may be difficult for them to handle the objects with shiny surfaces. For fringe projection techniques the major problem faced when they are used to inspect highly reflective areas is that the 3-D depth sensing is entirely relied on the image processing of captured patterns. Once the image pixel is saturated as a result of the intense reflected light at a highly reflective point, no fringe can be recorded and used for the 3-D shape reconstruction.

Thus to cope with shiny objects, Zhang et al. [18] proposed a high dynamic range measuring technique based on the multi-exposure strategy. By their method, the fringes on the highly reflective surface were obtained by fusing the ones captured at several pre-determined exposure times. A decreased exposure time was used to capture the fringes at shiny points. With the same principle, Waddington and Kofman [19] developed a technique which adjusts the illumination intensity of the projector to avoid the camera saturation. Subsequently, Jiang et al. [20] presented a method that combines both strategies to modify the exposure time of the camera and the projected light intensity simultaneously. Additionally, Feng et al. [21] reported a generic high dynamic range fringe projection method where the required exposure time was adaptively predicted and polarizers were introduced to remove the high intensity. For the above methods, however, they were developed for still objects and thus may not be appropriate for measuring dynamic scenes. For the method by polarization, the reduced intensity by polarizers may result in low signal to noise ratio for captured patterns. For methods based on the image fusion, they need to capture many patterns to synthesize into a single fringe image. Thus, it is difficult for camera pixels to measure unchanged points at different exposures given the movements of the object.

Therefore to handle the highly reflective surface with less patterns, Chen and Zhang [22] proposed to use traditional phase shifting algorithms with several saturated fringe patterns. Compared to multi-exposure methods, their method can perform the measurement with saturated fringes obtained from a fixed exposure time, which greatly reduces the number of required patterns. However, in their method the amount of patterns is proportional to the period of the fringe pattern. Thus to employ less patterns, one needs to reduce the fringe pitch, which may increase the difficulty in phase unwrapping if too narrow fringes are used [23]. Besides, additional patterns are still needed to meet the goal of unambiguous shape measurements. With the same strategy of utilizing saturated fringes, Chen et al. [24] and Hu et al. [25] suggested to use extra phase shifts (more than the minimum) to alleviate the effect of the shiny surface. To better eliminate the influence of the saturation, however, one still need to increase the number of the phase shifts to allow more unsaturated pixels to be used for phase measurements. Then, based on [19] the methods reported in [26,27] use adaptive modification of the illumination intensity of the projected pattern to inspect shiny surfaces. This strategy can provide local shiny areas with required illuminations by projecting adaptive patterns. Compared to the global method [19], the adaptive technique saves the patterns to be projected. But for the generation of adaptive patterns, the measured object should keep static for locations of the highly reflective regions. Thus they may not be suitable for dynamic objects. Moreover, Liu et al. [28] and Kowarschik et al. [29] resorted to the idea of changing the viewing angle to remove the effect of the high light intensity. But, for [28] it needed the multi-exposure technique to obtain an unwrapped phase map for the pixel matching in different views and for [29] the alteration of the viewing angle was achieved by manually modifying the orientation of the measuring platform. Therefore both of them would show difficulties for measurements of dynamic objects.

For the purpose of developing a method for fast measurements of varying highly reflective surfaces, we present a novel fringe projection strategy. In the work, to lower the sensitivity to motions we only employ four patterns among which three images are phase-shifting fringes and the remaining one is an image of digital speckles. The three-step phase-shifting algorithm is applied for the phase measurement. Because of the camera saturation caused by the high light intensity, the obtained phase for the shiny region is prone to be erroneous. Therefore, to correct phase errors we utilize another camera viewing from a different angle to build a stereo fringe projection system. The reason is that when observing from another side the reflected light at a shiny point will not be so strong that saturates the corresponding pixel. Thus the phase from the newly introduced camera can be used to compensate the erroneous phase in the former view. To find the corresponding area in these cameras, we use the speckle image to mark the local region uniquely. To obtain measurement results of high accuracy, we introduce the enhanced normalized cross correlation (ENCC) method [30] into this work to acquire a disparity map with sub-pixel precision. Once phase errors are corrected, the trifocal tensor obtained from the tri-view relation is used to unwrap the phase unambiguously. Experimental results demonstrate that the method can measure objects of highly reflective surface successfully and efficiently.

2. Principles

2.1. Overview of the algorithm

For an intuitive understanding of our method, at the beginning we provide an overview of the approach. As shown in Fig. 1, our method can be performed by four steps, which are represented with different colors. For the first step, we capture the phase-shifting and speckle patterns by both cameras, and rectify all of them based on the results of the stereo-camera calibration. Then, the rectified speckle images from both cameras are employed to find corresponding shiny areas in the two views. By the ENCC, a sub-pixel disparity map indicating the highly reflective areas can be obtained. In the second step, we firstly calculate the wrapped phase maps with the rectified fringe patterns and then conduct the phase error correction for both phase maps with the aid of the sub-pixel disparity map. Next, in the third step, with accurate phase maps from both cameras we can compute the fringe order by the trifocal tensor. In the final step, with the fringe order the wrapped phase maps are unwrapped unambiguously and converted to heights.

2.2. Three-step phase-shifting algorithm

N-step phase-shifting profilometry is a well-known technique for phase measurements. A set of fringe patterns with a certain phase shift is projected cyclically onto a measured scene. From a different position, a camera captures these distorted patterns for 3-D reconstructions. A schematic is shown in Fig. 2. To ensure the