Double-digital fringe projection for optical phase retrieval of a single frame

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Digital Fringe projection profilometry is widely used to measure the 3D surface shape of an object. In industrial applications, where dynamic situations are presented, single frame analysis techniques are suitable to work better and are desirable over other optical techniques due to the fast acquisition of data, the few elements needed to build an experimental set-up and the non-synchronization between all components required to do the measurement. In this paper we propose a method based on a double-digital fringe projection that only requires one fringe pattern for the extraction of the optical phase by means of the Isotropic Quadrature Transform. The method is very simple, fast, low cost and easy to implement for engineering purposes. The double-digital fringe projection allows the camera of the set-up to record the shadows corresponding to the shape of the object, giving the chance to get a good quality measurement considering details of the object that cannot be detected with other kind of illumination or other optical techniques. A few experiments are presented and the resulted retrieval phase of different objects is shown together with a profile of the phase across the y-axis in a selected point along the x-axis.

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1. Introduction

3D shape measurement is widely applied in some many fields like robot vision, medical image diagnosis, virtual reality, production automation [1,2], and other fields, such as 3D surface shape measurement of small systems, like Micro Electro Mechanical Systems (MEMS) [3-5]. Digital fringe projection profilometry (DFPP) for measuring the topography of 3D objects is a very active research area in optical metrology [6-10] and one of the most important 3D shape measurement methods [11]. This technique offers advantages like whole field acquisition, non-contact and non-invasive measurements, high resolution and fast data processing.

The fringe projection technique is based on the principle of triangulation [12] and it has been improved with the apparition of the digital projector, going from the projection of classic gratings to the projection of computer-generated fringe patterns. Furthermore, these fringe patterns can be modified on shape, color, size, frequency, etc. without the need of making any change in the physical set-up of the experiment because all those changes would be done on the computer directly. However, it has been reported that in the fringe projection technique by a digital fringe projector, the wrapped phase is obtained in an unconventional way, so the current phase quality criteria [13, 14] are not able to detect shadow areas being this an important consideration for doing good quality measurements.

In this paper we propose a double-digital fringe projection technique to detect shadows coming from the object to be measured. The fringe patterns projected come from two digital projectors that project to the object (and at the same angle) exactly the same fringe pattern previously generated by a computer.

With this double illumination over the object, the camera can register more information (including shadows) that will help to improve the quality of the measurement and to get a better phase retrieval according to the real shape of the object.

Many algorithms have been used to calculate the phase data, for example, the Fourier transform algorithm [15, 16], the wavelet transform algorithm, the multi-step and the spatial phase shift algorithms [17 – 20], the windowed Fourier transform algorithm [21, 22], and so on. In this work, a function based in the Isotropic Quadrature

Transform [23, 24] is employed to get the phase retrieval coming from a single fringe.

2. Experimental set-up and theoretical description

In the proposed technique, a fringe pattern of interference is formed by superposing two single frequency fringe patterns coming from two digital projectors, as it is shown in Fig. 1. Two digital projectors are simultaneously connected to a computer, as well as the camera. The projectors receive a fringe pattern generated digitally by software or a computer program code. These fringe patterns are then projected to the object to be measured. The combination of the fringe patterns, together with the object shape, gives a new fringe pattern of interference that is then recorded in the computer by means of the camera and finally processed to get the phase retrieval.

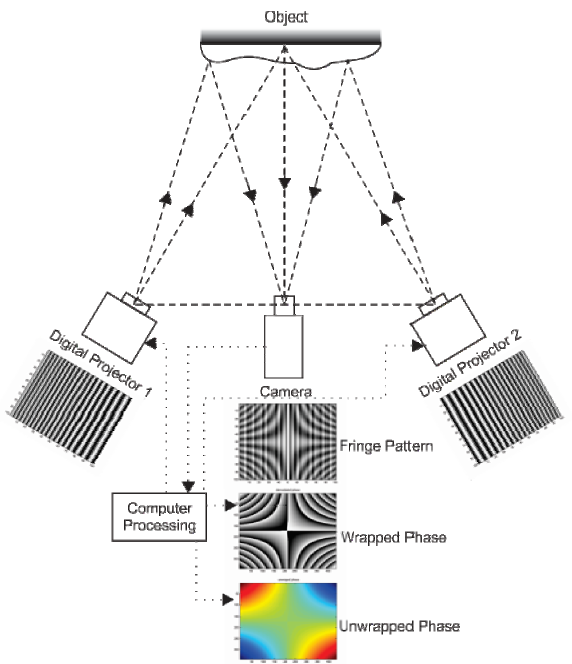

Fig. 1. Optical set-up for the double-digital fringe projection measurement.

