Optics and Lasers in Engineering 81 (2016) 11–20

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

A real-time, full-field, and low-cost velocity sensing approach for linear motion using fringe projection techniques

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ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form
20 December 2015
Accepted 21 December 2015

Keywords:
Fringe analysis
Profile measurement
Velocity measurement
Fringe projection

ABSTRACT

A velocity sensing approach using the fringe projection technique is presented. The moving object is projected with a sinusoidal fringe pattern. A CCD camera located at a different view angle observes the projected fringes on the dynamic object. The long exposure time of the CCD camera makes the fringes blurred by linear motion. The blurred fringes provide additional information to describe the depth displacement, and therefore the velocity vector can be identified. There is no need to take multiple-shot measurements to address the change in 3D positions at a sequence of time. Only one-shot measurement is required. Consequently, there is no need to perform image registration. The full-field approach also makes it possible to simultaneously inspect several objects.

1. Introduction

Velocity detection is an interesting topic in computer vision [1–4]. It successively takes a couple of image frames and evaluates the velocity from the change in positions between two sequent frames. However, using a sequence of 2D images to analyze the 3D motion is not an easy task. It defines lateral movements very well, but it is difficult to determine the velocity vector along the depth axis.

One solution to measure the velocity is to perform 3D profile measurements at a sequence of time. The velocity is then identified by the change in 3D positions with reference to the associated surface points. Several approaches have been proposed for 3D profile measurements [5–12]. They can be roughly categorized as scanning methods [6–8] and non-scanning methods [9–12]. Compared with the scanning methods which take time to scan the entire surface, non-scanning methods perform the measurements in a full-field way, therefore more efficient for dynamic inspection.

Among these non-scanning methods, the fringe projection technique is especially notable due to its superiority in low computation cost, high spatial sampling density, and real time inspection [11,12]. It projects a sinusoidal fringe pattern onto the inspected surface and uses an image sensor array to observe the projected fringes from another point of view. Phase of the projected fringes contains the depth information. Consequently, it is analyzable to reconstruct the 3D shape.

Phases can be extracted with the Fourier transform method [11] or the phase-shifting technique [12]. The Fourier transform method evaluates phases from only one-shot measurement, while the phase-shifting technique takes more than three images for phase-extraction. It seems that the phase-shifting technique is time-consuming and not suitable for dynamic inspection. Fortunately, the remarkable improvements of the digital projectors and high-speed cameras make it possible to illuminate fringes with a high pattern-switching rate and record images with a high frame rate. Hence the dynamic object is fairly static during the phase measurements. Extracting phases with the phase-shifting technique is desirable [13–15].

In the meantime, both the Fourier transform method and the phase-shifting technique analyze phases with the arctangent operation, resulting in principle values ranging from $-\pi$ to π. Unwrapping is consequently required to recover the true phase from the modulo 2π data. Several algorithms have been proposed for 2D phase unwrapping [16–22]. Algorithms developed by means of path-following or minimum-norm recover phases straightly from the phase map [16]. These algorithms are generally awkward for spatially isolated objects or surfaces with depth discontinuities. An inadequate multiple of 2π might be added to the unwrapped phase, leading to an error propagated over a large area. On the other hand, the fringe-encoding algorithms [17] do not encounter such a problem. Errors are generally restricted in a small area and do not spoil many pixels.

The fringe-encoding algorithms can be roughly divided into two categories, namely spatial projection methods [18,19] and temporal projection methods [20–22]. In the methods of spatial projection, a sinusoidal fringe pattern is spatially encoded with colors [18] or binary levels [19] in a unique order. Phases are extracted with the Fourier transform method. Unwrapping is then executed with reference to the

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http://dx.doi.org/10.1016/j.optlaseng.2015.12.015
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encoding scheme. Algorithms based on temporal projections project a couple of sinusoidal fringe patterns with different frequencies to the inspected object in a sequence of time. Unwrapping is performed with the comparison of the sequent phase maps. Errors can be reduced due to the multiple phase measurements. In general, the method of spatial projection is more flexible for dynamic objects because it takes only one image frame for data processing. Again, thanks to the outstanding performances of the digital projectors and the high-speed camera, the pattern-switching rate and the image frame rate are high enough that the inspected object keeps fairly static during each measurement. Using high-speed temporal projection methods to analyze dynamic surfaces is available [23–25].

Once a number of profiles are retrieved in a sequence of time, the velocity can be carried out by the change in 3D positions with reference to the associated surface points. To pick out the associated surface points from the sequent surface profiles, image registration [26] is an inevitable procedure. As a result, accuracy of the retrieved velocity is limited not only by accuracy of the profile measurement, but also by precision of the image registration. The overall setup is expensive, the measurement procedure is complicated, and the computation cost is high.

In this paper, we present a one-shot measurement approach to identify the velocity of a linearly moving object. Its optical setup is similar to the typical fringe projection system. The difference is the image exposure time. The exposure time in our system is relatively longer than that in a typical fringe projection system. Fringes on the obtained images are therefore blurred by linear motion. Our previous work [27] has shown that the blurred fringes can be used to retrieve the profile. In this paper, we extend its application to identify the velocity vector. Only one image frame is required for data processing. There is no need to perform image registration. Thus, the measurement procedure is simple, and the computation cost is very low. Its full-field property also makes it possible to inspect several objects at the same time.

