Real - Time Spatial Light Modulated Digital Holographic Interferometry Applied in Art Structural Diagnosis

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Abstract. In this paper we apply digital holographic interferometry as a structural diagnosis tool to investigate some surface defects in a XIXth century wooden icon. We use a fully digital experimental set-up for real time acquisition and digital optical reconstruction of holographic sequences. The light source is a He-Ne laser, the digital recording component consists of a CCD camera and a spatial light modulator (SLM) works as a digital holographic projector for the optical reconstruction of the interferograms. Both the acquisition set-up and the reconstruction one are functioning simultaneously therefore the changes in the surface structure are visualized in real-time like a digital holographic interferometry "fringe motion picture" with a 20 fps display. Detachment defects of the paint layer are identified using this non-destructive method and the real-time feature has proven to be useful because it gave a very useful dynamicity to the entire investigation process.

Keywords: Digital holography · Interferometry · Art conservation Lasers · Structural diagnosis

1 Introduction

Because a wave front encodes in itself information about a propagation environment or a reflecting surface, a method for wave front recording can be classified as a remote sensing tool for studying different classes of objects. In most cases light is not a destructive tool when interacts with a high range of objects and, because of this, it can be used to obtain information about their surface, shape, texture, size and their variations in time. Holography and holographic interferometry are methods for recording waves and due to this fact they can be used to obtain information about the environments that generates and reflects waves or support wave propagation [1, 2]. Artworks are a high interest class of objects and in the past years very important research resources are invested in their restoration and conservation. Lasers are widely used in this domain through holography and holographic interferometry as new tools to access invisible information about structural and mechanical properties of artworks. These

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being said holographic interferometry can be regarded as a non-destructive method for structural diagnosis in art [3, 4]. In this paper we intend to improve the speed of data acquisition when applying digital holographic interferometry in art diagnosis by eliminating the numerical reconstruction as a time consuming step and by creating an instant feedback of the method during its appliance by using a spatial light modulator as an instant wave front reconstruction device [5].

2 Theoretical Background

Holographic interferometry is a method through which more than one wave is holographically recorded on the same recording device whether it is a photographic emulsion or a digital pixel area.

Recording the amplitude distribution is a very familiar procedure in classical photography, but more than that, in holography also the phase is recorded by means of interference of an object wave, which carries the object information, with a reference wave, coherent to the object one.

The most of the information regarding a specific object properties like shape, contour, color, texture, etc. can be accessed by recording the wave originated by the object through emission or reflection [6, 7]. Thus being said, because of the phase recording and reconstruction which preserves the 3-dimensionality of the object, holography is a very powerful method for recording and reconstructing waves.

2.1 Digital Holographic Interferometry (DHI)

When an interferogram, which consists of two or more stacked holograms, is illuminated with a coherent light, the reconstructed waves will interfere with one another and the interference fringe pattern translates in itself the modification suffered by the wave between the multiple stacked holographic recordings. The waves corresponding to an initial reference state of the object (A_{o1}) and a consecutive one (A_{o2}) are described by the following equations:

$$A_{o1} = a_0 e^{i\varphi_{o1}}, \quad A_{o2} = a_0 e^{i\varphi_{o2}} \tag{1}$$

The modification suffered by the object between the two consecutive exposures will not affect the wave real amplitude but its phase. The intensity distribution on the sensor for the first and the consecutive holographic frames are:

$$I_{1,2} = \left|A_{o1,o2} + A_R\right|^2 = a_O^2 + a_R^2 + a_O a_R e^{i\left(\varphi_{O1,02} - \varphi_R\right)} + a_O a_R e^{-i\left(\varphi_{O1,02} - \varphi_R\right)}. \tag{2}$$

The two waves are numerically added, operation which is equivalent in classical holographic interferometry to a double holographic exposure. The hologram reflectance, R_H, is:

$$R_H = R_O - K(I_1 + I_2) = T_O - 2K\left(a_O^2 + a_R^2\right) - Ka_O a_R e^{i(\varphi_{O1} - \varphi_R)} \\ - Ka_O a_R e^{-i(\varphi_{O1} - \varphi_R)} - Ka_O a_R e^{i(\varphi_{O2} - \varphi_R)} Ka_O a_R e^{-i(\varphi_{O2} - \varphi_R)} \tag{3}$$

where R_O and K are constants for linear variation of the reflectance. The reconstructed wave, A_R, is modulated by the hologram reflectance, R_H:

$$A_R R_H = C_O a_R e^{i\varphi_R} - Ka_O a_R^2 e^{i\varphi_{O1}} - Ka_O a_R^2 e^{-i(\varphi_{O1} - 2\varphi_R)} \\ - Ka_O a_R^2 e^{i\varphi_{O2}} - Ka_O a_R^2 e^{-i(\varphi_{O2} - 2\varphi_R)} \tag{4}$$

