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Dynamic Digital Holography for recording and reconstruction of 3D images using optoelectronic devices

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***Abstract*— In this work, we present the optical recording and reconstruction of dynamic 3D digital holograms using optoelectronic devices. Digital Holography technique allows recording and reconstruction of three-dimensional images of real objects, since a hologram presents both the intensity and phase information about the object. The experimental implementation of digital holographic systems for recording, as well as for numerical and optical reconstruction of three-dimensional objects became possible. We developed an experimental setup that allowed the optical recording (construction) of dynamic digital holograms (DHs) from real three-dimensional objects in CCD cameras, together with their numerical reconstruction and their optical reconstruction in a dynamic process by using a spatial light modulator, SLM; it was used a single holographic experimental setup in the entire process. We have obtained good results that enable excellent prospects for applications in recording and reconstruction of 3D scenes.**

***Index Terms*—**Digital holography, Dynamic process, Imaging systems, Optoelectronic devices.

I. INTRODUCTION

Holography is a non-destructive interferometric-diffractive technique [1], which allows recording and reconstruction of three-dimensional (3D) images from objects, since a hologram presents both their intensity and phase information. This technique can be used to reconstruct the wavefront of 3D objects by recording the interference pattern of a reference coherent wavefront with the object's wavefront (scattered or transmitted from its surface) using coherent illumination. This recorded interference pattern is known as a hologram and contains information about the amplitude and phase of the object's wave field. The information can be reconstructed by diffraction, when the hologram is illuminated with the reference wave.

From the hologram, one can obtain an image containing all the information about the original object. The reconstructed image exhibits all the effects of perspective and depth of focus that the object would exhibit, in other words, it is an image with three-dimensional features [2] [3]. The realistic character of these images makes holography one of the most used techniques in three-dimensional displays nowadays [4].

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Holography was first implemented by using photosensitive materials as a recording and reconstruction media [5]; those materials required chemical processing prior to the reconstruction and are associated with *Classical Holography*. Subsequently, materials that dispensed the chemical processing emerged: the photorefractive crystals, which are used as recording medium in *Photorefractive Holography* [6, 7]. This technique has been broadly applied in surface contouring and in phase-shifting real time interferometry [8, 9, 10, 11, 12, 13, 14], as well as in microscopy [15, 16]. Another technique widely used is *Computational Holography*, where the holograms are generated computationally (Computed Generated Holograms, CGH) by means of processes of inverse light propagation. There are several papers in which this technique is used to generate three-dimensional scenes of objects that can be reconstructed either numerically [17] or optically, using optoelectronic devices [18, 19, 20, 21, 22], even for dynamic processes [23].

The development of faster and high resolution optoelectronic devices: CCD cameras (Coupled Charge Device) [24], Spatial Light Modulators (SLMs) [3], efficient laser fonts and stable optical and opto-mechanical systems of outstanding quality, made it possible to experimentally implement holographic systems for recording and reconstruction (numerical and/or optical) of optical waves from objects [25, 26, 27], as well as from optical beams [28, 29].

The holographic processes that utilize optoelectronic devices as a recording media, allowing numerical reconstruction of the holograms are associated to *Digital Holography*. In the same way, the processes of computational generation of holograms, where the recording of virtual objects is performed numerically (CGHs), are associated with *Computational Holography*; these holograms can be reconstructed both numerically (by using digital holography techniques) and optically (using laser light, optical and optoelectronic systems: SLMs [25, 30].

In order to reconstruct the three-dimensional features of objects is broadly used the phase shifting technique in digital holography [31], the images resulting from this process withdraw the zero order term and the conjugated image of the object, that are usually seen in DH; one disadvantage of this technique is the constrain to slowly varying phenomena and the constant phase during the recording.

The holographic recording of dynamical scenes has very interesting applications, due to the possibility of generate three-dimensional images of dynamic phenomena. Digital Holography has been used for this purpose using optoelectronic devices; in 2002, for example, Zhiwen Liu et. al. [32] managed to record ultrafast phenomena by recording several frames of DHs in a single frame in the CCD; Su et. al. [33] studied dynamical phenomena by using perfilometry for surface analysis; Zwick et. al. [34] used Spatial Light Modulators (SLMs) in the reconstruction of dynamic scenes from real objects by using statically recorded DHs and processing them in order to observe deep features: Paturzo et. al. [27]. The techniques that combine optical acquisition with later processing of the DHs are also reported, as in Matsushima et. al. [35], where optically recorded digital holograms from a real object are superimposed in order to produce a three-dimensional scene. More recently, Xu et. al. reported a dynamical reconstruction of CGHs [36], in the process were used 24 SLMs to get the

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reconstructed images. The dynamical recording of DHs was also performed for Li et. al. [37], who numerically reconstructed the amplitude and phase of the water droplet evaporation process.

We developed an experimental setup that allowed the optical recording (construction) of dynamic digital holograms (DHs) from real three-dimensional objects, together with their numerical reconstruction and, their optical reconstruction in a dynamic process by using a SLM; it was used a single holographic experimental setup in the entire process. We have obtained good results that enable excellent prospects for applications in recording and reconstruction of 3D scenes. We were able to optically record DHs from real diffuse opaque objects of different shapes and sizes; both in a static and a dynamic process. It was possible to optically reconstruct a three-dimensional scene from a spinning real opaque object of approximately 5.5cm high. The measurements were done using a high acquisition rate, good resolution and sensibility CCD camera; the optical reconstruction of the DHs was performed by means of a transmission spatial light modulator in the hologram plane in order to optically reproduce and project the 3D scene.

