Measurement of transient dynamics on a flexible membrane by double digital fringe projection

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This paper presents the graphical response of a latex membrane subject to a transient event decreasing its surface profile along time. To do this, the Isotropic Quadrature Transform is applied to spatially recover the phase maps of individual frame from fringe patterns. The fringe patterns come from a double-digital fringe projection along the object under study allowing, inclusive, the measurement of the extremes of the object, where with other techniques it is impossible due to shadows generated for the angle of projection. We demonstrate the recovery of a function obtained by simulated interference patterns and after that, it is presented the function resulting from the membrane profile through time.

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1. Introduction

3D shape measurement has been very important in the last several decades and today is widely applied in many fields like manufacturing, medical image diagnosis and medical sciences, computer sciences [1,2], and other applications like 3D surface shape measurement of Micro Electro Mechanical Systems (MEMS) [3-5].

For measurements of high accuracy used for interferometry, phase unwrapping algorithms are needed for obtaining continuous phase map. Many phase unwrapping algorithms have been also developed for this purpose [6].

According to [7-11], digital fringe projection profilometry for measuring the topography of 3D objects is a very active research area in optical metrology and one of the most important 3D shape measurement methods [12-13] that are used nowadays.

A digital fringe projection, by means of a modern digital projector, and a spatial unwrapping algorithm can control the phase of fringes projected and the wavelength accurately, this is because the projected fringes are digitally generated in a computer and can be changed according the application of the experiment or measurement that is done at that moment.

In this work we propose a simultaneous digital fringe projection, that we have called double digital projection [14,15], through two digital projectors and the application of a spatial unwrapping algorithm to obtain the phase of a flexible membrane that decrease its original volume along time.

The experiment uses a Garmin VIRB XE CMOS camera that records at a rate of 30 frames per second, with a resolution of 1440p. Also, are used two Epson Projectors PowerLite S27, with an illumination of 2700 lumens.

The complete event is recorded, from the original volume of the object, to a partially decreasing volume, with the intent of registering a change in the patterns of fringes projected onto the object. In this way, frame by frame is analyzed through the volume change and the unwrapped phase of each of them is extracted to record the behavior of the membrane over time and as a transitory natural response to the change of volume of the flexible membrane.

In section 2 of this work, the theoretical description of the proposed technique is described. It is also presented the experimental setup to be used for the experimental work to be done.

Section 3 shows a simulation of the process that will be applied experimentally.

Stripe patterns are simulated with sinusoidal variation over time, that is, the simulated bands change with respect to a sinusoidal function that moves in time.

The wrapped and unwrapped phase of each simulated fringe pattern is extracted to obtain the values of a representative, fixed point, for each of them with the idea of obtaining a representative function of the phase change with respect to time and compare it with the simulated sine to verify that the technique works.

In the same section, the results obtained by applying the proposed technique to a flexible membrane is shown that changes its volume in a transient way. Only few fringe patterns are presented due to the extend quantity of information generated and processed.

2. Experimental set-up and theoretical description

In this proposal two fringe patterns with the same frequency are superposed to form a new fringe pattern of interference. Three fringe elements are considered: the two fringe projected patterns and the fringe generated by the superposing of the two linear patterns simultaneously.

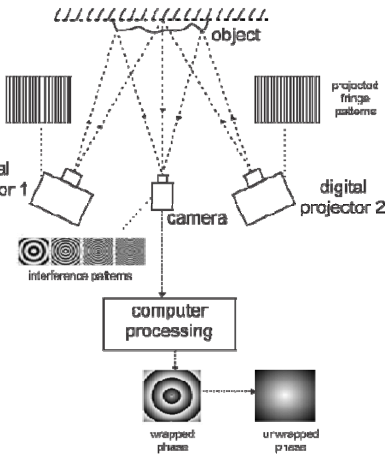

Fig. 1. Optical setup applied for the double digital fringe projection technique

In Fig. 1 the optical configuration used for this work is presented. The two fringe patterns are designed in a computer and are projected over the object by two digital light projectors simultaneously. A camera is used to capture an image of the deformed fringe. The computer then processes the resulted fringe pattern of interference to obtain the wrapped and unwrapped phase.