Numerically, in this superposition of fringes, we can consider three elements: the two single-frequency fringes and the fringe generated by the superposing of the two linear patterns simultaneously. So, the resulted fringe pattern of interference can be expressed as:

$$I(x,y)=a(x,y)+b_1(x,y)\cos[\phi_1(x,y)]+ \\ +b_2(x,y)\cos[\phi_2(x,y)]+b_3(x,y)\cos[\phi_3(x,y)] \quad (1)$$

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:

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

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

$$I(x,y)=a(x,y)+b_1(x,y)\cos[\varphi_\alpha(x,y)+\varphi_1(x,y)]+ \\ +b_2(x,y)\cos[\varphi_\beta(x,y)+\varphi_2(x,y)]+ \\ +b_3(x,y)\cos[\varphi_\gamma(x,y)+\varphi_3(x,y)] \quad (3)$$

However, the camera only records the combination of these 3 elements, so optically, the camera records only one fringe pattern of interference, which has been modified according to the shape of the measured object. In this case, the resulted fringe pattern of interference registered by the camera can be written as:

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

where $A(x,y)$ is the average intensity or the background 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.

Considering that $\phi(x,y)=2\pi f_0 x+\varphi(x,y)$, where f_0 is the spatial carrier frequency and $\varphi(x,y)$ is the phase modulation of fringes and is related to the shape of the measured object, Eq. (4) can be finally rewritten as:

$$I(x,y)=A(x,y)+B(x,y)\cos[2\pi f_0 x+\varphi(x,y)] \quad (5)$$

Phase demodulation from a single fringe pattern offers a big opportunity to venture in industrial applications under difficult conditions, for example, for transient vibrations measurements where it is not possible to repeat and synchronize the dynamic event with electronic components or special equipment. In recent years, many algorithms for phase extraction of single fringes have been published, some examples are shown in [25 – 31].

For this work, a function based in the Isotropic Quadrature Transform [20, 21] is used for the demodulation of fringe patterns with closed or opened fringes. Given the normalized version of a fringe pattern, according to [32] the corresponding quadrature term can be get as

$$Q\{I_{NORMALIZED}(x,y)\}=-\sin[\phi(x,y)] \quad (6)$$

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

$$W\{\phi(x,y)\} = \arctan\left(-\frac{Q\{I_{NORMALIZED}(x,y)\}}{I_{NORMALIZED}(x,y)}\right) \quad (7)$$

and finally, the wrapped phase $W\{\phi(x,y)\}$ is then unwrapped by means of multigrid techniques according to [33].

The recovered phase gives a lot of information about the measured object and this information could be very useful for further applications like 3D object reconstruction for example.

Fig. 2 shows an example of the method for phase recovery applied in this work. In figure 2a it can be seen a fringe pattern of interference, according to Eq. (5), then it is normalized as it is shown in figure 2b. The wrapped phase coming from Eq. (7) is presented in figure 2c, and finally the unwrapped phase is obtained and is exhibited in figure 2d.

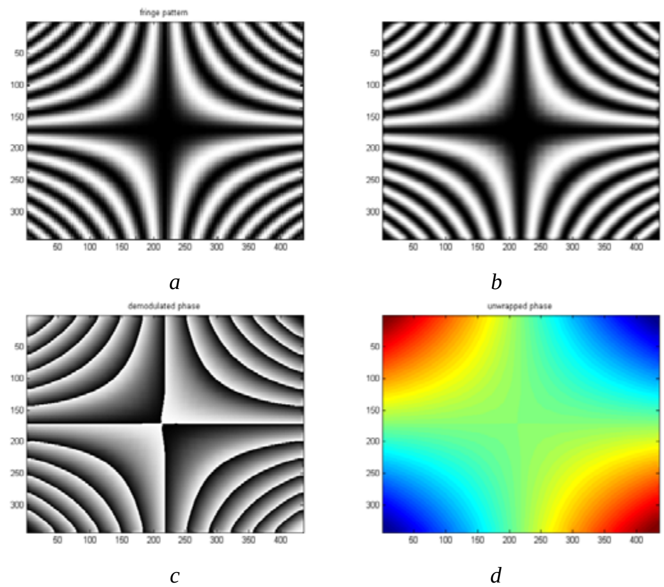

Fig. 2. Simulated phase recovery from a single fringe pattern of interference. (a) Simulated fringe pattern of interference; (b) Normalized fringe pattern; (c) Wrapped phase and (d) Unwrapped phase.

With the information obtained in Fig. 2, it is possible to plot the profile of any place of the surface of the object.

3. Experimental results

Fig. 3 shows an experimental example of the proposed technique. A wedge is presented in front of the camera and the phase of it is extracted by means of the double projection technique.

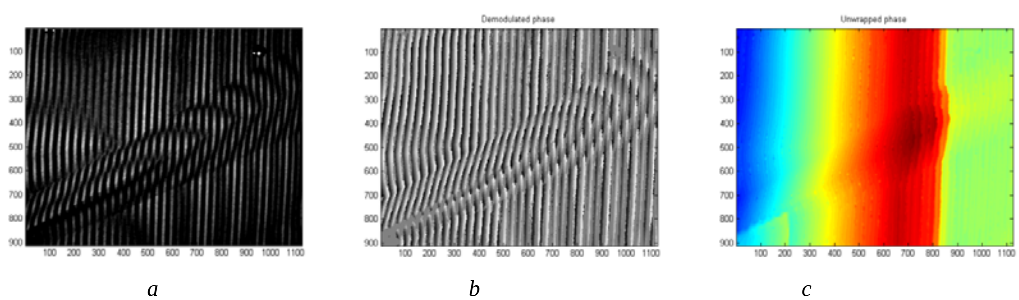

Fig. 3. Phase retrieval of a wedge. (a) Fringe pattern recorded by the camera; (b) Wrapped phase and (c) Unwrapped phase.

