Real-time digital holographic microscopy observable in multi-view and multi-resolution

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Abstract
We propose a real-time digital holographic microscopy that enables simultaneous multiple reconstructed images with arbitrary resolution, depth and positions, using shifted-Fresnel diffraction instead of Fresnel diffraction. In this system, we used four graphics processing units (GPUs) for multiple reconstructions in real-time. We demonstrate four reconstruction images from a hologram with arbitrary depths, positions and resolutions.

Keywords: digital holography, digital holographic microscopy, holography, real-time holography, graphics processing unit

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

In research fields such as micro-electromechanical systems (MEMS) and bio-imaging, digital holographic microscopy (DHM) [1–3] is attractive as a new microscopy technique, because the DHM allows both the amplitude and phase of a specimen to be simultaneously observed.

The technique can obtain a hologram whereby the information of a specimen is electronically recorded, via the use of a charge-coupled device (CCD) image sensor. In order to obtain a reconstructed image from a hologram, numerous calculations for the Fresnel diffraction [4, 5] are required; however, the Fresnel diffraction has a restriction, namely, the same sampling spacings must be set on the hologram and the reconstructed image, or the sampling spacing on the reconstructed plane depends on the propagation distance and the wavelength of a reference light. Therefore, we cannot observe the reconstructed image with arbitrary resolution due to the restriction of the sampling spacing. In addition, in current DHM, an objective lens is used to increase the resolution of the reconstructed image; however, using the objective lens sacrifices an area of the reconstructed image.

In this paper, without using an objective lens, we propose a DHM observable in multi-view and multi-resolution. The DHM can obtain multiple reconstructed images with arbitrary resolution, depths and positions, using shifted-Fresnel diffraction [6], instead of Fresnel diffraction. Shifted-Fresnel diffraction based on Fresnel diffraction can calculate a reconstructed image with different sampling spacings between the hologram and the reconstructed image, as well as a shift away from the propagation axis. In addition, we used four graphics processing unit (GPU) chips [7] in order to observe four reconstructed images in real-time from one hologram.

In section 2, we describe the concept and the calculation method for the proposed DHM. In section 3, we describe the results of an optical experiment. In section 4, we conclude this work.

2. Digital holographic microscopy using the shifted-Fresnel diffraction

The concept of the proposed DHM is shown in figure 1. In the DHM, we can simultaneously observe reconstructed images at different depths (figures 1(a) and (b)) along the depth.
direction. In addition, while observing a wide viewing area of a reconstructed image (figure 1(c)), we can simultaneously observe reconstructed images with the user-setting for arbitrary resolutions at arbitrary positions (figures 1(d) and (e)).

An objective lens can increase the resolution of the reconstructed image, while decreasing the viewing area of the reconstructed image. For this reason, the proposed DHM system does not use an objective lens, instead, the proposed DHM system uses arbitrary sampling spacing on the reconstructed image. If we observe a wide viewing area of a reconstructed image, we set a large sampling spacing on the reconstructed plane. Therefore in order to observe the reconstructed image in detail, we need to set a small sampling spacing on the reconstructed plane.

In order to realize the proposed DHM, the following methods are required:

(i) A computational method for obtaining reconstructed images with arbitrary resolution from a hologram.
(ii) A high-speed computational system for reconstructing from a hologram in real-time.

To solve these problems, we used shifted-Fresnel diffraction and multi-GPUs. An outline of the DHM system is shown in figure 2. The system consists of an optical system without using an objective lens and a high-speed computational system using four GPU chips. Some researchers have already used the GPU approach for real-time digital holographic reconstruction [8–10]. In the figure, we used a 5 mW He–Ne laser (the wavelength is 632.8 nm) as a reference light. ‘ND’ indicates a neutral density filter. We used a CCD camera, which has a resolution of 1360 × 1024 and a pixel pitch of 4.65 μm × 4.65 μm. In the reconstruction calculation from a hologram captured by the CCD, we resize the hologram with 1024 × 1024 grids in order to use a fast Fourier transform (FFT) for the calculation. We also used three samples, which are a USAF 1951 test target, the head of a mosquito and a fly. Holograms captured by the CCD are recorded as in-line Gabor holograms and are transferred to a personal computer via the USB2.0 interface. Then, four GPU chips calculate four reconstructed images from one hologram in real-time.