The second and the fourth terms describe up to the same real coefficient the two object waves recorded separately [9]. Their phase difference is:

$$\Delta\,\varphi(\vec{r}) = \varphi_{O2} - \varphi_{O1} \tag{5}$$

After renaming the coefficients in Eq. (4), the two waves corresponding to the two consecutive states of the object overlap and their superposition gives an amplitude distribution described by:

$$\Psi = Ca_O e^{i\varphi_{O1}} + Ca_O e^{i\varphi_{O2}} = Ca_O e^{i\varphi_{O1}}\left[1 + e^{i\Delta\varphi}\right] \tag{6}$$

The intensity distribution reveals a fringe pattern which encodes the object modifications through the recording steps:

$$|\Psi|^2 = 2C^2 a_O^2 [1 + \cos\Delta\varphi(\vec{r})] \tag{7}$$

In this paper we opted for an optical reconstruction method of the interference patterns using a SLM and not a numerical one because we tried to keep a specific dynamic feature of the deformation within the reconstructure procedure.

2.2 Optical Reconstruction in DHI Using a Spatial Light Modulator (SLM)

Real time DHI performed in this paper can be described as a sequence display of holographic interferograms generated by successive subtraction (or addition) of consecutive holograms from a reference one. As we pointed out, upwards two holograms stacked on the same recording medium generate a holographic interferogram which can be reconstructed with the help of a reference playback wave.

Choosing an optical reconstruction method we eliminated the time consuming numerical reconstruction process of waves [9] which in facts simulates the diffraction of the playback wave on the holographic amplitude distribution pixel matrix. Using the SLM we practically transform the virtual recorded holograms, consisting in grey levels pixel distributions, into “hard” SLM holograms, which can physically perform instantaneous diffraction and playback wave modulation. The only time consuming process is the subtraction operation of the successive holograms from a reference one.

But this single numerical procedure enables us to display ~15 holographic interferograms/second. This very convenient frame rate leads to a very dynamic investigation method for some structural diagnosis of diffusive objects.

Because of its real time feature one can also use the method for real time monitorisation of object shape variation through a reconstruction or a restoration procedure. The real time DHI ensures an almost instant feedback of a supposed invasive restoration procedure. All this practical advantages makes the method very useful for in situ noninvasive diagnosis and restoring monitorisation.

3 Experimental Set-up

The recording coherent light source was a He-Ne laser working in 632.8 nm wavelength and having a 30 mW output power and the reconstruction one was a green Nd: YAG (532 nm) working in continuous regime. The digital sensor consisted in a CCD monochrome camera with a sensor set at 1280 × 960 pixel resolution which can record at ~30 fps convenient speed. The holographic acquisition was performed through a classical configuration optical set-up (Fig. 1). For the wave optical reconstruction we used a phase only SLM, HEO1080 from HoloEye having a resolution of 1980 × 1080 pixels and a 15.36 × 8.64 mm active area size. Each pixel can display 256 phase levels within 2π phase domain.

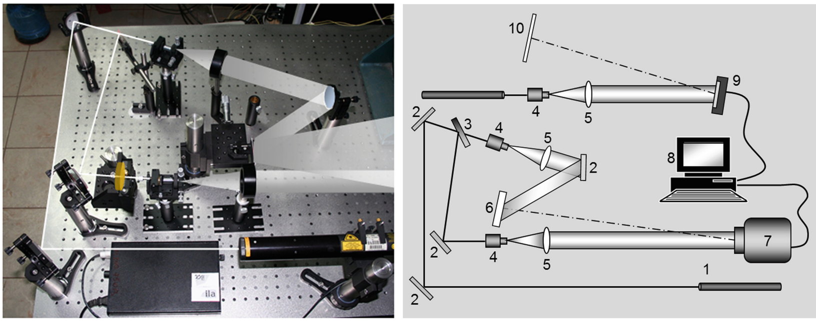

Fig. 1. Experimental set-up for digital recording of holographic sequence in reflexion regime - lab picture (left) and the entire hybrid both acquisition and reconstruction set-up – schematic representation (right). He-Ne laser (1), deflecting mirrors (2), variable beam-splitter (3), spatial filters (4), collimating lens (5), object (6), CCD camera (7), computer (8), phase only SLM (9), projection screen for fringe dynamic pattern real-time visualisation (10). The fringe image is a real one and can be displayed on a projection screen

To the computer unit there are connected the CCD camera sensor, the usual display monitor which shows the holograms in amplitude and also the phase only SLM which converts the virtual amplitude holograms in “hard” phase holograms.

