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One shot profilometry using phase partitions

C.A. García-Isáis, Noé Alcalá Ochoa *

Centro de Investigaciones en Óptica, A.C., Loma del bosque 115, Col. Lomas del campestre, C.P. 37150 León, Guanajuato, Mexico

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ABSTRACT

Shape measurement using structured light systems involves the difficulty of detecting sharp discontinuities higher than one period of the projected fringe pattern; moreover, phase unwrapping becomes a problem. In this paper, a method to retrieve surface topography trough the projection of a single fringe pattern in gray levels is proposed. The correct phase is unwrapped through the use of Fourier methods and partition functions obtained from the phase. Experimental results show that the method can deal with the projection of high frequency fringes, being limited mainly by the resolution of the projector–detector system.

1. Introduction

For years, multiple efforts have been made in order to develop methods for measuring the topography of objects with fringe projection. Such methods are not universal and have their own niche of applications. For example, those using phase shifting techniques [1] that require the projection of various images are limited to being used for objects whose movements are static during the acquisition time. Fourier techniques require only one image to attain the phase, but at the cost of increasing the processing time and reducing the exactitude of the calculated phase [2,3]. None of the methods is able to deal with sharp discontinuities that are greater than one period of the projected fringes or equivalent to 2π rad in their phase, nor can they cope with isolated surfaces. In order to overcome those problems, some methods based on Fourier and phase shifting techniques have been developed. Perhaps, the most successful for static measurements is the temporal phase shifting method that uses many wrapped images of different frequencies [4]. Other methods that also use phase shifting techniques are, for example: the dual-frequency method, which combines a unit-frequency fringe pattern with a high-frequency [5]; the amplitude modulation method, where the unit frequency is obtained from amplitude modulation of the fringes [6]; the method of selected frequencies, which requires two fringe patterns and a look up table to calculate the fringe orders [7]; those methods that use gray-coding in amplitude [8,9] or in phase [10]; and the method that projects a stair to detect the fringe orders [11]. To avoid the use of multiple image methods that use a single color pattern can be found in [12–14], but they suffer from channel crosstalk; therefore, when projected on areas of complementary colors, stripe contrast can be notoriously reduced. There is also a fringes projection method that uses multiple images [15] to perform measurements with fringes of one period. In that proposal eight images are superposed: four of high frequency and four of one period. The high frequency fringes poses the same orientation (vertical) and works like carrier fringe to get the phase of the one period fringes (horizontal). Also, two filtering processes are carried out: a high-pass filtering process to isolate the high frequency peaks and a posterior low-pass filter to get the one period fringes.

In recent research, a method to recover the shape of objects that have abrupt heights [16] or isolated surfaces was reported. In that study, a single image in gray levels and Fourier techniques to calculate an equivalent unit-frequency phase and a high frequency wrapped phase were used. The low-frequency phase was used to unwrap the high-frequency phases and to detect the abrupt phase changes. Unfortunately, this method involves a scale phase factor that introduces errors in fringe order when the frequency is too high (about 20 fringes). In this work, we overcome such drawback and build a more robust algorithm; to do so, we project a single fringe pattern with four frequencies: three as described in the previous paper and an additional medium frequency. Thus, phase partitions to unwrap the high-frequency phase unambiguously were constructed. As a result, a method that uses only one pattern in gray levels was achieved, which was able to deal with isolated areas and phase steps greater than 2π; henceforth, its high-frequency term may help to obtain high accuracy measurements. The fundamental differences between our work and that of Guen et al. [15] are: a) we superpose four patterns instead of eight, which leads to increasing the gray-level dynamic range of the

* Corresponding author.
E-mail address: alon@cio.mx (N. Alcalá Ochoa).

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projected fringes and b) we use the phase of the low frequency fringes to calculate the phase of the high frequency fringes, increasing in this way the accuracy of the measurement. In [15] this scaling procedure was not considered. A detailed comparison of both methods is carried out in Appendix A.

In the next section, an explanation of this method along with some simulations shall be provided; subsequently, experimental results are shown in Section 3.

2. Description of the method and simulations

Our proposal can be summarized as follows: (a) the projection of a single image that is made up of four fringe patterns, (b) its acquisition and analysis with Fourier methods in order to calculate the individual phase maps corresponding to each frequency and the calculation of a unit-frequency phase map, (c) the creation of phase partitions, (d) the determination of the fringe numbers and its correction and finally (e) the unwrapping of the high frequency phase map.

