ADVANCED DIGITAL LENSLESS FOURIER HOLOGRAPHY BY MEANS OF A SPATIAL LIGHT MODULATOR

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ABSTRACT

We present an optical setup which makes use of a Spatial Light Modulator (SLM) in order to electronically control the modification of the reference wave in Digital Lensless Fourier Holography. The SLM provides the advantage of avoiding any mechanical adjustments in order to adapt the reference wave to different object positions. A rule for the complex transmittance required to be generated by the SLM is presented and experimental results prove the big potential of the configuration in regards to Digital Holography.

Index Terms — Holography, Optical Signal Processing, Spatial Light Modulators, Discrete Fourier Transforms

1. INTRODUCTION

Digital Holography can be used to recover the complex amplitude of a monochromatic wave field scattered by an object [1]. Therefor, the scattered wave field is superposed by a reference wave with known characteristics and the resulting interference pattern is recorded by means of a camera sensor. Subsequent to the measurement the complex amplitude can be recovered across any remote reconstruction plane parallel to the recording plane by means of numerical determination of the diffraction integral [2]. Throughout the past decade, its unique properties made Digital Holography become a valuable tool in regards to optical metrology [3, 4] and as a recording technique for holographic 3D display technology[5].

A specific configuration of the digital holographic scheme is Digital Lensless Fourier Holography[6]. Here, the reference wave is chosen to be a spherical wave front with the corresponding origin located in the reconstruction plane, which in the utmost of applications coincides with the object plane. Hence, the characteristics of the reference wave depend on the position of the object with respect to the camera sensor. In this publication we present an experimental configuration which allows for the adaption of the reference wave to different positions of the object along the optical axis without the requirement of mechanical adjustment. This functionality is realised by means of an electrically addressed phase only liquid crystal Spatial Light Modulator (SLM), which allows for the manipulation of the phase distribution of a wave field and therefore can be regarded as a programmable optical device. SLMs are already used in a wide field of applications, such as optical signal processing[7], bio-photonics [8] and optical metrology [9, 10].

In the following section the digital holographic scheme is outlined within the scope of scalar diffraction and Digital Lensless Fourier Holography is explained. In section 3 the experimental setup is described in detail. Finally, an analytical expression for the determination of the complex transmittance to be generated by the SLM is presented and experimental results prove the big potential of the presented configuration in regards to Digital Lensless Fourier Holography.

2. THEORETICAL CONSIDERATIONS

2.1. Wave Field Propagation and Digital Holography

Within scalar diffraction, the phenomenon of optical wave field propagation is most accurately described by Rayleigh's integral formulas [11]. However, without loss of generality we will restrict the following discussion to the Fresnel approximated representation because it will be of particular convenience from a didactic point of view. According to Fresnel diffraction, the process of propagation can be expressed in terms of a single Fourier transform [12], e.g. given the complex amplitude $O(\vec{x})$ of a wave field across a plane $\{\vec{x}\}$, the complex amplitude $O_p(\vec{u})$ observed across a parallel plane $\{\vec{u}\}$ in a distance z_0 is well approximated by

$$O_p(\vec{u}) = S_1(\vec{u}) \cdot \mathcal{F}\{O(\vec{x}) \cdot S_2(\vec{x})\} \left(\frac{\vec{u}}{\lambda z_0} \right), \qquad (1)$$

where $S_1(\vec{u})$ and $S_2(\vec{x})$ are given by

$$S_1(\vec{u}) = -\frac{\mathrm{i}}{z_0 \lambda} \exp \left(\frac{\mathrm{i}k}{2z_0} |\vec{u}|^2 + \mathrm{i}kz_0 \right), \qquad (2)$$

$$S_2(\vec{x}) = \exp \left(\frac{\mathrm{i}k}{2z_0} |\vec{x}|^2 \right). \qquad (3)$$