II. THEORETICAL BASIS

In Fourier optics, a hologram is an optical element (transparency or processed holographic recording medium) that presents information about an optical wave. Thus, considering a monochromatic wave whose complex amplitude in a plane is $E_o(x,y)$, object wave, and a second monochromatic plane wave $E_r(x,y)$, reference wave. A hologram, with complex transmittance $t(x,y)$ proportional to the intensity $|E_r(x,y)+E_o(x,y)|^2$ produced by the interference of these two waves(Fig.1.a), object and reference, has de full information of the optical waves, in other words,

$$t(x,y)\propto|E_r(x,y)+E_o(x,y)|^2 \tag{1}$$

$$t(x,y)\propto|E_r|^2+|E_o|^2+E_r^*E_o+E_rE_o^* \tag{2}$$

$$t(x,y)\propto I_r+I_o+E_r^*E_o+E_rE_o^* \tag{3}$$

where $I_0=|E_0|^2$ and $I_r=|E_r|^2$ are the intensities of the object and reference waves respectively.

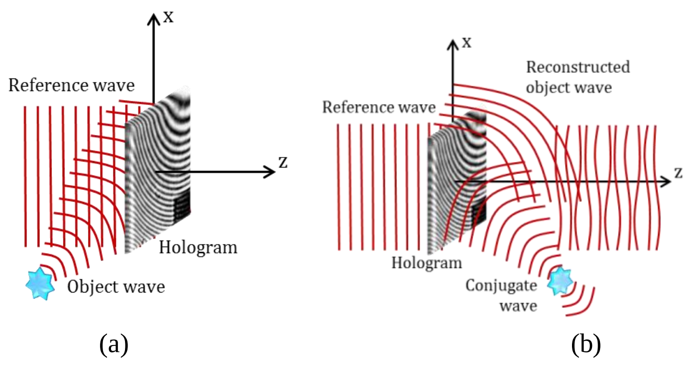

Fig.1. Recording and Reconstruction processes. (a) Holographic recording and (b) reconstruction processes.

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Numerical Reconstruction via Digital Holography. For digital reconstruction, we used the Double Propagation Method (DPM) [31] [38] which consists in two steps for digital hologram reconstruction: first, is made the numerical calculus of propagation until the focal plane; following, the complex amplitude of the diffraction pattern in this plane is calculated and a new calculus of propagation until the image plane.

This method allows performing the image reconstruction begin from holograms focused in the CCD plane, or out of it, and with only one hologram can be calculated the phase field.

The description of this method can be made by: the first step, the Angular Spectrum $A(k_\xi, k_\eta; z=0)$ of the hologram is obtained. The Angular Spectrum is defined as the Fourier Transform of the digital hologram:

$$A(k_\xi, k_\eta; z=0) = \iint E_H(\xi_0, \eta_0, 0)\exp[-i(k_\xi \xi_0 + k_\eta \eta_0)]d\xi_0 d\eta_0 \tag{4}$$

where, k_ξ and k_η are the spatial frequencies of ξ and η. $E_H(\xi_0, \eta_0, 0)$ is the complex amplitude of the digital hologram. Then, the virtual image and the zero order are removed digitally and the field correspondent to this new spectrum on the hologram plane is calculated. Is performed a propagation until the focal plane of the image $z = D$ and a new Angular Spectrum is calculated in the position z: $A(k_\xi, k_\eta; z)$.

$$A(k_\xi, k_\eta; z=D) = A(k_\xi, k_\eta; z=0)\exp(ik_z D) \tag{5}$$

where $k_z = \sqrt{k^2 - k_\xi^2 - k_\eta^2}$.

Using the inverse Fourier Transform, the field correspondent to this plane is calculated $E_H(u, v, z)$.

The next step of this method is based on a second propagation until the image plane d_j. The field is determinate on this plane:

$$A(k_\xi, k_\eta; z=d_j) = A(k_\xi, k_\eta; z=D)\exp(ik_z d_j) \tag{6}$$

$$E_H(x', y', d_j) = \iint A(k_\xi, k_\eta; z=d_j)\exp[i(k_\xi x' + k_\eta y')dk_\xi dk_\eta \tag{7}$$

This calculation results in a matrix of complex numbers and the amplitude and phase of the object wave can be determined:

$$I(x', y') = \mathrm{Re}[E_H(x', y')]^2 + \mathrm{Im}[E_H(x', y')]^2 \tag{8}$$

$$\Phi(x', y') = \arctan\frac{\mathrm{Im}[E_H(x', y')]}{\mathrm{Re}[E_H(x', y')]} \tag{9}$$

The relation between the phase $\Phi(x', y')$ and high of the object $h(x', y')$ is given by phase $\Phi(x', y')$ = $(2\pi/\lambda)\, h(x', y')$.

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III. EXPERIMENTAL METHODS

The experimental holographic setup we developed is based on a Mach-Zehnder interferometer. This setup allowed us to record three-dimensional real scenes digital holograms, as well as to perform their numerical and optical reconstructions.

