Optics Communications 414 (2018) 185–190

Contents lists available at ScienceDirect

Optics Communications

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

3D-shape of objects with straight line-motion by simultaneous projection of color coded patterns

Jorge L. Flores [a,*], Gaston A. Ayubi [b], J. Matías Di Martino [b], Oscar E. Castillo [a], Jose A. Ferrari [b]

[a] Departamento de Electrónica, Universidad de Guadalajara, Av. Revolución 1500, C.P. 44840 Guadalajara, Mexico
[b] Instituto de Física, Facultad de Ingeniería (UdelaR), J. Herrera y Reissig 565, Montevideo, Uruguay

ARTICLE INFO

Keywords:
Instrumentation
Measurement
Metrology
Fringe analysis
Phase retrieval

ABSTRACT

In this work, we propose a novel technique to retrieve the 3D shape of dynamic objects by the simultaneous projection of a fringe pattern and a homogeneous light pattern which are both coded in two of the color channels of a RGB image. The fringe pattern, red channel, is used to retrieve the phase by phase-shift algorithms with arbitrary phase-step, while the homogeneous pattern, blue channel, is used to match pixels from the test object in consecutive images, which are acquired at different positions, and thus, to determine the speed of the object. The proposed method successfully overcomes the standard requirement of projecting fringes of two different frequencies; one frequency to extract object information and the other one to retrieve the phase. Validation experiments are presented.

1. Introduction

There are many different 2D (and 3D) applications for optical metrology systems in industrial manufacturing [1–3]. Today machine vision systems have been widely used in manufacturing and quality control, as for example, sorting parts, verifying hole locations and dimensions, and checking overall shape and fit according design requirements [2]. Only just to name a few examples that can be handled in 2-dimensions.

On the other hand, with recent technological advancements on digital light projection and digital imaging, 3D optical metrology based on digital fringe projection and phase-shifting methods (PS) have improved considerably. In the last decade, one of the major research challenges has been to improve the ability to work on a wide range of surfaces with wide reflection variations, automated profile reconstruction and high-speed 3D shape measurements [2,4]. One of these applications is the 3D shape measurement of an object with straight-line motion.

In general, by using phase shift algorithms, it requires to project/acquire at least three phase-shifted fringe patterns, and needs additional information to estimate the lateral displacement of the object. In this way some approaches have been proposed, e.g., Peng and co-workers [5,6] suggested the use of orthogonal two-frequency fringe patterns. In the high-frequency one, the phase-shifting direction is along the moving direction, while that the low-frequency fringes are perpendicular to the moving direction, or vice versa [6]. But, the main idea is the same: One kind of patterns is used for phase retrieval, and the second is used to estimate the lateral displacement of the moving object using pixel matching methods. There are other proposals to estimate the lateral displacement, e.g., utilizing markers for pixel matching [7] or other strategies [1,8].

For phase retrieval from fringe projection, one must acquire a set of fringe patterns, which are described by

$$I_k(x,y) = a(x,y) + b(x,y)\cos\left[2\pi f x + \phi(x,y) + \delta_k\right], \tag{1}$$

where $(x; y)$ are Cartesian coordinates, $a(x,y)$ is the background illumination, $b(x,y)$ is the amplitude modulation, f is the spatial frequency of the fringe on the reference plane, $\phi(x,y)$ is a phase related to the profile of the measured object, and δ_k is the phase shift: Usually by 3D-profiling of static object the phase step δ is known a priori, but when the test object is moving often one has to estimate this quantity a posteriori.

In general, for N-step phase-shifting algorithms the phase could be retrieved from N intensity patterns as the arctangent of the ratio between two linear combinations of values $I_k(x,y)$, as for example [9–11]

$$\phi(x,y) = \arctan\left\{\frac{\sum_{k=1}^{N} I_k(x,y)\sin\delta_k}{\sum_{k=1}^{N} I_k(x,y)\cos\delta_k}\right\}. \tag{2}$$

Expression (2) presupposes that the phase steps δ_k are known and evenly spaced in the interval $[0; 2\pi)$, e.g., $\delta_k = (k-1)2\pi/N$. In fact, Hoang

* Corresponding author.
E-mail address: luis.flores@cucei.udg.mx (J.L. Flores).

https://doi.org/10.1016/j.optcom.2017.12.087
Received 18 September 2017; Received in revised form 27 December 2017; Accepted 30 December 2017
Available online 6 February 2018
0030-4018/

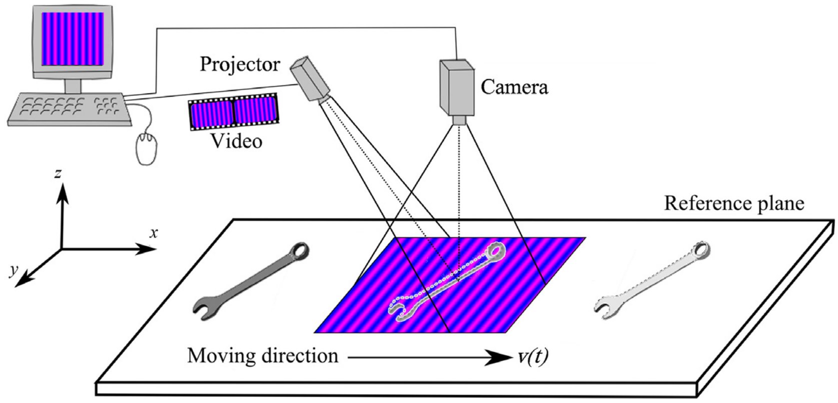

Fig. 1. Experimental setup.