Regarding Eq.(1) the ultimate goal of phase shifting Digital Holography [13] could be interpreted as to measure the wave field $O_p(\vec{u})$ scattered by an object in order to numerically recover the complex amplitude $O(\vec{x})$ in the object plane $\{\vec{x}\}$. For this, the wave field in the sensor plane is superposed by a reference wave $R(\vec{u})$ and the intensity $I_H(\vec{u})$ of the resulting interference pattern is recorded by a camera:

$$I_H = |O_p + R|^2 = |O_p|^2 + |R|^2 + O_p R^* + O_p^* R. \qquad (4)$$

By applying standard phase shifting techniques [14] it is straight forward to extract for example the first cross term in Eq.(4), yielding

$$H_p(\vec{u}) = O_p(\vec{u}) R^*(\vec{u}). \qquad (5)$$

If the characteristics of the reference wave are known, the wave field $O_p(\vec{u})$ can be extracted from Eq.(5) and substituted into Eq.(1) in order to numerically recover the complex amplitude $O(\vec{x})$ of the wave field across the object plane.

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2.2. Digital Lensless Fourier Holography

Considering the sampling properties of the camera sensor, a prudent choice of the reference wave appears to be a spherical wave $R_S(\vec{u})$ with its origin located in or close to the object plane. This scheme is called Digital Lensless Fourier Holography and its main advantage can be best understood from the structure of the Fourier transform of the recorded cross term in Eq.(5). Substituting Eq.(1) we find in accordance with the convolution theorem

$$\mathcal{F}(H_p)(\vec{\nu}) = [\mathcal{F}\{R^* \cdot S_1\} \otimes (O \cdot S_2)](\vec{\nu}). \quad (6)$$

If the origin of the spherical wave is located in the object plane it has the same structure as the linear chirp $S_1(\vec{u})$, i.e. $R_S^*(\vec{u}) = S_1^*(\vec{u})$. Thus, in this case the first term in the convolution in Eq.(6) becomes a Dirac-distribution and consequently the support of the band of the recorded signal is minimized. While there may be many reasons to minimize the support of the band, perhaps the most obvious one is the avoidance of unnecessary averaging due to the finite size of the sensors pixel.

As an additional benefit, if $R_S^*(\vec{u}) = S_1^*(\vec{u})$ holds and $\vec{\nu} = -\vec{x}\cdot(\lambda z_0)^{-1}$ is substituted, Eq.(6) directly yields the reconstructed wave field $O(\vec{x})$ in the object plane, yet conjugated and multiplied by the known linear chirp function $S_2^*(\vec{x})$. Hence, the reconstruction only requires a single Fourier transform which might be considered an advantage in regards to the computational effort.

3. EXPERIMENTAL SETUP

Numerous experimental implementations of the Digital Lensless Fourier Holography are known, including optical fibres in close vicinity to the object or additional optics to precondition the reference wave. However, if the distance between the sensing device and the object is changed, all of these approaches require either mechanical adjustments or they are restricted to sufficiently small objects in order to have a fibre placed close to them.

Therefore, in the following we present an experimental setup which makes use of an electronically addressed reflective phase only SLM which allows for the adaptive manipulation of the reference wave. This concept is exemplarily outlined by Figure 1. It is based on a Twyman-Green interferometer [15] using a coherent linearly polarised spherical reference beam. The object is not illuminated straight through the polarizing beam splitter but by an external illumination, which is not shown by Figure 1. Since the SLM is a birefringent device, the reference wave passes a quarter wave plate and a polarizing filter before being incident on it. This adjusts the polarization in accordance with the fast axis of the SLM of which the refractive index can be changed electronically. After being reflected by the SLM the quarter wave plate transforms the linearly polarized wave into a circularly polarized one. A part of this wave travels straight through the polarizing beam splitter towards the charge coupled device (CCD). The polarizing filter in front of the CCD generates interference between the orthogonally polarized reference wave and object wave across the CCD. This configuration allows for the manipulation of the phase distribution of the reference wave only by electronic means. It does not only enable the adaption to different object planes as it is shown in the following section, but also provides the capability of temporal and spatial phase shifting as well as correction of optical aberrations for example. Thus the setup allows for designing a compact yet considerably flexible wave field sensing device.