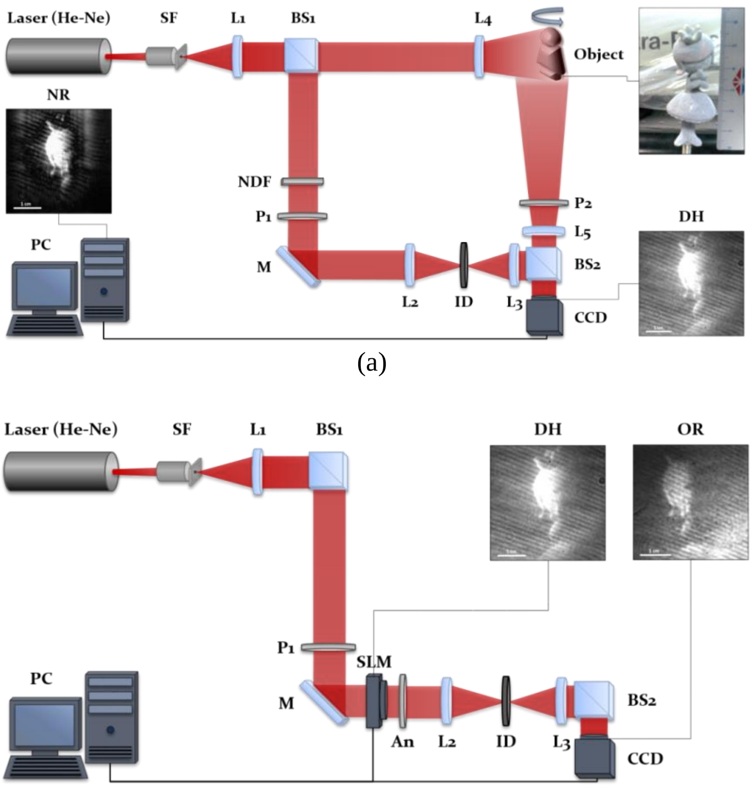

Fig.2. Schematic arrangement of the (a) digital holographic recording and (b) optical reconstruction processes, using a CCD camera and a transmission spatial light modulator (SLM) respectively. It was used a He-Ne laser and a 3D object; SFs are spatial filters, Ls are lenses, BSs are beam splitters, Ms are mirrors, Ps and An are polarizers, ID is an iris diaphragm and NDF is a neutral density filter. The insets show the three-dimensional object under study, one of the digital holograms recorded in our system (DH), its numerical reconstruction (NR) and its optical reconstruction (OR).

The experimental setup used the devices: He-Ne laser (R-30995 Red He-Ne Laser) of 632.8nm e 17.0 mW, optical and opto-mechanical systems and, as a recording medium it was used a high speed and good resolution *CCD* camera (Photron FASTCAM-PCIR2) with 7.4x7.4 μm^2 pixel size and acquisition rate up to 250 *FPS* at the maximum resolution (512x480 pixels) in the holographic recording and reconstruction processes. Also, it was used a transmission spatial light modulator SLM (LC 2002 SLM Holoeye Photonics) in order to optically reproduce a 3D scene.

The numerical reconstruction of digital holograms (DHs) was performed using the program HOLODIG, in MATLAB, double propagation method [38]. All the DHs were reconstructed numerically before the optical reconstruction.

It was necessary to make a readjustment to the DHs because of the difference in the camera and software resolution 512x480 and 640x480 respectively; this conversion was done using a routine in MATLAB, which was developed based digital imaging processing methods [39].

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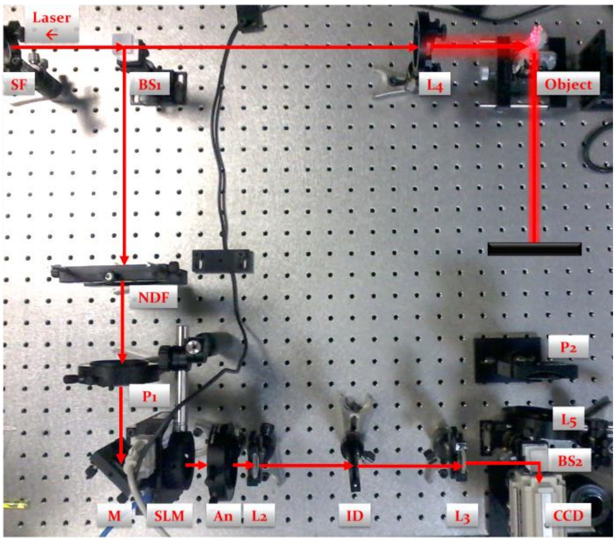

Fig.3. Experimental setup of the digital holographic recording and reconstruction processes. It was used a He-Ne laser, a CCD camera and a transmission spatial light modulator SLM; Ms are mirrors, Ps and An are polarizers, SFs are spatial filters, Ls are lenses, BSs are beam splitters, ID is a iris diaphragm and NDF is a neutral density filter.

A. Holographic recording process

In this section, it will be shown the optimized arranges for holographic optical recording of 3D objects in motion.

It was used a single lens (*L5*: focal distance f = 50.2 mm) focusing the object beam information on the camera surface (see arrange in Fig.2.a). In both processes (recording and reconstruction) was used a 4F optical filtering technique [3] and a spatial light modulator in the last one [29]. In the recording process, the *4F filter* only inverts the reference beam, since there is not an iris diaphragm for frequency selection. In Fig.2, it is shown the schematic arrangement used, the difference between the elements used in recording and reconstruction is limited to the SLM and the neutral density filter *NDF*.