Numerically, the resulted fringe pattern of interference can be expressed as:

$$\begin{aligned} I(x,y) = a(x,y) &+ b_1(x,y)\cos[\phi_1(x,y)] \\ &+ b_2(x,y)\cos[\phi_1(x,y)] \\ &+ b_3(x,y)\cos[\phi_1(x,y)] \end{aligned} \tag{1}$$

where $a(x,y)$ is the average background intensity, $b_{n=1,2,3}(x,y)$ is the intensity modulation and $\phi_{n=1,2,3}(x,y)$ denotes the phases that can be rewritten in function of carried phases and initial phases as follows:

$$\begin{aligned} \phi_1(x,y) &= \varphi_\alpha(x,y) + \varphi_1(x,y) \\ \phi_2(x,y) &= \varphi_\beta(x,y) + \varphi_2(x,y) \\ \phi_3(x,y) &= \varphi_\gamma(x,y) + \varphi_3(x,y) \end{aligned} \tag{2}$$

then, Eq. (1) can be rewritten in function of Eq. (2):

$$I(x,y) = a(x,y) + b_1(x,y)\cos[\varphi_\alpha(x,y) + \varphi_1(x,y)] + b2(x,y)\cos[\varphi\beta x,y+\varphi 2x,y]+b3(x,y)\cos[\varphi\gamma x,y+\varphi 3x,y] \tag{3}$$

However, the digital camera used in the experimental set-up has only the possibility of register one fringe pattern of interference, coming precisely from the superposition of the fringe patterns digitally projected over the object. Then, the final fringe pattern of interference can be written as:

$$I(x,y) = A(x,y) + B(x,y)cos[\phi(x,y)] \tag{4}$$

where $A(x,y)$ is the average intensity, $B(x,y)$ is the amplitude modulation of fringes and $\phi(x,y)$ is the phase to be solve for, also known as the wrapped phase.

For transient events measurements we use phase demodulation from a single fringe pattern implementing a function based on the Isotropic Quadrature Transform [16, 17]. Given the normalized version of a fringe pattern, the corresponding quadrature term can be gotten as

$$Q\{I_{NORMALIZED}(x,y)\} = -sin[\phi(x,y)] \tag{5}$$

where { } , is the isotropic quadrature operator. The wrapped phase of the modulation phase can be obtained from

$$W\{\phi(x,y)\} = arctan\left(-\frac{Q\{I_{NORMALIZED}(x,y)\}}{I_{NORMALIZED}(x,y)}\right) \tag{6}$$

And finally, the wrapped phase $W\{\phi(x,y)\}$ is then unwrapped by means of multigrid techniques [18]. In this case, many frames of a transient event video were processed to get their unwrapped phase maps.

Once we get all unwrapped phase maps, a sample pixel is extracted to graph the behavior of the event.

To determine the deflation speed of the membrane in volume V change of the sphere through time t, considering a negative variation and the decrease of its radius:

$$-\frac{dV}{dt} = 4\pi r^2 \frac{dr}{dt} \tag{7}$$

where we have the velocity $v = \frac{dr}{dt}$, then this factor is given by the following equation:

$$v = \left(\frac{-1}{4\pi r^2}\right)\frac{dV}{dt} \tag{8}$$

3. Simulated and experimental results

According to the theoretical description presented in Eq. (4), we simulate several interference patterns considering a sine function (0-2π) excitation. The number of fringes increase or decrease depending on the frequency entered in each interference pattern.

We obtain the wrapped phase $\phi(x, y)$, computed according to Eq. (6) of each pattern, and subsequently we process the unwrapped phases. Once unwrapped all phases, we choose the same pixel (x, y) from every phase maps and graph the new function.

Fig. 2 shows some points in sine function and its corresponding simulated interference patterns, as well as the wrapped and unwrapped phases and the signal obtained.