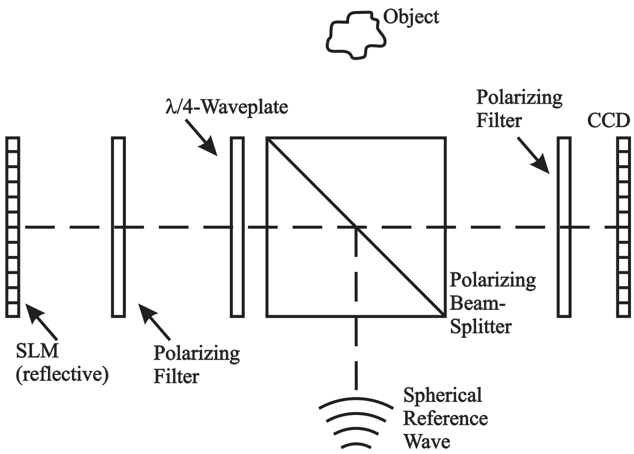

Figure 1. Experimental setup which is similar to a Twyman-Green interferometer [15] but instead of a direct illumination of the object through the polarizing beam splitter the object is illuminated by an external coherent light wave (not shown) originating from the same source providing the reference wave. The key element of the setup is a phase only reflective Spatial Light Modulator which allows for the modification of the reference wave.

4. EXPERIMENTAL INVESTIGATION

The key component of the introduced holographic setup is the SLM which allows for an electronically addressed modification of the reference wave. In this section we will present experimental results which demonstrate that this feature may be used to adapt the reference wave in Digital Lensless Fourier Holography to different object planes along the optical axis. This enables the minimisation of the recorded signal's band as outlined in section 2.2 yet independently from the relative distance between the object and the sensor of the CCD.

4.1. Complex Transmittance to be generated by the SLM

By default, the reference wave used in the presented holographic setup is a spherical wave generated by a fibre tip sitting on the optical axis in a distance r_0 from the SLM. Consequently, within the scope of the Fresnel approximation the corresponding complex amplitude across the plane $\{\vec{v}\}$ of the SLM can be expressed as

$$R_S(\vec{v}) = -\frac{\mathrm{i}}{r_0\lambda} \exp\left(\frac{\mathrm{i}k}{2r_0}|\vec{v}|^2 + \mathrm{i}kr_0\right). \quad (7)$$

The SLM may be used to change the radius of the wave front by modulating it with a complex transmittance $\chi(\vec{v})$. In order to change the radius by Δr it is straight forward to show that the complex transmittance to be generated by the SLM is given by

$$\chi(\vec{v}) = \exp\left(-\mathrm{i}\frac{k\Delta r}{2r_0(r_0+\Delta r)}|\vec{v}|^2 + \mathrm{i}k\Delta r\right). \quad (8)$$

Despite a constant amplitude, the modified reference wave $R'_S(\vec{v}) = R_S(\vec{v}) \cdot \chi(\vec{v})$ appears to originate from a virtual source point shifted by Δr with respect to the fibre tip, thus the setup can be electronically adapted to different object planes without the requirement of mechanically moving parts. However, the technique is of course limited by the finite pixel pitch of the SLM which was $\Delta p_{SLM} = 8\,\mu$m in our case. Effects arising from the discrete nature of the SLM are beyond the scope of this publication,

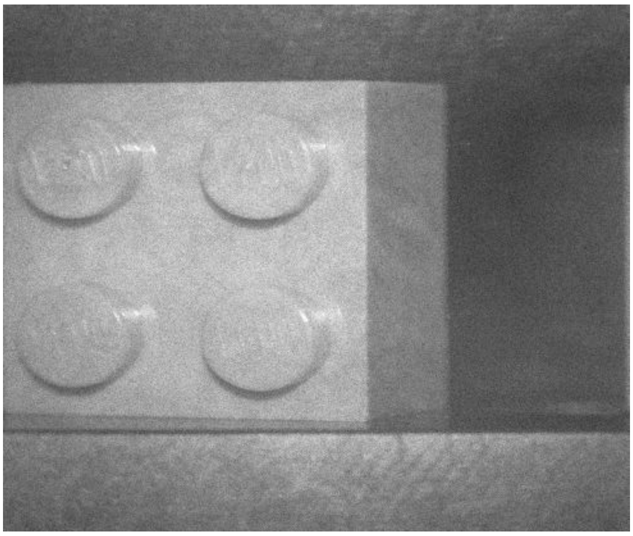

Figure 2. Module of the DFT of a hologram of a Lego® brick which is located in the default object plane of the experimental configuration.