The experimental setup, as well as the path followed by the reference and object beams in the recording process is shown in Fig.3; it was used a holographic setup based on a Mach-Zehnder interferometer. The light coming from the laser propagates towards the spatial filter *SF* (10×microscope objective with a 25μm pinhole); it is collimated by the lens *L1* (f = 150 mm) and then split by *BS1*; the transmitted part of the beam, object beam, is directed to the object (which is placed on a motor that allows it to spin in its own axis), it pass through the lens *L4* (f = 25.4 mm) to intensify the light reaching the object. This light scattered from the object is then polarized by *P2*, focused on the CCD by *L5* and recombined in *BS2* with the reference beam. The reflected part of the beam, reference beam, pass through an absorption neutral density filter in order to reduce its intensity, since it is more intense than the object beam; light is then polarized by *P1* (in the same polarization that *P2*) and directed to the mirror *M1*, where it is reflected towards a 4F filter; there, the beam pass through the lens *L2* (f = 100 mm), an iris diaphragm and the lens *L3* (f = 100 mm), which focus the beam on the *CCD* surface. Finally, the reference and object beams are recombined in *BS2* and interfere in the surface of the *CCD* camera, forming the digital hologram DH.

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Using this setup was analyzed a USAF resolution target and three-dimensional 5.5 cm high opaque object: ‘ballerina’, in Fig. 4. In ‘ballerina’, it was necessary to paint it with retro-reflective paint (*Reflective Paint 8010*, made by 3M and composed of pigmented micro glass beads) so that the scattered lights arriving at the camera were approximately uniform. The first digital holograms obtained from this object were recorded while it was static; then, it was used a small motor so that the object could spin and be able to record the dynamic holograms for the moving object.

The acquired holograms in the dynamic process were saved as separate holograms, in order to reconstruct them numerically and optically.

(a) (b) (c) (d)

Fig.4 (a) USAF resolution target and three-dimensional object used in the setup (ballerina): (b) original opaque object, (c) painted object, and (d) motor detail.

B. Holographic reconstruction process

The arrangement shown in Fig.2.b was used in the holographic optical reconstruction process of digital holograms by using a SLM (it was used one of the arms of the Mach-Zehnder interferometer used in the recording process). This arrange allowed the dynamic reconstruction process of the acquired holograms.

The experimental setup is shown in Fig. 3; light coming from the laser propagates towards the spatial filter *SF*, the beam is collimated by the lens *L1* and then split by the *BS1*, the transmitted part of the beam is blocked in order not to interfere in the process, the reflected part, reference beam, is polarized by *Po1* and directed to the spatial light modulator SLM by the mirror *M1*. Since the modulator has a twisted nematic display, light coming out from it is perpendicular polarized to the initial light, therefore it was used another polarizer *An* after the SLM. It was also used a 4F filter: the beam passes through a lens *L2*, an iris diaphragm in the Fourier plane in order to select the diffraction orders and a lens *L3*, focused in the CCD surface. Before reaching the camera, the beam passes through the last beam splitter *BS2* and the light reflected by it carries the reconstructed image, which can be observed in real time by means of a computer.

The 3D object digital holograms were reconstructed using the first order of diffraction of the beam; this optic reconstruction was done both for the statically and dynamically recorded holograms.

In the optical reconstruction process, as its name implies, the reconstruction is done by using an arrangement of optics elements. The computer is only used as an intermediary storage medium for the digital holograms, unlike the numerical reconstruction, where the whole process is done

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computationally.

In the optical reconstruction of computer generated holograms (CGHs) or digital holograms, the spatial light modulators can be used as a tool for dynamic exchange of holograms in real time. We used a transmission liquid crystal spatial light modulator SLM (LC 2002 Holoeye Photonics). In order to determine its diffraction efficiency and amplitude modulation were used experimental setup and an optical power meter.

It was measured the light optical power after passing through the polarizer Po, the modulator SLM and the analyzer *An*; the polarizers were set in order to have the maximum transmission in the arrangement, considering that they should always be perpendicular to each other. The amplitude modulation of the system as a function of the grayscale values of the SLM was obtained. It was considered the total transmitted intensity and the zero-order diffraction intensity.

It was also calculated the modulator diffraction efficiency by comparing the zero-order diffraction and the input optical power (44 mW and 336 mW respectively), resulting in a 13.1% diffraction efficiency. When using one of the DH acquired in the recording process, the diffraction efficiency fell to 7%; because of this limitation, the *NDF* was removed from the reconstruction arrangement in order to get a reasonable intensity in the reconstructed images.

IV. RESULTS AND DISCUSSION

The experimental results for the holographic recording and reconstruction are shown. It will be done a comparative analysis between the two techniques used in the reconstruction process, i.e., numerical reconstruction by means of the Fresnel algorithm and optical reconstruction using optoelectronic devices in an arrangement with a 4F filter.

A. Optical recording process of DH

One of the advantages of the digital recording of holograms is that it allows us to numerically reconstruct them without any additional processing for converting the interference pattern into a PC compatible format. We used this feature in order to verify if the recorded holograms could be numerically reconstructed and identify which ones would be appropriated for an optical reconstruction. Once verified that the technique was able to record static digital holograms that could be numerically reconstructed, it was implemented a system that allowed to record holograms from moving objects, i.e., dynamical acquisition of digital holograms.