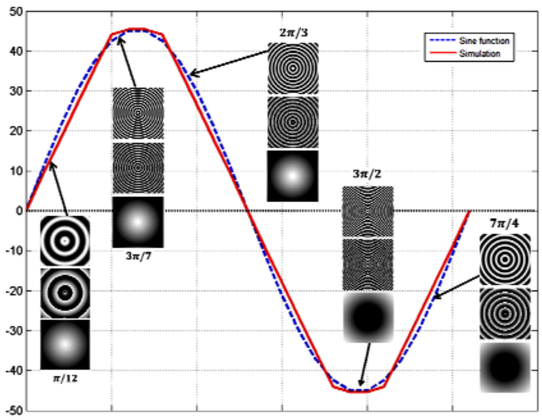

Fig. 2. Some simulated interference patterns and its wrapped and unwrapped phases. The graph indicates the comparison between a sine function (0-2π) and the function obtain from the unwrapped phase maps.

Once the simulation is done, a latex membrane is placed in front of the camera according to the experimental setup shown in Fig. 1. The membrane was subjected to an increase in its surface with air and then was deflated to measure the transient event. The event was captured just over 13 seconds in video with a rate of 30 frames per second, which was separated into 400 frames.

According to the actual measurements of the membrane's area which is covered by the camera, and the measurements of the captured images, we have a magnification of 1.7x, considering images with a resolution of 72ppi.

Fig. 3 in row 1 shows the fringe patterns generated by the interference of the two fringe patterns projected on the latex membrane, taken from some frames of the video; in Row 2 and row 3 we can observe wrapped and unwrapped phase maps corresponding. We notice that fringes are gradually decreasing in size due to the shrinkage of the membrane over time, having the same effect as the simulation.

For each unwrapped phase map, the same pixel was extracted to determine its response. Fig. 4 shows the resulting curve of the 400 frames for three different positions in the extraction of the pixels.

