Three-Dimensional Holographic Reconstruction of Brain Tissue Based on Convolution Propagation

Rania M. Abdelazeem¹, Doaa Youssef¹, Jala El-Azab¹, Salah Hassab-Elnaby¹ and Mostafa Agour²

¹Engineering Applications of Laser Department, National Institute of Laser Enhanced Sciences “NILES”, Cairo University, 12613, Giza, Egypt
²Physics Department, Faculty of Science, Aswan University, 81528 Aswan, Egypt
E-mail: rabdelazeem@niles.edu.eg

Abstract.
In this study, a dynamic holographic projection system for brain tissue and its anatomical structures extracted from Magnetic Resonance (MR) plane slice is reported. Computer holograms are calculated using a modified Gerchberg-Saxton (GS) iterative algorithm where the projection is based on the plane wave decomposition. First, brain anatomy includes white matter (WM), grey matter (GM) and brain tissue are extracted. Then, phase holograms using the proposed method are generated. Finally, single phase hologram for the whole brain anatomy is generated and is optically reconstructed by a phase-only spatial light modulator (SLM) at different depths. The obtained results revealed that the three-dimensional holographic projection of MR brain tissue can aid to provide better interpretation of brain anatomical structure to achieve better diagnostic results.

Keywords: Three-dimensional holographic display, computer-generated holography, spatial light modulator and brain tissue

1. Introduction
Computer-generated holography (CGH) is a method that is used to obtain the complex wavefield by numerical simulation, not by optical recording [1–3]. CGHs have been used in different applications, e.g., 3D holographic projection systems, head-up displays, security and optical elements [1,3]. Digital images are reconstructed from numerically generated interference patterns based on diffraction formula to model real or virtual objects [4,5]. The phase distribution of the resulting numerical wavefields can be displayed on a phase-only spatial light modulator (SLM) for efficient real-time optical reconstruction [6–8]. The great advantage of CGH that it can provide the complete 3D information of the object from single 2D hologram [1]. In addition, most of SLMs artifacts, e.g. dc-term and amplitude envelope modulation, can be compensated within the design process of the CGH [9–11]. In the next few years, medical holography may be a part of the surgeon’s tool kit to project different patient’s organs floating in air with high resolution [12]. Some studies have been presented in the literature [13,14] providing feasible holographic projections of different body organs. Although, they lack studying the organs’ anatomical structures.

Here we report on a holographic projection system for brain tissue and its anatomical structures extracted from MR plane data. The presented method employs digital image
segmentation through grey-level threshold and grey-intensity difference [15] to extract the brain tissue and its white matter (WM), grey matter (GM) from an MR image. Brain holograms are then calculated using a modified iterative approach analog to the well-known Gerchberg-Saxton (GS) algorithm [16]. In the proposed iterative scheme, the utilized projection operator is based on convolution plane wave decomposition. For the optical reconstruction of the generated phase holograms, a reflective phase-only SLM is used.

2. Methods
Phase holograms are calculated and optimized using the following approach which is analog to the well-known GS algorithm [16]. The flowchart of the algorithm is shown in Fig.1.

Figure 1. Flowchart of the GS for producing phase holograms

Starting with a complex-valued object \( (U_{\text{Obj}}) \) consisting of an initial phase guess \( (\phi_0^{(0)}) \) and the amplitude that is calculated from the extracted brain tissue image \( (A_i = \sqrt{I_i}) \), where \( i \) refers to the image of the extracted tissue. Such a complex amplitude is propagated to the SLM plane using the plane wave decomposition approach [17, 18]. At the \( n^{th} \)-iterations the complex amplitude at the object plane can be written in the form:

\[
U_{\text{Obj}}^{(n)} = T \left\{ U_{\text{Obj}}^{(n-1)} \right\} = \frac{A_i}{|U_{\text{Obj}}^{(n-1)}|} P^{-1} \left\{ \frac{1}{|U_{\text{SLM}}^{(n-1)}|} P \left\{ U_{\text{Obj}}^{(n-1)} \right\} \right\}.
\]