Note That the fringe pattern of interference showed in figure 3a, gives a notion of the shape of the object measured without the need of doing a computational processing , in other words , it can be seen at a glance the physical form that has the measured object. This effect is precisely done by the interference of the two fringe patterns projected over the object by the two digital projectors.

In Fig. 4 it can be seen a cylinder measured by the double-digital fringe projection, the phase retrieval of it, and a profile of the object measured across the y-axis to demonstrate that the technique can very easily work for 3D reconstruction of objects for engineering applications.

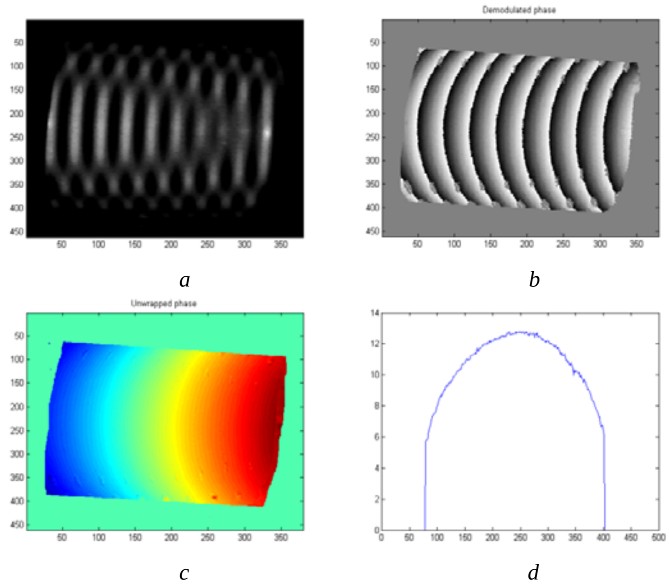

Fig. 4. Phase retrieval of a cylinder. (a) Fringe pattern of interference; (b) Wrapped phase; (c) Unwrapped phase; (d) Profile across y-axis.

For cylindrical objects, it is difficult to get the phase retrieval with optical techniques; however, the proposed technique gives a good quality measurement of a cylinder as it shown in Fig. 4. The double illumination coming from the digital projectors allows the camera to get an image containing, inclusive, the shadows formed by the cylinder. Fig. 4d shows the profile of the cylinder across the y-axis in a specific place over the x-axis.

Finally, the phase retrieval of a hand is shown in Fig. 5. As in the previous results, it can be seen that the technique works very well for phase retrieval of an irregular surface of an object, like the hand.

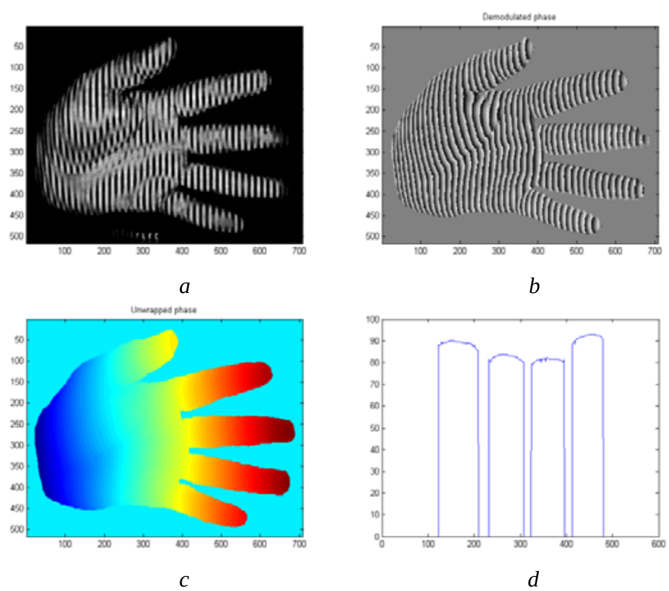

Fig. 5.Phase retrieval of a hand. (a) Fringe pattern of interference; (b) Wrapped phase; (c) Unwrapped phase; (d) Profile across y-axis.

A profile of the phase retrieval along y-axis that goes through the fingers is shown in Fig. 5d.

Note that the shape is well recovered as the surface of the finger is good identified.

4. Conclusions

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 easy application of the technique allows fast measurements and is an excellent option for engineering applications.

The digital projectors give a good quality and uniform illumination over the object, but, because the light projected is coming from different directions, the 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.

This technique can be improved to get better results, but, for a first understanding of the object to be measured, it's a good alternative for non-contact and non-destructive optical technique for phase retrieval.

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