It was used the arrangement showed in Fig.3, where the object was able to rotate around its own axis. The first holographic record was done for a static 3D object (ballerina), shown in Fig.6.b; although the interference fringes were a bit undefined and the object could not be recorded completely (only the upper half), it was possible to reconstruct its intensity distribution numerically (Fig.6.c). After optimization of the lens system, it was possible to record about 80% of the object. It was performed a static holographic recording with this lens setup and, since the main characteristics of the

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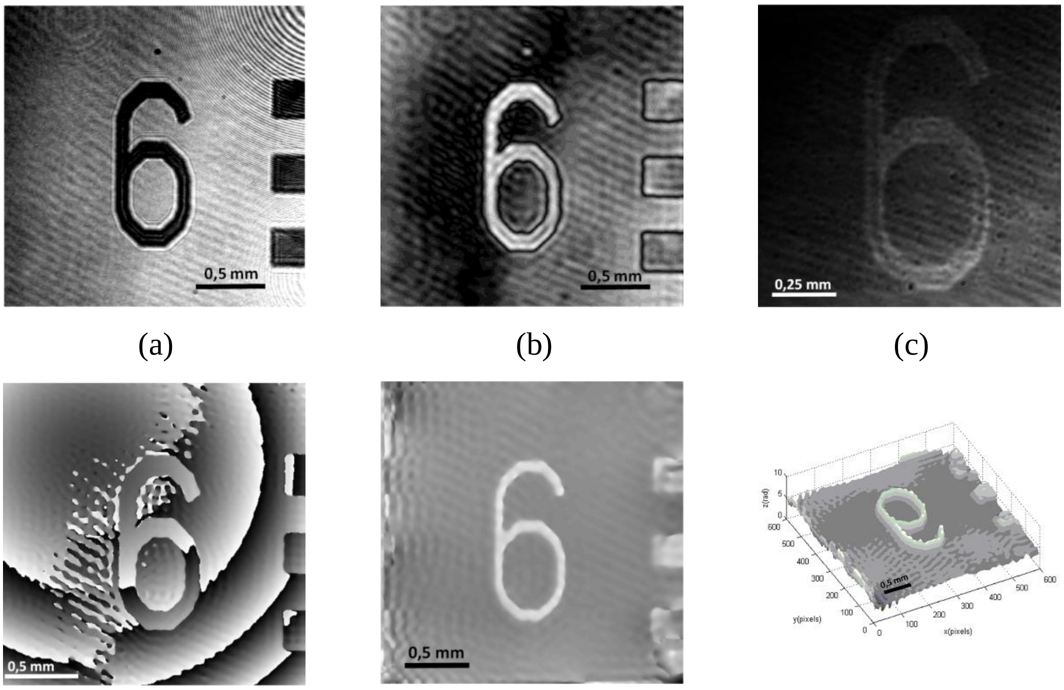
original object remained in the numerical reconstruction, it was maintained this arrangement in the dynamical recording.

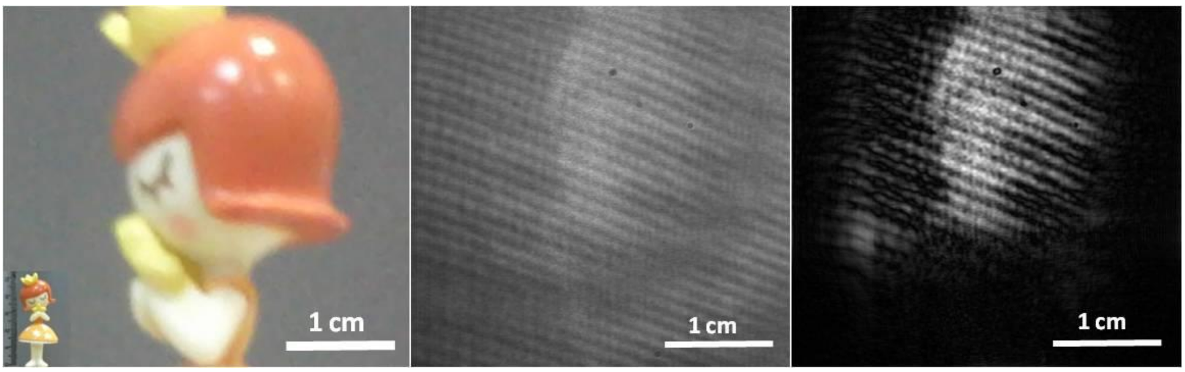


(a) (b) (c)

(d) (e) (f)

Fig.5. USAF resolution target: (a) digital hologram (b) numerical reconstruction (c) optical reconstructions (d) phase map (e) unwrapped phase map and (f) three-dimensional profile.

The dynamical holographic recording of the moving object was done using an acquisition rate of 125 fps and the maximum resolution of the CCD (512x480 pixels); it was recorded a 360º spin of the object in 294 frames. In Fig.7 is shown a sequence of four (4) digital holograms recorded in a dynamical process.



(a) (b) (c)

Fig.6. (a) 3D object (b) digital hologram and (c) numerical reconstruction.

Despite the dynamical acquisition of holograms generally requires adjustments on the intensity of the illuminated object, as well as in the illumination direction and exposure time for each position [27], the digital holograms recorded using our experimental arrangement shown well-defined fringes, without the need for any individual adjustment.