These optical reconstruction procedure enables us to perform “live” diffraction on the SLM and also to instantly display the reconstructed waves at a repetition rate given by the subtraction numerical program ($\sim$15 fps). In the end we practically visualise a live holographic interferometry fringe motion pictures which translates the changes induced in the object surface.

4 Experimental Results

The object used for testing the real time DHI with optical SLM reconstruction was a wooden painted XVIIIth century icon.

There are some consecrated methods to produce interference fringes generated by some changes in the object. Hence, the objects loads can be induced thermally, mechanically or by vibration. We choose the thermal method for noninvasive considerations. So the objects where slightly heated with a hot air flow to induce changes in their surface. The object shape recurrence induces fringes and the structural defects are visible in the fringe patterns discontinuities.

The wave divergence correlated with the light source coherence allowed us to investigate an area with $\sim$30 cm in diameter. Quantitative measurements can be made only for instant intermediate holographic frames (Fig. 2)

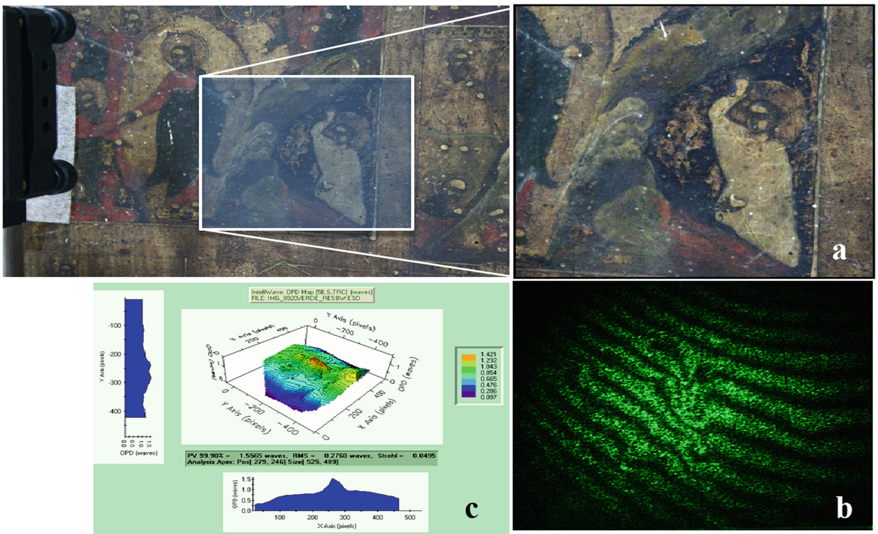

Fig. 2. Structural surface defect in the paint layer of an XVIIIth century wooden icon investigated with real time DHI. In usual visual investigation the defect cannot be noticed (a). In the interferogram one can observe the paint detachment defect (b). The surface profile is generated with OPD (optical path difference) function in IntelliuWave (c).

The fringe orientation and the fringe distance changes constantly as the objects surface returns to its original state before the heat load. This dynamicity of the fringes eases the observation of surface structural defects.

5 Conclusions

Real-time digital holographic interferometry is performed as a noninvasive structural diagnosis tool for defects localization in artworks. The experimental set-up consists in both acquisition and reconstruction configuration working simultaneously. The holographic interferogram sequence reconstruction is done by optical means to eliminate the time consuming numerical method.

Thus being said we may state that, using a hybrid holographic acquisition and reconstruction set-up, we perform both DHI recording and DHI reconstruction in the same time and this detailed description of the experimental set-up can confirm the advantages of optical reconstruction in holography using a SLM pointed in the upper section. Hence, the dynamicity of the process is kept through the reconstruction and the real time fringe visualization and the instant observational feedback confers some very useful features to the optical holograms reconstruction using a SLM.

In the present paper we keep the investigations and the experimental set-up to a demonstrative framework. In the future work we intend to apply the method in more detailed quantitative and qualitative features.

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