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Fast simulations in Computer-Generated Holograms for binary data storage

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Abstract: We present an efficient simulation of the recording and playback phases of a 2D image in a reflection volume hologram. The proposed algorithm uses the free-space Green's function propagation and assumes the Born approximation.

With the increased prevalence of large data sets the need for scalable and efficient data storage is more relevant than ever. Optical storage devices have the advantage of both low maintenance costs as well as having exceptional durability. One optical storage technology which has been of interest for many years is volumetric holographic memory storage [1]. This technique encodes data into a volume hologram and then the information can be recovered by illuminating the hologram in specific ways and measuring the scattered field. Multiple measurements can be recorded to the same volume hologram either by recording patterns which will only 'play back' when illuminated by a specific wavelength, specific incidence angle, or by recording the diffraction patterns in separate and disjoint regions of the volume hologram.

Holography can be split up into two basic steps, the recording and playback processes. To record a diffraction pattern in the volume hologram, the desired output field must be illuminated onto the object along with the desired playback light configuration, resulting in an interference pattern. This interference pattern is etched into the volume hologram through a chemical process [2]. In the case where images are stored in the volume hologram the correct field within the material must be pre-computed using numerical techniques. Different configurations of these Computer-Generated Holograms (CGH) have been recently studied to increase the recording efficiency [3], using a Spatial Light Modulator (SLM) to display the images. We propose the following setup: The object and reference SLMs are placed at each side of the hologram so that the two counter-propagating beams interfere in certain hologram locations. As these waves reach the thick hologram from opposite sides, it produces a reflection hologram. Between the SLMs and the hologram, a 4f system will be used to demagnify the beam by a factor of $M = 100$. To record the first image, the reference SLM displays a plane wavefront where only half of the pixels are illuminated. The complementary pixels will be illuminated to record the second image. This allows us to store two diffraction patterns in different locations.

We will simulate the holographic phases of recording and playback of two binary images using spatial multiplexing [4]. There exist several methods to perform these simulations [5]. Analytical solutions require assumptions such as plane-waves gratings or the paraxial approximation. Therefore, it is necessary to employ numerical models for more complex configurations. Rigorous Coupled-Wave Analysis has been widely used in the literature, but it is inefficient when dealing with large volume holograms. We present here a fast algorithm for recording and playback a data page in a volume hologram. We assume that a group of 200 x 200 SLM pixels are activated to produce the reference and object fields, and that the SLM pixels size is 10 x 10 μm^2. The SLMs display low-frequency binary images, the hologram is considered to be 10 μm thick, and the beams incident area 20x20 μm^2. This work is in progress, and for now, we have limited it to the recording and playback of a single data page, as shown in Fig. 1 (a). We have used a plane wave as a reference beam. This project's extension corresponds to the recording of a second image using spatial multiplexing.

During recording, we will carry out wave propagation using the free-space Helmholtz Green function. Prior to recording, we assume that the volume hologram has a constant refractive index of $n_0 = 1.5$. Given an incident light source distribution $E_{in}(x,y,z) = E_{in}(x,y,z=z_0)$ and null elsewhere, the electrical field E can be determined according to the inhomogeneous Helmholtz equation: $(\nabla^2 + k_0^2)E(x,y,z) = E_{in}(x,y,z)$, with $k_0 = 2\pi/\lambda$ and λ the monochromatic light wavelength of the laser beam. This source corresponds to the field generated by one of the SLMs, it is found on one side of the hologram, and has finite support D. We must enforce the Sommerfeld boundary conditions to ensure that the sources do not act like sinks [6] and correspond with the appropriate physical solutions described by

$$E(\mathbf{r}) = \int_D G(\mathbf{r}-\mathbf{r}') \cdot E_{in}(\mathbf{r}') d\mathbf{r}' = (G * E_{in})(\mathbf{r}) \quad . \tag{1}$$

Here, G is the Green function that verifies the inhomogeneous Helmholtz equation $(\nabla^2 + k_0^2)G(\mathbf{r}) = \delta(\mathbf{r}-\mathbf{r}')$, $\mathbf{r} = (x,y,z)$, and $r = ||\mathbf{r}||_2$. The analytical solution for the Green's function is $G(\mathbf{r}) = \frac{e^{ik_0 r}}{4\pi r}$ in the three-dimensional case, with $\mathbf{r}' = 0$ [6] to avoid the singularity. We can now apply the convolution theorem to obtain $E = \mathscr{F}^{-1}[\mathscr{F}[G] \cdot \mathscr{F}[E_{in}]]$. Knowing the source reference field $E_r(x,y,z=0)$, we can calculate the wave after it propagates through the volume hologram, $E_r(x,y,z)$, using the Green's function approach [7]. The object wave $E_o(x,y,z)$ can be found using a similar Green's function approach. Considering $n = n_0 + \Delta n$ and assuming that Δn varies linearly with respect the intensity distribution within the hologram, we have that $\Delta n(\mathbf{r}) \propto I(\mathbf{r}) = |E_r(\mathbf{r}) + E_o(\mathbf{r})|^2$.