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As expected, the holograms have some undesired interference due to vibrations from the surroundings and some experimental limitations. Since our experimental arrangement is compact, there were very small spaces between the optical elements in which the dust particles accumulated, making it difficult to remove them completely. Even though, it was possible to obtain the intensity images (2D) of the object by means of a numerical reconstruction process.

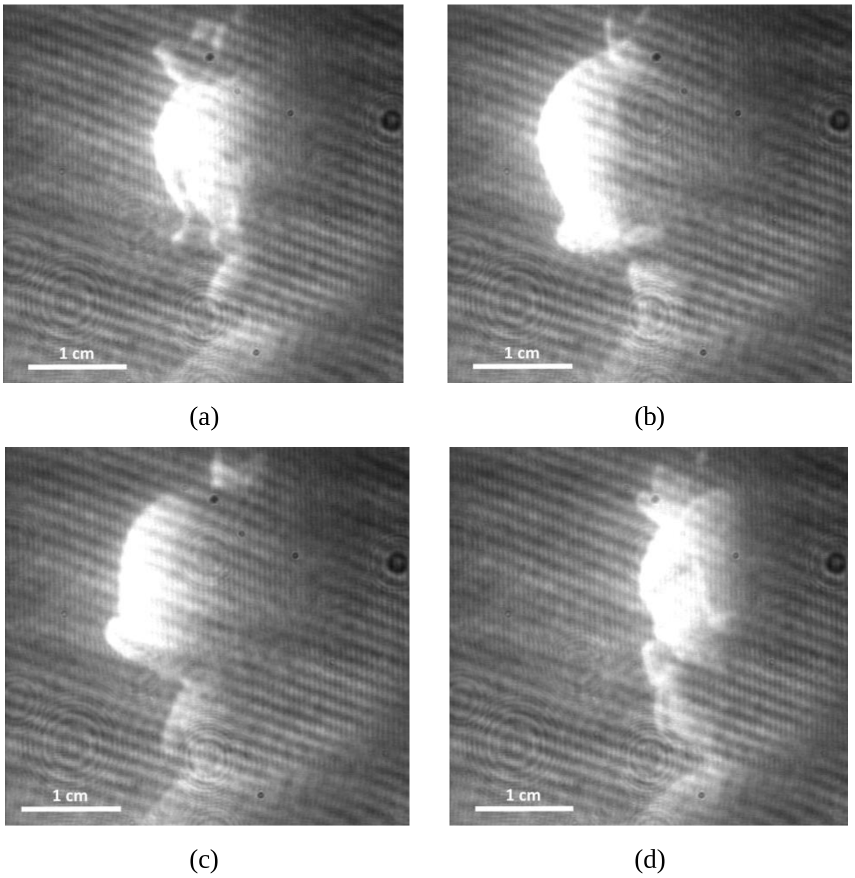

Fig.7. Digital Holograms for 4 different views of the object (ballerina).

B. Numerical reconstruction process of DH

The numerical reconstruction of the digital holograms was performed using the software HOLODIG, that uses the holographic reconstruction techniques: Double Propagation Method (DPM) [31] [38]. This numerical reconstruction was performed for sixty (60) of the 294 digitally recorded holograms; here are shown some of them, together with their numerical reconstructions. In Fig.8 can be observed several views of the numerical reconstruction from the dynamic digital holograms; we can see that the main object features were conserved and some signals from the reference beam, that may occur if in the diffractive process the reference and object beams were not completely separated.

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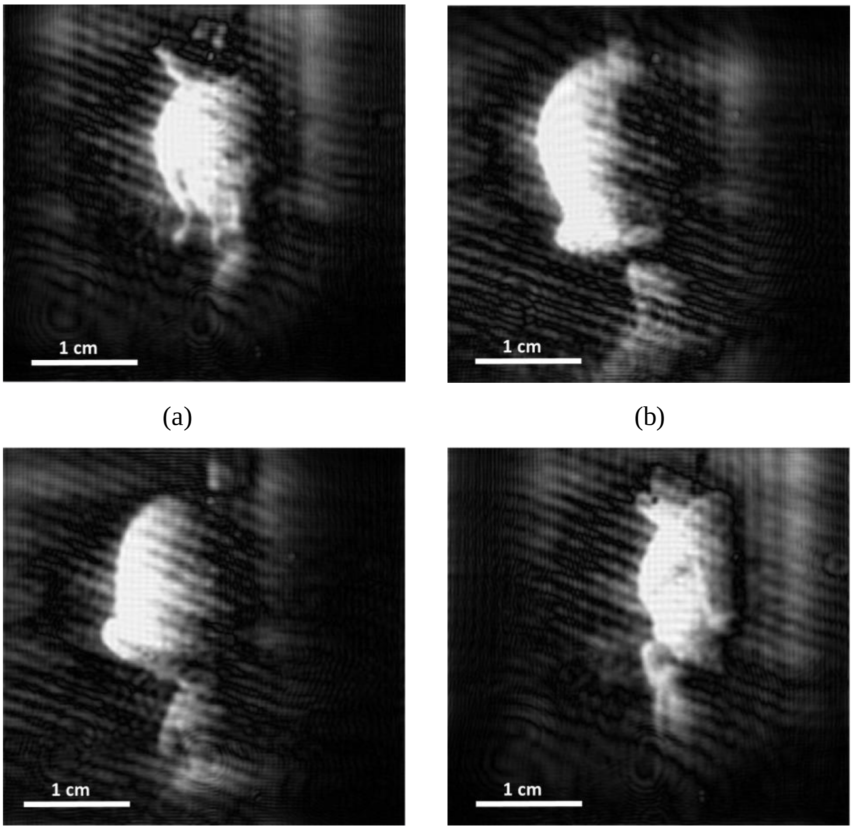

(a) (b) (c) (d)

Fig.8. Numerical reconstructions for 4 different views of the object (ballerina).