2. Theory

An example is provided to observe the blurred fringes caused by linear motion. A ball moving with a known velocity vector was selected as the inspected sample. A sinusoidal fringe pattern was projected onto the dynamic object. Fringes on the ball were recorded by a CCD camera. With long exposure photography, fringes are blurred by motion. Appearance of the ball moving from the left to the right is depicted as Fig. 1(a). A comparison is shown in Fig. 1(b), in which the ball was static. Fringe contrasts shown in Fig. 1(a) are decreased, especially at the right side of the ball. It illustrates that a larger depth displacement leads to a lower fringe contrast. A similar situation can be observed in Fig. 1(c). The ball was moving from the bottom to the top, resulting in worse contrasts both at the top and the bottom area. Another comparison is shown in Fig. 1(d), in which the ball was moving from the distant to the near. Fringe contrasts were uniformly blurred, because all the depth displacements were the same. There must be some correspondences related to the velocity vector, the surface profile, and the fringe contrast. Our purpose is to identify such a correspondence.

A velocity detection system is shown in Fig. 2. To simplify the procedure of formula derivation, both the fringe projection system and the image acquisition system are telecentric. The figure plane is denoted as the x–z plane, and the y-axis is normal to the figure plane. An object is moving with a velocity vector $(\upsilon_x, \upsilon_y, \upsilon_z)$. Its depth profile is a function of time and can be described as

$$Z(x,y,t)=Z_0(x,y)+\left[\frac{\partial Z_0(x,y)}{\partial x}\upsilon_x+\frac{\partial Z_0(x,y)}{\partial y}\upsilon_y+\upsilon_z\right]t, \tag{1}$$

where $Z_0(x, y)$ is the depth profile at $t=0$.

A sinusoidal fringe pattern is projected onto this object. Illumination intensity of the projected fringes is given by

$$I_f(x,z)=a+b\cos\left(\frac{2\pi x}{T_x}+\frac{2\pi z}{T_z}\right), \tag{2}$$

where a is the background intensity, b is the modulation amplitude, and T_x and T_z are fringes periods in the x- and z-axes, respectively.

A CCD camera records the projected fringes on the moving object. The coordinate system (c,r) is located on the detection plane, where c and r axes are parallel to the column and the row directions of the sensor array respectively. The mapping transformation

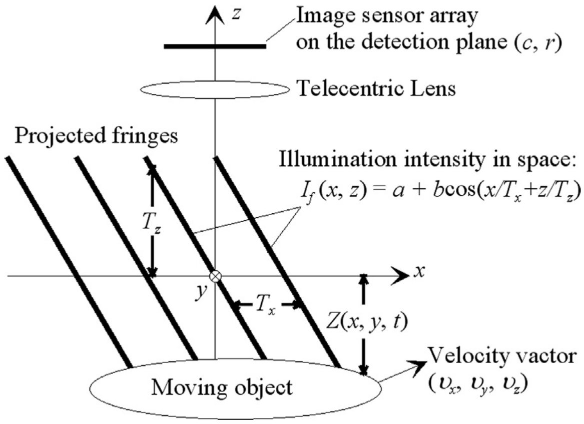

Fig. 2. Schematic setup of projected fringe profilometry. An object moving along a specific direction is observed by an image sensor array. The image acquisition time is long enough that the recorded image is blurred by motion.

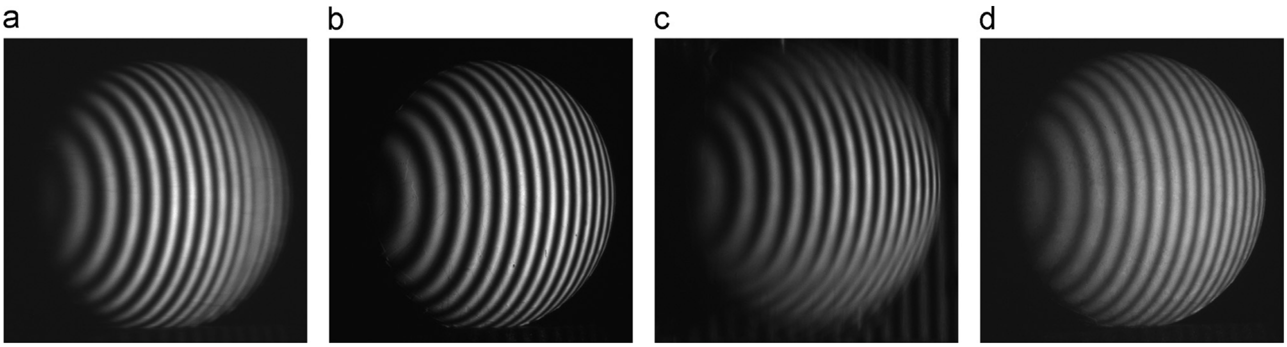

Fig. 1. Appearance of the projected fringes when the object is (a) moving from the left to the right, (b) keeping static, (c) moving from the bottom to the top, and (d) moving from the distant to the near.