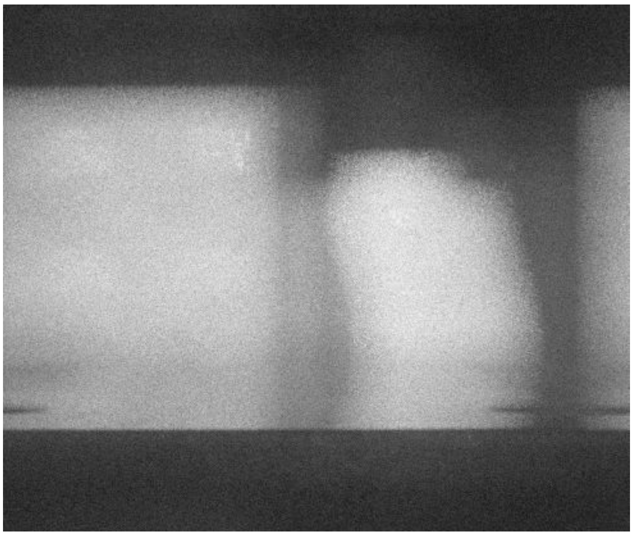

Figure 3. Module of the DFT of a hologram of two Lego® bricks which are located 55 mm away from the default object plane. The reference wave is not being modified. The size of the support of the band can be estimated by regarding the right edge of the DFT, where parts of the blurred scene appear as aliased frequencies.

but it should be mentioned that no significant consequences have been observed as long as the band of $\chi(\vec{v})$ satisfied the Nyquist-Shannon criteria [16].

4.2. Results and discussion

In order to verify the adaption of the reference wave to different object planes, digital holograms have been captured using the presented experimental setup. The employed SLM is a phase only reflective liquid crystal on silicon display supplied by HOLOEYE Photonics AG with a resolution of 1920 × 1080 pixel. Its configuration provides full 2π phase modulation with a linear electro-optical characteristic. Further informations about the calibration of the SLM can be found in Ref. [17]. The used CCD supplied by Allied Vision Technologies has 2452 × 2054 pixel with a pixel pitch of 3.45 μm. The reference wave as well as the object illumination have been provided by a coherent spherical light wave having a wavelength of $\lambda = 532\,\text{nm}$. In order to extract the cross term $H_p(\vec{u})$ given by Eq.(5) from the recorded interference patterns, temporal phase shifting has been applied by adding constant values to the distribution generated by the SLM.

As already mentioned in section 2.2, the discrete Fourier transform (DFT) of a digital hologram captured in a Lensless Fourier configuration reconstructs the wave field in the object plane and therefore lets appear the object to be in focus. As an example, Figure 2 shows the DFT of a hologram of a Lego® brick captured that way. In this case, the Lego® brick was located 176 mm away from the CCD which matches the optical path between the fibre tip and the CCD and therefore could be considered the default object plane of the sensing device. Consequently, the complex transmittance generated by the SLM was set to $\chi(\vec{v}) = 1$ in this case, i.e. apart from its phase shifting capabilities the SLM acted as a simple mirror.

Figure 3 shows the DFT of a hologram of a second scene, which is located in a distance of $\Delta r = 55\,\text{mm}$ from the default object plane. The hologram has been captured under the same conditions like the first scene, but the reconstructed scenario is seriously blurred because the first term of the convolution in Eq.(6) is not a Dirac-distribution in this case. In order to estimate the support of the recorded signal's band, it is helpful to regard the right edge of the DFT where parts of the blurred scene actually appear as aliased frequencies. In Figure 4 the DFT of a hologram of the same scenario is shown, but this time the SLM was used to generate the complex transmittance of which the phase distribution $\phi_\chi(\vec{v}) = \arg[\chi(\vec{v})]$ is shown by Figure 5 in order to adapt the reference wave to the shift of the object plane. The distribution was determined by means of Eq.(8), where the optical path between the fibre tip and the SLM is an intrinsic value of the setup and was given by $r_0 = 86\,\text{mm}$. The most obvious effect caused by the modification of the reference wave is that the scene appears to be in focus again, hence the Lensless Fourier scheme is restored.