et al. [12] suggested that Eq. (2) can be used in a $(p+2)$ step uniform phase-shifting scheme to the retrieve phase accurately from fringe patterns with nonlinear harmonics up to the p th order. In dynamic 3D profiling, however, this requirement is often difficult to meet exactly because the effective phase steps are determined by the velocity of the motion of the linear travel stage, which is not necessarily uniform, even though N deformed patterns be captured in a constant rate, the phase steps will not evenly spaced. On other hand, the algorithms used to determine the phase steps from the experimentally obtained intensity patterns present some errors (see, e.g., [13,14]). Thus, the actual (measured) phase steps will not coincide with their nominal values for a given N-sample algorithm, and not be evenly spaced. Considering phase-shift values are not evenly spaced and/or they present small errors, the use of Eq. (2) is not the best method for phase retrieval, although this has been proposed in [5,7]. Something similar happen with the procedure proposed in [1,6,8] to retrieve the phase, which is based on a well-known five-sample Stoilov's algorithm [15]. It has the peculiarity of being a tunable algorithm, i.e. it does not require to know the phase steps, but presents high sensitive to phase-shift errors. To eliminate this inconvenience, Yang Li et al. [16] proposed a three-dimensional on-line measurement method based on a five-step algorithm with unequal phase shift. However, we found that this algorithm presents some inconsistencies, which will be described below.

In this work, we propose a novel method for 3D-profiling of moving objects by the simultaneous projection of a fringe pattern and a homogeneous light pattern, which are encoded in two of the color channels of a RGB image. The fringe pattern, red channel, is used to retrieve the phase, while the homogeneous pattern, codified in the blue channel, is used to match pixels from the test object in consecutive images. On the basis that one of the problems is that intensity fringe patterns may not be equal spaced, we proposed the use of the PS algorithm with N arbitrarily spaced phase-steps for phase retrieval [10,11]. Particularly, we are proposing the use of the generalized phase-shifting algorithms for N-step (N-sample GPSA) described in [11] that have shown good minimization of phase noise occurred by phase-shift miscalibration and Gaussian noise.

2. Description of the method

The setup for online 3D-shape measurement of moving objects is shown in Fig. 1. It consists of a projector, which is used to project a RGB software-generated fringe pattern, and a high-resolution (CCD) camera which is employed to capture a video wherein the fringe pattern is modulated by the object's surface. The test object is on a platform, which is moving along the x-axis direction with approximated constant velocity. Moreover, the platform can be replaced for a conveyor belt; therefore, the proposal method can be used for industrial applications.

Firstly, one sinusoidal fringe pattern (with fringes in x-direction, and arbitrary origin) and a uniform background (256 gray level) are encoded into the red (R) and blue (B) channels of a color image, respectively. This color image is then projected by a LCD or DLP projector onto the surface of the moving object under measurement and simultaneously an image sequence is acquired by a color camera. And then, two set of gray level images of the moving object are extracted (recovered from the Red and Blue channels) from the acquired sequence. In the detected red channel we acquire the modulated fringe patterns, which are used to estimate depth of the object under test by the use of PS algorithms. The blue channel consists of a series photographs of the object as it moves along x-direction, which are used for tracking the object frame by frame. A detailed description of both, the phase recovery process and object tracking is illustrated in Fig. 2 and developed below.

In the experimental arrangement, the camera is always static, so the first problem is to find the position of the object into each frame. The target for the correlation filter is a photograph of the object (blue channel information), which is given by a window centered on the object and extracted from the first frame. In the rest of photographs, the target (i.e., the test object) is tracked during its movement by a correlating filter over a search window in the next frames; the location corresponding to the maximum value in the correlation output indicates the new position of the target into a given frame. Thus, the object position is updated, and a new search is then performed based on that new location in the following frame. To create an optimal tracker, target and the rest of frames are filtered to enhance features for shape characterization of the object. Enhancement process were obtained by employing Sobel filter for edges detection. The correlation for tracking the target in an image sequence is given by

$$g(x,y) = I_{B,k}(x,y) \otimes h(x,y), \tag{3}$$

where $\otimes$ represents the symbol of correlation, and $h(x,y)$ and $I_{B,k}(x,y)$ are the correlation filter associated with target and the filtered kth-frame of a given sequence, which is extracted from B channel, respectively. The correlation operation can be implemented in Fourier domain [17]. From the correlation output, $g(x,y)$ one can determine the position of the object into kth frame or the object-shift δ.

For phase retrieval, a static sinusoidal fringe pattern is projected onto a test object, which ideally is moving along the x-direction with a given constant velocity, v. Thus, the camera acquires a stationary signal modulated by the height of the object.

Therefore, the intensity in R channel of N color images, which are acquired as a sequence (video), can be expressed as

$$I_k(x,y) = a(x,y) + b(x,y)\cos\left[2\pi f x + \phi(x-k\delta, y)\right], \tag{4}$$

where, $\phi(x-k\delta,y)$ is a phase change related to the profile of the test object, δ is the object-shift for a given frame, and $k = 1,2,\ldots,N$. The displacement of the object between consecutive frames is given by $\delta = v\Delta t$ where Δt is the time between consecutive frames, i.e. Δt is the inverse to frame rate, f_s. Under this assumption, we could build a set