(1)

here \( T \) represents the utilized projection operator consisting of forward \( P \) and backward \( P^{-1} \) propagation operators which can be realized using fast Fourier transform \( (F) \) [17] as

\[
P \{ U_{\text{Obj}} \} = F^{-1} \{ F \{ U_{\text{SLM}} \} \cdot H_z \} \quad \text{and} \quad P^{-1} \{ U_{\text{SLM}} \} = F^{-1} \{ F \{ U_{\text{Obj}} \} \cdot H_z^* \}.
\]

(2)
Where $F^{-1}$ represents the inverse Fourier transform and $H_z$ is the transfer function of free space propagation which can be expressed as [19]

$$
H_z(\vec{v}) = \exp\left[\frac{2\pi}{\lambda}z\sqrt{1 - \lambda^2|\vec{v}|^2}\right],
$$

where $H_z^*$ is its complex conjugation, $\vec{v}$ denotes the spatial frequency of $H_z$ in the Fourier space, $\lambda$ is the wavelength of the illumination and $z$ represents the propagation distance. It is noted that within $T$ the two amplitude constraints are applied at the object and SLM planes without altering the corresponding phase distributions. Simply the amplitude constraints are; at the SLM plane it is assuming a plane wave illumination and at the object plane by restoring the original object amplitude. The iterative process is continued until no change in the SLM plane phase distribution is observed ($\phi_{SLM}^{(n)} - \phi_{SLM}^{(n-1)} < \epsilon$).

The brain structure phase holograms including ($WM$), ($GM$) and brain tissue ($WG$) containing WM and GM are generated at different depths ($z$) separately using the previously described algorithm. Consequently, the three complex amplitude designed at the SLM plane for the brain tissue anatomies are coherently superimposed into a single complex amplitude $U_{all}$ which has the form:

$$
U_{all} = U_{WM} + U_{GM} + U_{WG}.
$$

The phase only hologram $\phi_{all}$ which will be displayed on the SLM can be calculated by taking the arg of $U_{all}$

$$
\phi_{all} = \arg\{U_{all}\}.
$$

Here $\arg$ is the complex argument of a complex number which is calculated by taking the arctangent of the result of dividing the imaginary part by the real part of a complex number.

### 3. Experimental Setup

The demonstration setup used for holographic projection system is implemented as shown in Fig.2. It is a simple configuration that uses a red laser source of wavelength $\lambda = 670nm$. The laser is expanded by a beam expander (BE) and collimated to illuminate the SLM surface. The used SLM is a phase-only modulator (HoloEye’s Pluto: resolution, pixel pitch and switching rate are $1920 \times 1080$ pixels, $8 \mu m$ and $60Hz$ respectively). Since the SLM is a birefringent element, polarizer (P) and analyzer (A) are placed before and after the SLM to select the correct polarization state. Thus, only the modulated beam corresponding to the slow axis of the SLM is selected. A Pike CCD camera sensor (model: $F_505B$, resolution: $2452 \times 2054$ pixels, pixel pitch: $3.345 \mu m$ ) is placed at different depths to capture the reconstructed images.

### 4. Holograms and optical reconstruction results

The MR plane slices were collected from Kasr El-Ainy hospital, Cairo University, Egypt. As shown in Figure 3(a), the image presents coronal brain slice on sequence T1. The MR plane slice attributes to carry grey-level intensity difference values for the two main areas of interest, white and grey matter tissue. Therefore, digital image segmentation process is employed through grey-level threshold and grey-intensity difference [15] to extract the brain tissue and its white matter, grey matter from the MR plane slice and the results are shown in Figure 3(b-d).

Each individual segmented structure is subjected to the proposed iterative approach to calculate the complex amplitude across the SLM plane. The three holograms designed for the three tissues are calculated for reconstruction distances of $z = 200, 250, and, 300$ mm respectively. Then, the three complex amplitudes are coherently superimposed to generate $U_{all}$ given by Eq. (4). Finally the phase $\phi_{all}$ described by Eq. (5) is calculated to be displayed by the SLM. These steps are summarized in Fig.4 showing only the phase distributions.
Figure 2. Holographic projection system where BE is a beam expander, P and A are two polarizers and SLM refers to a reflective phase-only spatial light modulator: a) a schematic draw, and b) an image of the experimental setup.