2.1. Shifted-Fresnel diffraction

Recently, a new diffraction calculation, shifted-Fresnel diffraction, has been proposed [6]. The method enables arbitrary sampling spacings to be set on a hologram and a reconstructed plane as well as a shift away from the propagation axis. Other methods capable of changing sampling spacing have also been studied [11, 12]. We chose shifted-Fresnel diffraction because one can do a shift away from the propagation axis. Shifted-Fresnel diffraction is expressed by the following equations:

\[
u_1[m_1, n_1] = C_1 \sum_{m_0} \sum_{n_0} u_0[m_0, n_0] h[m_1 - m_0, n_1 - n_0] = C_1 u_0[m_1, n_1] * h[m_1, n_1] = C_1 \text{FFT}^{-1}[\text{FFT}[u_0[m_1, n_1]]] \text{FFT}[h[m_1, n_1]]
\]

(1)

\[
C_1 = \frac{\exp(ikz)}{i\lambda z} \exp\left(\frac{\pi}{\lambda z} (x_1^2 + y_1^2)\right) \times \exp\left(-\frac{2\pi}{\lambda z} \left(- \frac{N_s}{2} + O_{ux}\right) p_{ux} x_1 \right. \right.
\]

\[
+ \left. \left(- \frac{N_s}{2} + O_{uy}\right) p_{uy} y_1 \right) \right) \exp(-i\pi (S_x m_1^2 + S_y n_1^2))
\]

(2)

\[
u_0[m_0, n_0] = u_0[m_0, n_0] \exp\left(\frac{\pi}{\lambda z} (x_0^2 + y_0^2)\right) \times \exp\left(-i2\pi \left(m_0 S_x - \frac{N_s}{2} + O_{ux}\right) \right.
\]

\[
+ \left. n_0 S_y \left(- \frac{N_s}{2} + O_{uy}\right) \right) \exp(-i\pi (S_x m_0^2 + S_y n_0^2))
\]

(3)

\[h[m_1 - m_0, n_1 - n_0] = \exp(i\pi (S_x (m_1 - m_0)^2 + S_y (n_1 - n_0)^2))
\]

(4)

where the operators FFT and FFT\(^{-1}\) denote the FFT and the inverse FFT, 'i' is \(\sqrt{-1}\), \(\lambda\) is the wavelength of the reference light, \(z\) is the distance between the hologram and the reconstructed image, \([m_0, n_0]\) and \([m_1, n_1]\) are the discretized coordinates on the hologram and the reconstructed image, \(u_0[m_0, n_0]\) and \(u_1[m_1, n_1]\) are the hologram and the reconstructed image, \(p_{ux}\) and \(p_{uy}\) are the sampling spacing on the hologram, \(p_s\) and \(p_v\) are the sampling spacing on the reconstructed image, \((O_{ux}, O_{uy})\) and \((O_s, O_v)\) are the
shift distances away from the propagation axis. We define $S_i = \frac{p_{xi}p_{yi}}{\lambda}$, $S_i = \frac{p_{xi}p_{yi}}{\lambda}$, $x_0 = m_0p_{xi} + O_{x}, y_0 = n_0p_{yi} + O_{y}$, $x_1 = m_1p_{xi} + O_{x}$, and $y_1 = n_1p_{yi} + O_{y}$. For more details, see [6].

Finally, we can obtain the light intensity as a reconstructed image using the following equation:

$$I[m_1, n_1] = |u_1[m_1, n_1]|^2.$$

Calculating equations (1) and (5), we can obtain a reconstructed image with an arbitrary depth, resolution and shift to change the parameters $z$, $p_x$, $p_y$, and $O_x$, $O_y$, respectively. Note that we can neglect the coefficient $C_1$ because we need the light intensity.

2.2. Fast calculation of the shifted-Fresnel diffraction using multi-GPUs

Recent GPUs with many stream processors allow us to use highly parallel processors. The stream processor can operate 32-bit (or 64-bit) floating-point addition, multiplication and multiply-add instructions. We have already reported a real-time DHM system based on the Fresnel diffraction using a GPU [8].

In this paper, for the shifted-Fresnel diffraction, we used the GPU-based Wave Optics (GWO) library [13]. The library is a numerical calculation library for the diffraction calculations using a GPU. If optics engineers and researchers have no knowledge of GPUs, the GWO library provides them with the GPU computation power easily. The current GWO library runs on Microsoft Windows XP and is provided as a dynamic link library (DLL). The library and a sample code can be downloaded from [14].

As shown in equation (1), shifted-Fresnel diffraction can accelerate the computational time using two FFTs and one inverse FFT; however, recent central processing units (CPUs) do not have sufficient computational power for real-time calculation. Therefore, we use GPUs instead of CPUs.