C. *Optical reconstruction process of DH*

The DHs showed in Fig.7 were optically reconstructed using the He-Ne laser and a transmission spatial light modulator with liquid crystal display (LC SLM 2002). The optical reconstruction of the holograms recorded in the dynamic process was performed for the same (60) DHs reconstructed numerically; all of them were equally adjusted in the SLM, with fixed levels of gamma, brightness and contrast. The holograms (DHs) were positioned on the SLM at the same distance from the camera as in the recording. The SLM was set to invert the images and, using the 4F filter, the first orders of diffraction were selected. The reconstructed images were obtained by projecting them into the CCD (*Photron*) surface using the experimental setup showed in Fig.3.

Every opto-electronically reconstructed hologram was individually saved. When combining all of them, it was possible to observe the movement of the original object.The original features of the object were preserved, making it possible to clearly distinguish its shape and dimensions from the two-dimensional images generated in the process.

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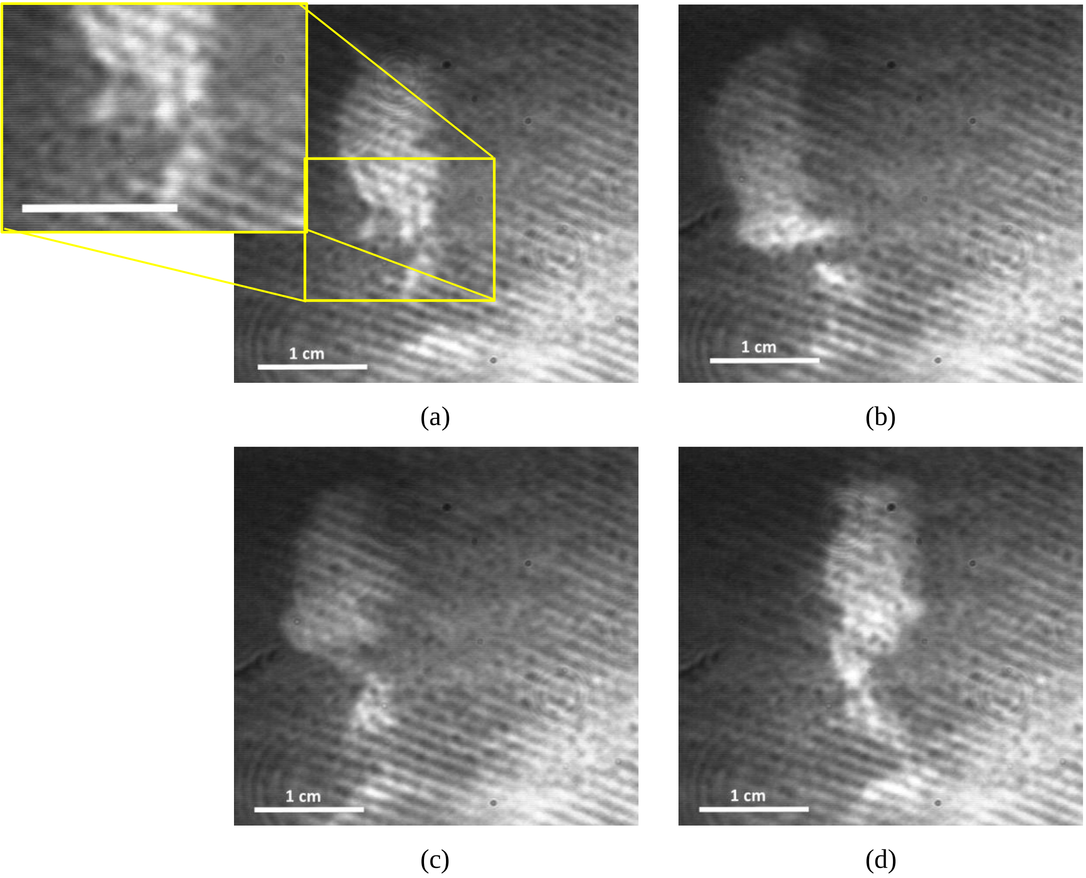

Fig.9. Optical reconstructions for 4 different views of the 3D object (ballerina). Detail is shown in the inset.

Fig.8 and Fig.9 show a sequence of views of the numerical and optical reconstructions from the 3D object studied, respectively. When comparing both reconstructions, we see that the high contrast diminish in the optical one, allowing us to perceive greater details in the shape of the object as a whole. The optoelectronic reconstruction let us distinguish the original features of the 3D object in movement with a high degree of clarity.

Some advantages of this configuration include the requirement of only one system alignment, as well as the use of a single camera for both processes: recording and acquisition of the intensity images in the optical reconstruction. This setup allowed us to optimize the optical recording and reconstruction of three-dimensional real (static and dynamic) objects.

The quality of the reconstructed holograms generated by a SLM depends upon several factors, as the modulation properties (amplitude variation to according the gray level), the number and geometry of the pixels (that may lead to low contrast), pixel refresh rate (in our case, 60Hz), dependence on the temperature (increase caused by incident light) and, the geometry of the reconstruction (incident angle e.g.). The main disadvantage in applying SLMs in dynamic processes is their finite response time: when a static pattern is placed on the SLM, the pixel's refresh rate influences the hologram reconstruction and, may lead to fluctuations in the intensity reconstruction.