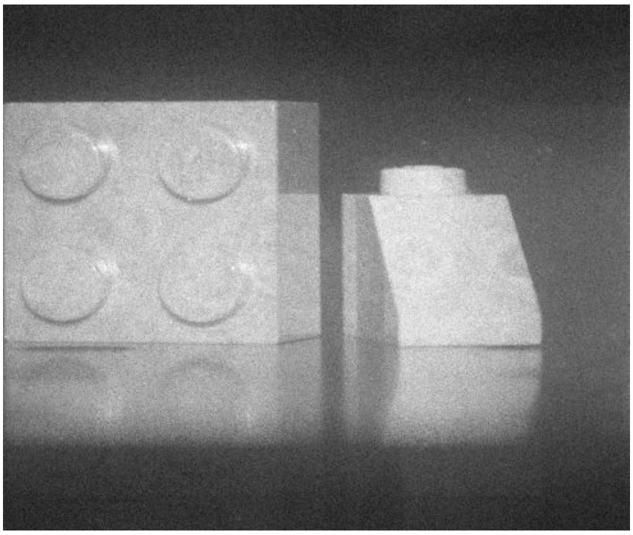

Figure 4. Module of the DFT of a hologram of two Lego® bricks located 55 mm away from the plane of the reference source point. The reference wave is being modified by the complex transmittance $\chi(\vec{v})$ of the SLM and the Lensless Fourier scheme is restored. The aliased frequencies disappeared, hence the support of the recorded signal's band is minimized.

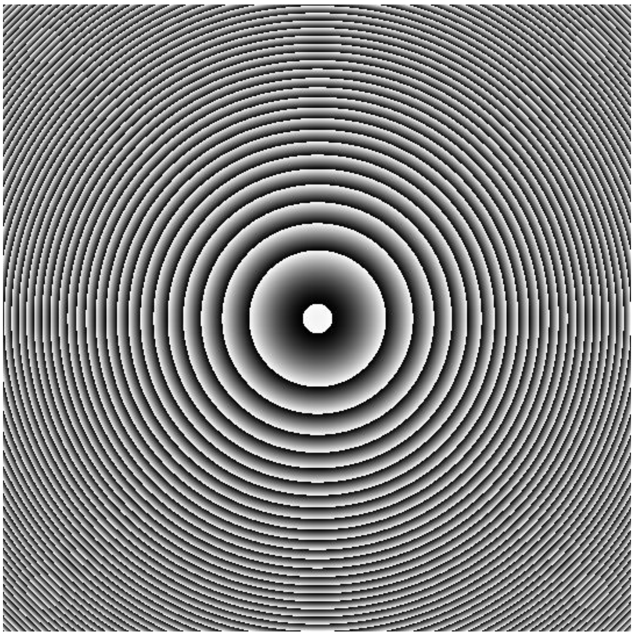

Figure 5. Central region of the phase distribution $\phi_\chi(\vec{v}) = \arg[\chi(\vec{v})]$ of the complex transmittance to be generated by the SLM in order to adapt the reference wave according to the shift of the object plane (540 × 540 pixel).

However, the DFT also represents the band of the recorded signal and in comparison to Figure 3 it is seen that the aliased frequencies disappeared, i.e. the support of the band has been minimized as explained in section 2.2. The results therefore prove the applicability of this method in regards to Digital Lensless Fourier Holography.

5. CONCLUSIONS

We have presented an experimental configuration for Digital Lensless Fourier Holography. The key element of the setup is a reflective liquid crystal Spatial Light Modulator which allows for the manipulation of the reference wave by electronic means. Experimental results have proven that the scheme may be used to adapt the setup to different positions of the object along the optical axis without the requirement of mechanical adjustments. For this, an analytical expression has been given for the calculation of the complex transmittance to be generated by the SLM. As an additional benefit it was shown that the SLM can be used to perform temporal phase shifting.

Future investigations will focus on applications based on further manipulation of the reference wave, such as optical encryption, spatial phase shifting with variable carrier or corrections of optical aberrations.

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