Figure 3. a) T1-weighted MR plane image, b) the extracted WM tissue, c) the extracted GM tissue and d) the extracted brain tissue including WM and GM. Note that: the physical size of the test image is 2676 x 2676 µm². The dynamic range of the images shown in b), c), and d) indicates 0 for black and 1 for white (binary images).
Figure 4. Superposition of the three complex amplitude holograms for WM, GM and WG that are propagated at $z = 200, 250$ and $300$ mm respectively. Note that, only the phase ($\phi$) of the complex amplitudes is shown here.

The 3D optical reconstruction of brain tissue and its anatomical structures for the images presented in Fig.3(b-d) are shown in Fig.5. The quality of reconstructed images was measured quantitatively in terms of signal to noise ratio (SNR). The SNR values for the reconstructed WM, GM and WG tissues were 0.9891, 0.8096 and 0.9841 respectively.

Figure 5. Intensity captured images for the 3D optical reconstruction of a) the extracted WM tissue at $z = 200$ mm, b) the extracted GM tissue at $z = 250$ mm and c) the extracted brain tissue at $z = 300$ mm, computed in 100 iterations

5. Conclusions
A real-time 3D holographic projection system for displaying brain structures at multiple depths using single 2D phase hologram is successfully constructed. The brain phase holograms for each individual structure including brain tissue, white matter and grey matter are calculated using a modified iterative approach based on plane wave decomposition. Subsequently, one phase hologram is calculated by coherent superposition of the three designed complex amplitudes which is then displayed on a reflective phase-only SLM. The obtained optical reconstruction results were satisfactory for displaying brain tissues at different depths. This is our first step to develop a medical holographic projection system that can aid physicians in diagnosis, surgical planning and treatment.
References

[1] Park J H 2017 *Journal of Information Display* **18** 1–12
[2] Agour M and Kreis T 2009 *3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video* (IEEE) pp 1–4
[3] Agour M, Falldorf C, von Kopylow C and Bergmann R B 2013 *2013 3DTV Vision Beyond Depth (3DTV-CON)* (IEEE) pp 1–4
[4] Yoshikawa H, Yamaguchi T and Uetake H 2016 *SPIE Newsroom* **10** 006331
[5] Xu L, Chang C, Feng S, Yuan C and Nie S 2017 *Optics Communications* **402** 211–215
[6] Yaras F, Kovachev M, Ilieva R, Agour M and Onural L 2008 *2008 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video* (IEEE) pp PD–1
[7] Falldorf C, Agour M, von Kopylow C and Bergmann R B 2010 *AIP Conference Proceedings* vol 1236 (AIP) pp 259–264
[8] Agour M, Falldorf C and Bergmann R B 2016 *Optics express* **24** 14393–14405
[9] Agour M, Kolenovic E, Falldorf C and von Kopylow C 2009 *Journal of Optics A: Pure and Applied Optics* **11** 105405
[10] Agour M, Falldorf C and Von Kopylow C 2010 *Journal of Optics* **12** 055401
[11] Liang J, Wu S Y, Fatemi F K and Becker M F 2012 *Applied optics* **51** 3294–3304
[12] Bruckheimer E, Rotschild C, Dagan T, Amir G, Kaufman A, Gelman S and Birk E 2016 *European Heart Journal-Cardiovascular Imaging* **17** 845–849
[13] Lu Z and Sakamoto Y 2018 *Applied optics* **57** A142–A149
[14] Wolfe A and Hart S 1997 Digital volumetric holograms for medical imaging URL http://spie.org/news/digital-volumetric-holograms-for-medical-imaging.htm
[15] Gonzalez R C and Wintz P 1977 *Reading, Mass., Addison-Wesley Publishing Co., Inc.(Applied Mathematics and Computation* 451
[16] Gerchberg R W 1972 *Optik* **35** 237–246
[17] Goodman J W 2005 *Introduction to Fourier optics* (Roberts and Company Publishers)
[18] Poon T C and Liu J P 2014 *Introduction to modern digital holography: with MATLAB* (Cambridge University Press)
[19] Sherman G C 1967 *JOSA* **57** 546–547