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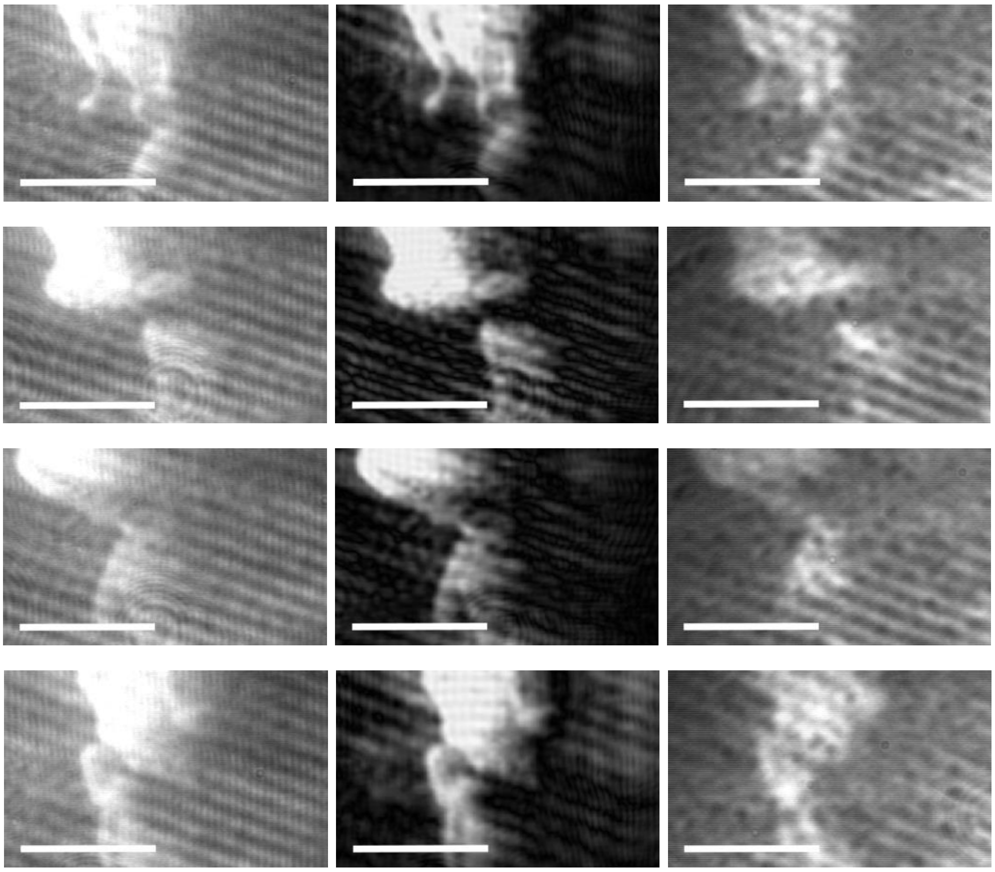

(A)
(B)
(C)
(D)

(a) (b) (c)

Fig.10. Detail for each of the 4 different views (A, B, C and D): (a) Digital Holograms, (b) Numerical reconstructions and (c) Optical reconstructions. The white bar represents 1cm. (Provavelmente vou tirar esta imagem)

V. CONCLUSIONS

In this work, we employed digital holographic techniques with the aim of implementing a system for the optical recording and reconstruction of dynamic holograms. We used a Mach-Zehnder based experimental set up for the optical recording of three-dimensional dynamic real objects digital holograms. This set up was also utilized in the optoelectronic reconstruction of these DHs in a dynamic process. These processes were performed by using optoelectronic devices as holographic recording and reconstruction medium: CCD cameras and a transmission SLM respectively. The optical reconstructed holograms were also compared to those reconstructed numerically.

We recorded static DHs from a reflective *USAF* resolution target (numeral 6) and a 5.5cm 3D object (ballerina), which allowed us to validate the acquisition process for well-defined objects. It was possible to perform both the numerical and optoelectronic reconstruction of the objects wavefronts. In a second stage, we were able to acquire dynamic DHs for the 3D object by using a high speed CCD camera. It was recorded a 360º rotation at 125fps in the maximum resolution of the CCD (512X480 pixels).

The recorded DHs have small defined interference fringes, besides slight interferences from vibrations in the environment. When comparing the holograms of the reflective smooth surface (resolution target) with those of the 3D object, we see that many undesired interference fringes arising from the roughness and diffusivity of the material were not present in the former. This may be explained due to the fact that light is scattered more uniformly in smooth surfaces. The digital recording of holograms, in addition to enable the numerical and optoelectronic reconstruction of two-dimensional intensity images, allowed us to observe the three-dimensional profile of real objects by means of their phase maps.

All the DHs were numerically reconstructed. The optical reconstruction process was done for every DH acquired statically, as well as for sixty DHs acquired dynamically: It was possible to optically reproduce a 3D scene projected in the CCD surface. The reconstructed images preserve the main features of the object and allow distinguishing clearly its shape and dimensions while rotating. When comparing these results to those of the numerical reconstruction, we perceive that the optoelectronic reconstruction clearly reveal more details from the original object.

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