Multiple reconstructions using multi-GPUs are shown below:

(i) The CPU sends a hologram captured by the CCD to the memories on the two GPU boards.

(ii) Each GPU chip expands the doubled size of the hologram (2048 x 2048 grids) with zero-padding to avoid the circular convolution [4, 15].

(iii) Each GPU chip calculates the complex multiplication of the hologram $u_0[m_0, n_0]$ and the exponential terms in equation (3).

(iv) Each GPU chip calculates the FFT of the result in Step 3 using the CUFFT library [16]. The CUFFT library is the fast FFT library on the NVIDIA GPU.

(v) Each GPU chip generates the propagation term $h[m_1 - m_0, n_1 - n_0]$ in equation (4).

(vi) Each GPU chip calculates the FFT of the propagation term $h[m_1 - m_0, n_1 - n_0]$.

(vii) Each GPU chip calculates the complex multiplication of the results of Steps 4 and 6.

(viii) Each GPU chips calculates the inverse FFT of Step 7.

(ix) Each GPU chips reduces the area of the results in Step 8 to 1024 x 1024 grids.

(x) Each GPU chips calculates the complex power (equation (5)) of the result in Step 9.

(xi) The CPU receives the four reconstructed images from the memories on each GPU.

We used OpenMP library to operate each GPU chip because each GPU must be controlled by CPU threads. Each GPU can operate in parallel. For real-time reconstruction, we repeat from Steps 1 to 11.

3. Results

Figure 3 shows the reconstructed images of the USAF 1951 test target using the shifted-Fresnel diffraction. The USAF 1951 test target was set at about 5 cm from the CCD. The shifted-Fresnel diffraction can calculate a reconstructed image with different sampling spacings.

Figure 3(a) shows a large area reconstruction with the sampling spacing $p_x \times p_y = 4.65 \text{ mm} \times 4.65 \text{ mm}$. Then, the area of the reconstructed image is about 4.8 mm x 4.8 mm. Figure 3(b) shows a higher resolution reconstruction in the yellow line of figure 3(a) with the sampling spacing $p_x \times p_y = 4.65 / 2 \text{ mm} \times 4.65 / 2 \text{ mm}$. Figure 3(c) also shows a higher resolution reconstruction in the yellow line of figure 3(a) with
Of equation (1) we expand the calculation area to double-1024 grids; however, in order to avoid circular convolution the sampling spacing \( p_{x} \times p_{y} = 4.65/4 \, \mu m \times 4.65/4 \, \mu m \). We can observe the reconstructed image at the minimum resolution of about 11 \( \mu m \).

Figure 3(d) shows a reconstructed image using a bi-cubic interpolation algorithm which is an image enlargement method. In comparison, figure 3(c) is a better quality image than figure 3(d).

Figure 4 shows an example of multiple reconstructed images from a hologram. The DHM system can observe four reconstructed images simultaneously.

We used Intel Core2Quad Q6600 as the CPU, memory of 3 GB and the operating system of Microsoft Windows XP Professional SP2. Also, we used two GPU boards, NVIDIA GTX295, with the CUDA (Compute Unified Device Architecture) version 2.3 as a programming environment for the GPU chip. The GPU board has two GPU chips on one, therefore, the DHM system can use four GPU chips.

The hologram and four reconstructed images are 1024 \( \times \) 1024 grids; however, in order to avoid circular convolution of equation (1) we expand the calculation area to double-size during the calculation [4, 15]. Under the condition that the number of multiple reconstructed images is four, the calculation time using the CPU alone is 9542 ms, whereas that using the four GPU chips is about 60 ms.

In the movie of figure 4, we can observe four reconstructed images in real-time. A movie version of this figure is available from stacks.iop.org/JOpt/12/065402/mmedia. ‘View 1’ shows the reconstructed image of the head of a mosquito. ‘View 2’ shows the reconstructed image of the fly. ‘View 3’ shows the reconstructed image of the USAF test target. ‘View 4’ shows the reconstructed image with a large viewing area of about 4.8 mm \( \times \) 4.8 mm. All of the views can be observed in arbitrary resolution, depth and positions.

4. Conclusion

In this paper, we presented the DHM system observable in multi-view and multi-resolution. For multiple reconstruction, we used the four GPU chips. In addition, we used the shifted-Fresnel diffraction to obtain reconstructed images with arbitrary depth, resolution and view position. The method enables us to observe multi-view reconstructed images with large area and higher resolution.

In future research, we will try a super-resolution method such as [17–19] in order to observe greater resolution of a reconstructed image and we will develop the computational system using more multiple GPUs in order to obtain more reconstructed images at the same time.

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