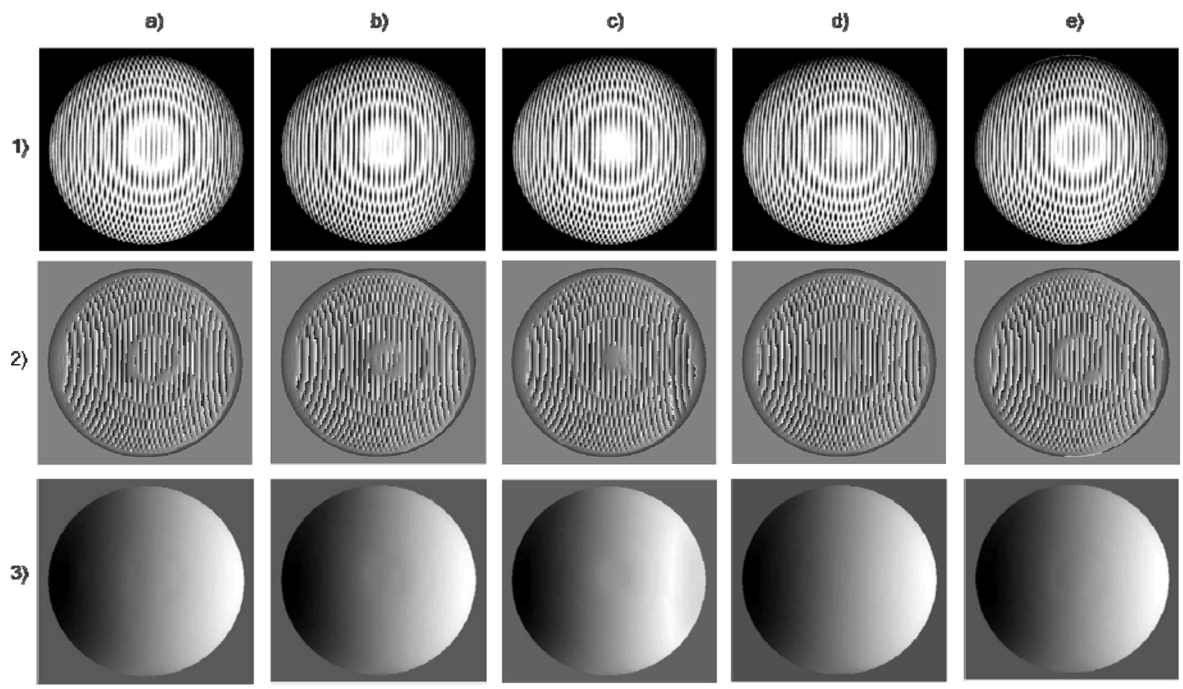

Fig. 3. Row 1) Fringe patterns of frames: a) 1 (0 seconds), b) 100 (3.33 sec.), c) 200 (6.7 sec.), d) 300 (10 sec.) and e) 400 (13.3 sec.), Row 2) Wrapped phase maps and Row 3) Unwrapped phase maps for corresponding frames in Row 1)

Curves obtained were approximated into a cubic function $ax^3 + bx^2 + cx + d$ giving the polynomials shown in Fig. 4:

b) $y = 7.4244 \times 10^{-7}x^3 - 4.9468 \times 10^{-4}x^2 + 7.9925 \times 10^{-2}x + 2.0839$ (upper pixel),
c) $y = 8.4689 \times 10^{-7}x^3 - 5.0019 \times 10^{-4}x^2 + 6.3832 \times 10^{-2}x + 4.8365$ (central pixel)

and

d) $y = 8.4541 \times 10^{-7}x^3 - 5.4155 \times 10^{-4}x^2 + 8.2991 \times 10^{-2}x + 2.0638$ (lower pixel)

