The 7Th International Conference on Modern Trends in Physics Research, MTPR-018
20-24 April 2019, Sharm El Sheikh, Egypt

Three-Dimensional Visualization of Retinal Surface Using Computer-Generated Hologram

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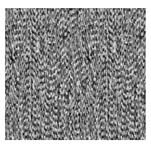
Abstract

Unlike the two-dimensional photography which is amplitude only recording of the wavefront, holography is a recording method for both amplitude and phase of the light field, which is called the complex-amplitude. Computer-generated holography has become one of the most promising methods for reconstructing high quality three-dimensional images without the existence of the real object. Therefore, it plays an important role in medicine where medical holograms floating in air without special eyewear may become one of the surgeon's toolkit. This study attempts to visualize the whole retina and its anatomical structures in three-dimensional hologram giving the surgeon an opportunity to examine the structure of the eye. Since all fundus cameras capture images for only a portion of the retina, retinal image registration is applied on the captured retinal images of the same eye to obtain a mosaic containing the complete map of the retina to allow proper diagnosis. By means of that accurate detection of the main anatomical structures of the retina, retinal blood vessels, macula and optics disc, are extremely important for ophthalmologist' decision, they are extracted from the mosaic. Thereafter, from the modified mosaic, four holograms are acquired sequentially at different phases to generate a complex-hologram of the retinal surface using a four-step phase shifting algorithm. The benefits of using this algorithm is that zeroth-order beam and twin image which are common problems in the hologram reconstruction are removed. Via a spatial light modulator, optical reconstruction of the retinal anatomical hologram can be displayed.

Introduction

Hologram is an interference pattern recorded between object light and reference light



Computer-Generated Holography deals with generating hologram digitally. Different methods have been developed for calculating the computer-generated hologram (CGH). The resulting hologram can be subsequently printed on a film or displayed on a spatial light modulator (SLM) for holographic reconstruction. The off-axis configuration is an effective method for isolating the zeroth-order light and twin image that always disturb the reconstructed images. Among of different existing techniques, phase-shifting algorithm is the most effective technique for eliminating the zeroth-order light and twin image. Furthermore, a single order reconstructed image can be obtained.

Methods

Mosaic Implementation

The color fundus images in the dataset used in this work were gathered from NILES using a Carl Zeiss Visucam 500 fundus camera. To generate a complete map of retina, the well-known rubber-sheet transformation were used to perform image registration that takes two fundus images of the same retina captured from different portions and aligns in a mosaic, see figure 1. The process was repeated between the mosaic and other fundus image until obtaining the mosaic of the whole retina. It must be mentioned that the rubber-sheet transformation is a geometric transformation that can modify the spatial relationships between pixels in an image by scaling, rotation, shearing or translation depending on the use of some control points whose locations in the two images are selected.

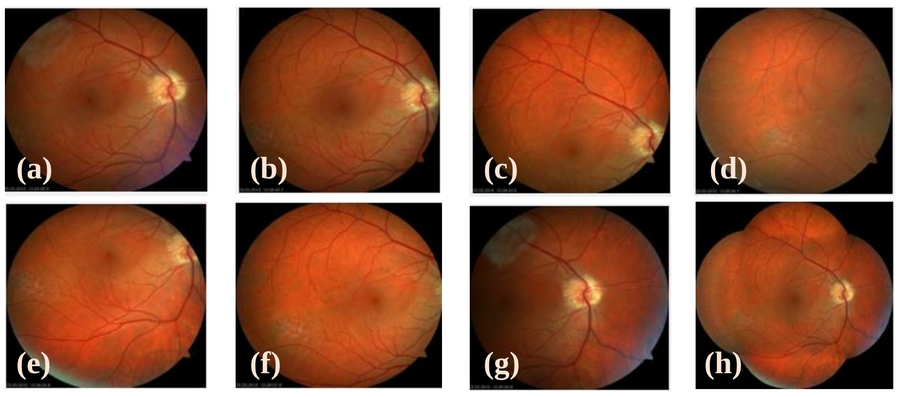


Fig. 1: (a)-(g) Fundus images of different portions of retina and (h) mosaic image of the whole retina.

Anatomical Structures Segmentation

Efficient segmentation of the main anatomical structures of the retinal image namely optic disc, macula and blood vessels is an important task in ophthalmology (Fig. 2). Whereas, their morphological structures are an important sign for estimating the existence of retinal disorders. Besides, it may be essential to mask the structures out to accurately detect the retinal abnormalities such as exudates, microaneurysms and hemorrhages. Above all, highlighting the anatomical structures avoids the laser maltreatment resulting from ophthalmologist's error.

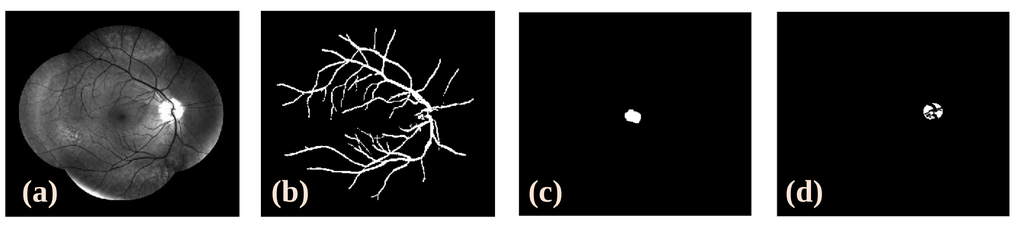


Fig. 2: (a) Mosaic image, (b)-(d) blood vessels, macula and optic disc segmentation.