To model the playback of the hologram, we must solve a related Helmholtz problem with the predetermined refractive index variation. This equation can be rewritten as $(\nabla^2 + k_0^2)E(\mathbf{r}) = -S(\mathbf{r}) \cdot E(\mathbf{r})$, with the scattering potential $S(\mathbf{r}) = k_0^2 \left(\frac{n(\mathbf{r})^2}{n_0^2} - 1 \right)$. We seek a solution of the form $E = E_{in} + E_s$, where E_{in} is the incident field that verifies the homogeneous Helmholtz equation (the propagation of the incident field) and E_s the scattering field verifying the inhomogeneous Helmholtz equation [8]. Assuming $E_{in} \gg E_s$, the first-order Born approximation leads us to the solution: $E(\mathbf{r}) = E_{in}(\mathbf{r}) + \int_D G(\mathbf{r}-\mathbf{r}') \cdot S(\mathbf{r}') \cdot E_{in}(\mathbf{r}') d\mathbf{r}' = [G * (S \cdot E_{in})](\mathbf{r})$. Moreover, because we are using a reflective hologram, the incident field E_{in} is transmitted, while the scattering field E_s is reflected, carrying the information from the holographic image's playback. Using the same artifice as above with the Fourier transform, we get $E_s = \mathscr{F}^{-1}[\mathscr{F}[G] \cdot \mathscr{F}[S \cdot E_{in}]]$. The playback image can be seen in Fig. 1 (b).

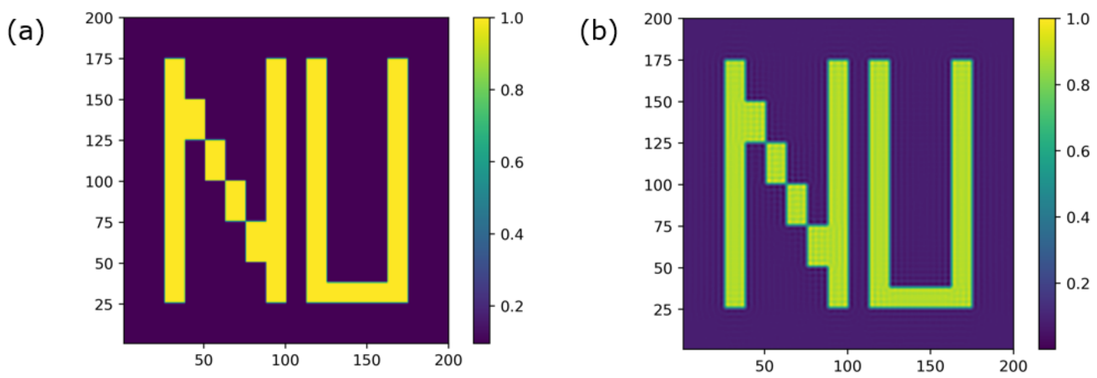

Fig. 1. (a) Image displayed by 200x200 pixels of an amplitude SLM, (b) Playback holographic image using our fast algorithm programmed in Python 3.0..

This study concludes that the propagation with the Green's functions approach and the Born approximation assumption represents an effective strategy to simulate holographic processes in large volume holograms. In the course of this project, we will use the present algorithm to explore the memory storage limitations of binary images using spatial multiplexing.

References

1. Naru Yoneda, Yusuke Saita, and Takanori Nomura. Binary computer-generated-hologram-based holographic data storage. Applied optics, 58(12):3083–3090, 2019.
2. Parameswaran Hariharan. Basics of holography. Cambridge university press, 2002.
3. Wenjian Cai and Rafael Piestun. Computer generated volume holograms: design and fabrication. In Information Photonics, page JTuA6. Optical Society of America, 2005.
4. Javid Khan, Ian Underwood, Alan Greenaway, and Mikko Halonen. A low-resolution 3d holographic volumetric display. In Optics, Photonics, and Digital Technologies for Multimedia Applications, volume 7723, page 77231B. International Society for Optics and Photonics, 2010.
5. F Kalkum. Fast numerical simulation of diffraction from large volume holograms. JOSA A, 26(11):2393–2397, 2009.
6. Colin JR Sheppard, Shan S Kou, and Jiao Lin. The green-function transform and wave propagation. Frontiers in Physics, 2:67, 2014.
7. Felipe Vico, Leslie Greengard, and Miguel Ferrando. Fast convolution with free-space green's functions. Journal of Computational Physics, 323:191–203, 2016.
8. Paul Müller, Mirjam Schürmann, and Jochen Guck. The theory of diffraction tomography. arXiv preprint arXiv:1507.00466, 2015.