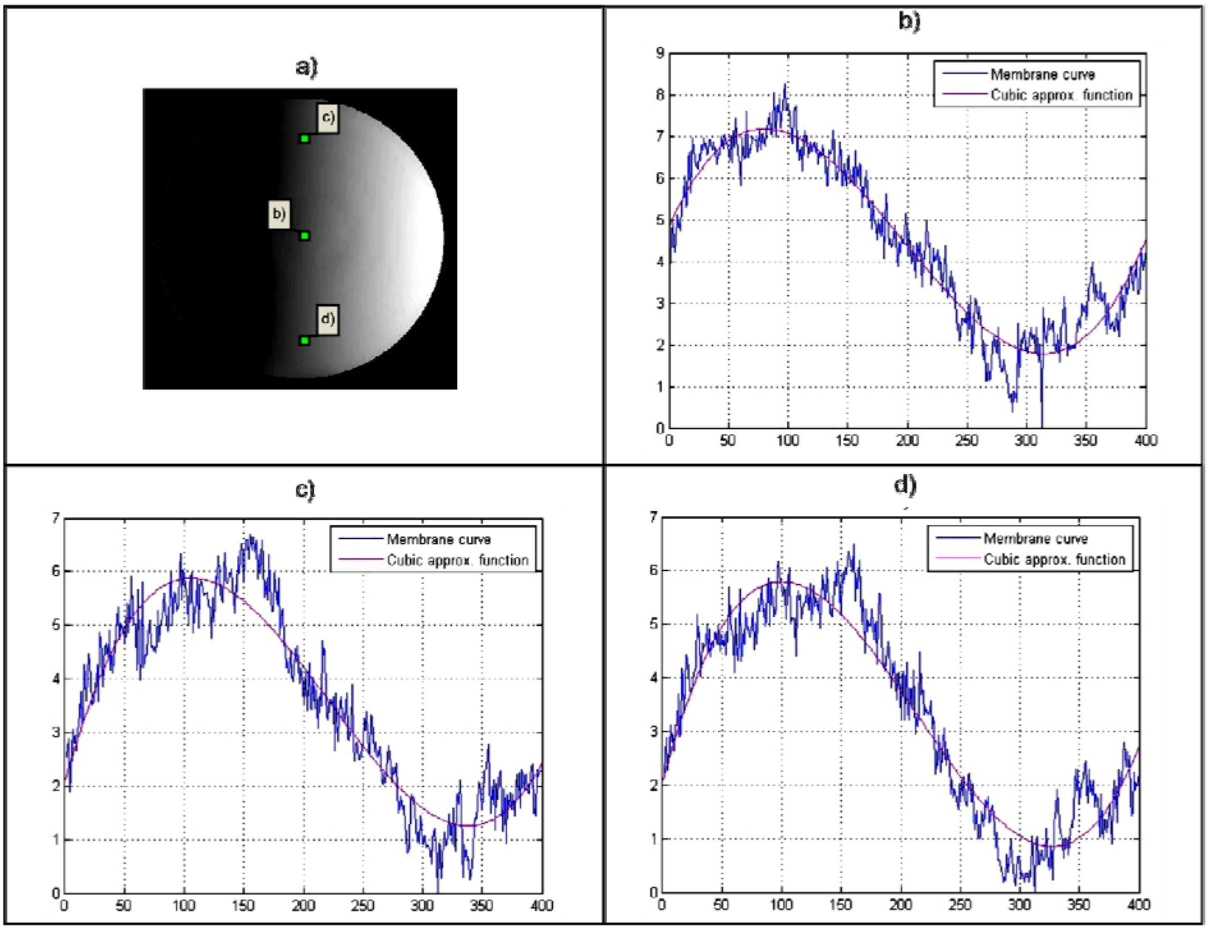

Fig. 4. a) Latex membrane unwrapped phase map which indicates the coordinates of the extracted pixels. Membrane curves of coordinate compared to the cubic function: b) Central pixel, c) upper pixel and d) lower pixel

Fig. 5 compares the graphs of the curves at the three measurement points of the membrane which is submitted to a transient event. Here we can observe the differences between the heights of three measured points.

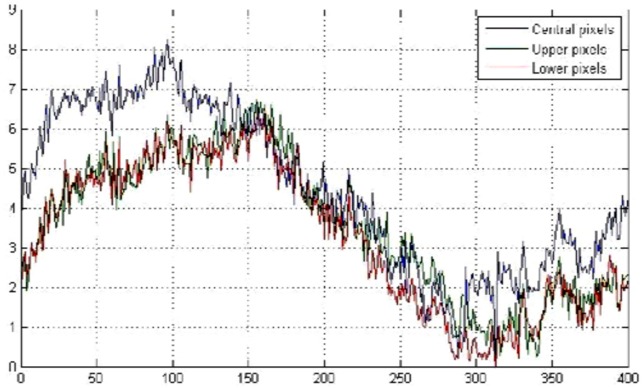

Fig. 5. Comparison of the three measuring points of the transient event in the latex membrane

4. Conclusions

In this work we have presented a fast way to obtain the behavior of the profile surface of a latex membrane subject to a transient event. The proposed method doesn´t need of calibration, synchronization or other kind of experimental consideration to work properly. Double-digital fringe projection for phase retrieval is a technique that offers a good approximation to the profile of an object that can be under extremal conditions. The application of this technique is very easy and allows fast measurements, so, it is an excellent option for engineering applications. The experiment can be implemented for many dynamic events, considering the frame rate.

The interference fringe pattern obtained over the object exhibits its shape considering even its shadow areas and can be seen in real time without the need of any computer processing, just by watching and interpreting the form of the fringes. For observation of these overlapping fringes there are some technical parameters in the procedure developed that should be considered, such as relation among focal distance of projectors, the projector-object distance with the number of projected fringes. In addition to this, each projector allows to adjust the trapezoidal correction for the projected image, which depends on the camera-projector-object angle.

In the experimental results shown in Figs. 4 and 5 it can be observed that the technique provides information about changes in the membrane when is subjected to a transient event, which in this case, reduced its volume. In consequence, the procedure proposed in this paper can be translated to other kind of materials with similar or different transient events as well as periodic events, implementing modifications in the procedure developed which should be minimal compared to the results that could be obtained.

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