Phase Shifting Algorithm

Four holograms are acquired at different phases between the reference light and the object light. The first hologram is acquired at phase difference $\delta = 0$, then the next three holograms are acquired at $\delta = \pi/2$, π and $3\pi/2$. The four holograms are expressed as:

$$I_0 = |\psi_0|^2 + |\psi_r|^2 + \psi_0\psi_r^* + \psi_0^*\psi_r \quad (1)$$
$$I_{\pi/2} = |\psi_0|^2 + |\psi_r|^2 + j\psi_0\psi_r^* - j\psi_0^*\psi_r \quad (2)$$
$$I_{\pi} = |\psi_0|^2 + |\psi_r|^2 - \psi_0\psi_r^* - \psi_0^*\psi_r \quad (3)$$
$$I_{3\pi/2} = |\psi_0|^2 + |\psi_r|^2 - j\psi_0\psi_r^* + j\psi_0^*\psi_r \quad (4)$$

ψ_0 stands for the complex field of the object light, ψ_r and ψ_r^* are the complex field and complex conjugate of the reference light respectively. $|\psi_0|^2 + |\psi_r|^2$ is the zeroth-order light that can be removed from the above equations by subtractions. The final complex amplitude of the object light can be calculated from:

$$\psi_0 = \frac{(I_0 - I_\pi) - j(I_{\pi/2} - I_{3\pi/2})}{4\psi_r^*} \quad (5)$$

The calculation parameters are:

Used Software: MATLAB 2018a **Image Size:** 600 (H) X 600 (V)
Light Wavelength: 632.8 nm **Propagation Distance:** 2.7 cm
Layer Separation: 7 mm

Results

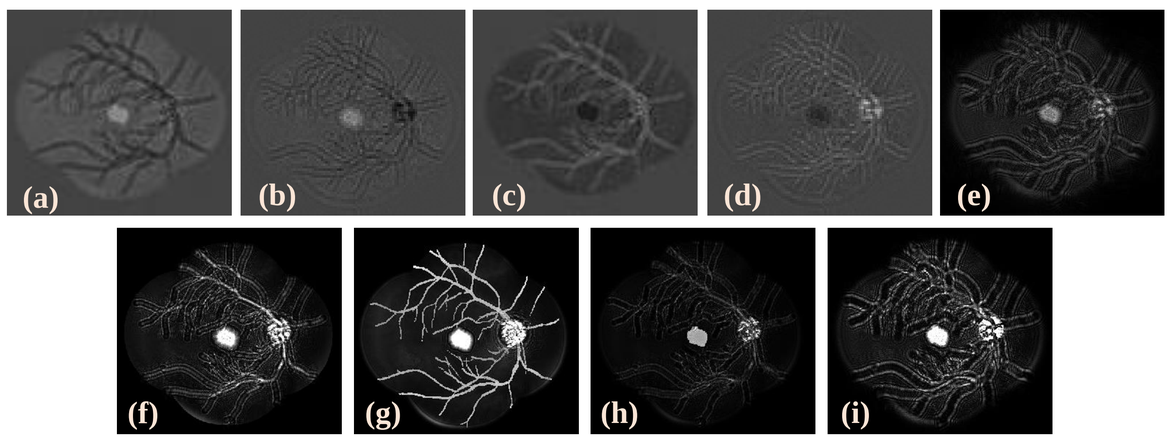


Fig. 3: (a)-(d) Four holograms acquired at $\delta = 0$, $\pi/2$, π and $3\pi/2$ respectively, (e) complex hologram, and (f)-(i) reconstructed images of complex hologram at z = 2.7, 2, 1.3 and 0.6 cm respectively.

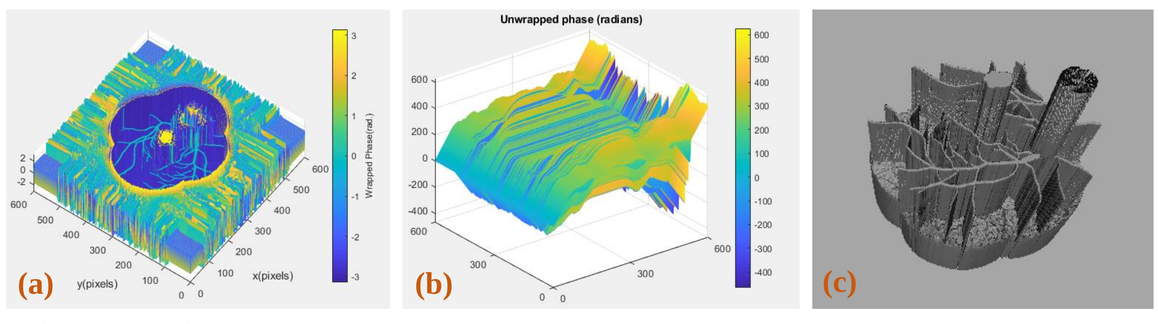


Fig. 4: (a) and (b) Wrapped and unwrapped phase plots at section z = 2cm respectively, and (c) 3-D reconstructed image from phase shifting algorithm.

Conclusion

- Computer holography is the latest technology for reconstructing and displaying high quality three-dimensional images.
- Phase-shifting algorithm can eliminate the effect of zeroth order light and twin image.
- Accurate detection and visualization of retinal anatomical structures avoid the laser maltreatment resulting from ophthalmologist error.

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