2.1. Construction of the composite fringe pattern

The composite pattern to be projected is described by

$$i(x,y)=\frac{G}{8}\{4+\cos(2\pi f_1 x)+\cos(2\pi f_2 x)+\cos(2\pi f_2 y) + \cos[2\pi(f_2+1)x+2\pi f_2 y]\} \tag{1}$$

where f_1 and f_2 are medium and high carrier frequencies, G is a constant that represents the amplitude value introduced to obtain the maximum gray level range (i.e. $G=255$ for 8 bit images), (x,y) are the normalized pixel coordinates, and $i(x,y)$ is the image with its gray levels in the range $[0,G]$. We will choose $2f_1<f_2$ for purposes that will be later explained. The four carrier terms are given by

$$c_{x1}(x,y)=2\pi f_1 x;\quad c_x(x,y)=2\pi f_2 x;\quad c_y(x,y)=2\pi f_2 y; \quad c_{xy}(x,y)=2\pi(f_2+1)x+2\pi f_2 y. \tag{2}$$

Thus, as described in [16], the following relation holds:

$$c_{xy}(x,y)-c_x(x,y)-c_y(x,y)=2\pi x, \tag{3}$$

which is a unit frequency fringe.

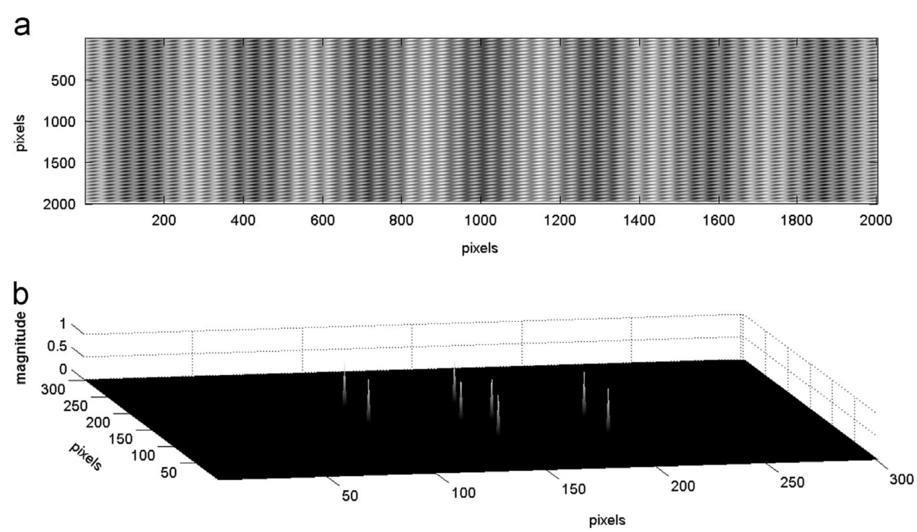

Fig. 1. (a) Digital composite pattern with $f_1=7$, and (b) Fourier spectrum of the pattern without the zero order.

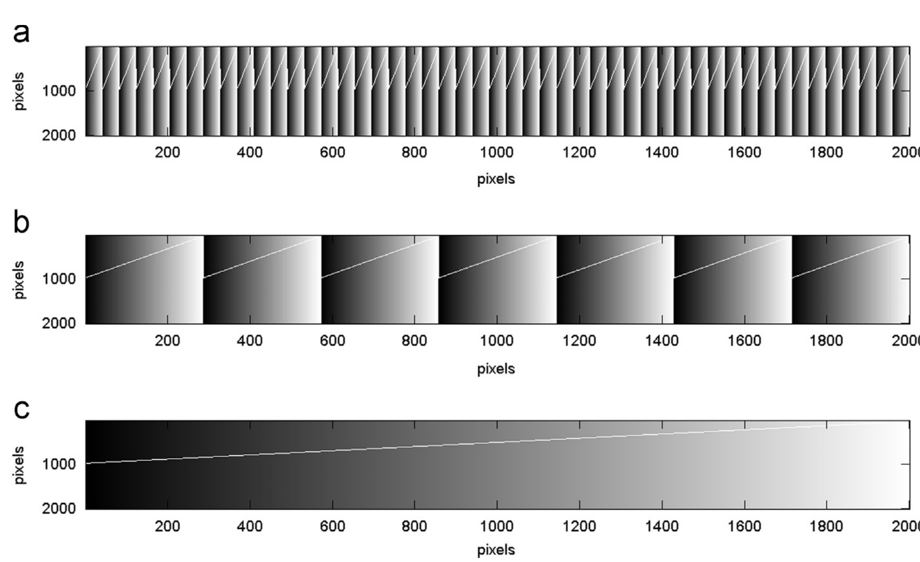

Fig. 2. (a) Wrapped phase for the high frequency pattern (49 periods), (b) Wrapped phase for the medium frequency pattern (7 periods), and (c) Wrapped phase calculated for one fringe pattern.