Efficient Digital Holographic Image Reconstruction on Mobile Devices

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ABSTRACT

Advanced digital holography attracts a lot of attentions for 3D visualization nowadays. The representation of digital holographic images suffers from computational inefficiency on the mobile devices due to the limited hardware for digital holographic processing. In this paper, we point out that the above critical issue deteriorates the digital holographic image representation on the mobile devices. To reduce computational complexity in digital holographic image reconstruction, we propose an efficient and effective algorithm to simplify Fresnel transforms for the mobile devices. Our algorithm outperforms previous approaches in not only smaller running time but also the better quality of the digital holographic image representation for the mobile devices.

CCS Concepts

•Computing methodologies → Image representations;

Keywords

Digital Holographic Image Reconstruction, mobile devices.

1. INTRODUCTION

Digital holography [3] enables PC to record and represent the 3D information of real world objects by capturing their illuminated part and desired perspectives. The recorded 3D information of the object is called digital hologram. The digital holographic image can be constructed by propagating the wave field to the digital hologram with the theory of diffraction. Different from AR and VR, the digital holography can represent a more real 3D object with the recorded illuminated and perspective information of a real scene. In recent years, the digital holography has been a promising technology for various 3D visual applications. For example, Microsoft 10 has launched its own holographic headset HoloLens to interact with virtual objects appearing in your real world [1]. The digital holography is thereby becoming popular in the visual entertainments and video games. Since the optical diffraction on the digital hologram leads to large computational complexity, the digital holographic image reconstruction suffers from large burden on running time [13] [15] [16]. In addition to the high computational complexity for the digital holography reconstruction, Cheng et al. [5] pointed out that the cost for the representation of the digital holographic image is still expensive due to the need of extra hardware on the display devices such as a high-end GPU. Compared with the high-end digital holographic display devices, it is much more difficult for a user to view the high quality of the digital holography with a consumer mobile device because the current mobile devices lack dedicated digital holography imaging hardware. In addition, Kantabutra [10] indicated that the efficiency of the hardware-based methods [2] [5] [15] is limited for the digital holography imaging. This is because most hardware-based digital holography representations adopt iteration-based arithmetic algorithms to calculate exponential functions and trigonometric functions, but they result in large convergent time to reconstruct the holographic image. Therefore, we indeed require a scheme to efficiently represent the digital holography for the mobile devices.

We briefly introduce the procedure of the digital holographic reconstruction as follows. The digital hologram is an image plane photographically recording interference pattern between a wave field scattered from the real 3D object and the reference wave. Therefore, the digital hologram contains real scene information with the entire 3D wave field. We can reconstruct a digital holographic image by superimposing the bright reconstruction wave with the digital hologram. In contrast to the interference of the waves in the digital hologram, the digital holographic image reconstruction adopts the diffraction of the reconstruction wave. The diffraction of the light wave at the digital hologram is modeled as the Fresnel integral [12]. However, many prior works [13] [15] [16] showed that the Fresnel integral still suffers from high computational complexity due to recursive manners in the calculation for the exponential function. Additionally, Kim et al. [11] further demonstrated that most lookup-table-based methods for the digital holography required large memories. In this paper, we thereby aim to reduce the high complexity for calculating the Fresnel integral and large table sizes in the digital holographic reconstruction.

Given a digital hologram and a reference wave, our proposed method is to reduce the computational complexity and memory sizes for the digital holographic image reconstruction. The complexity of calculating the Fresnel integral

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in the digital holographic reconstruction can be seriously reduced by many factors such as reduction in the number of FFT (Fast Fourier Transformation) and the simplification of an exponential function. First, we propose a method called Efficient Digital Holographic Image Reconstruction (EDHIR). Specifically, EDHIR re-formulate the Fresnel integral in the digital holographic reconstruction to reduce two FFTs to one FFT. In addition, EDHIR fastens the exponential function used in the Fresnel integral. EDHIR minimizes the tables and speeds up the exponential function. More specifically, the domain of the argument x in the exponential function is equally divided into smaller subintervals. Next, EDHIR calculates the values of the exponential function for each subinterval boundary point, and stores them in a table. Then, EDHIR finds a close subinterval boundary point p to x. Finally, EDHIR adopt a polynomial approximation [14] to approximate the exponential function with the remaining argument r (i.e., $r = x - p$). Our main contributions focus on practical values and hardware cost to design our algorithm in the mobile devices. With our approach implemented into a practical mobile APP, the generic mobile devices are able to efficiently view the digital holographic image without expensive digital holographic imaging hardware and large memory sizes. The main contribution of EDHIR is that we propose an efficient process to reconstruct the digital holography on the current mobile devices. Our method not only needs fewer arithmetic costs and memory sizes allowed by the mobile devices but also achieves high precision in the digital holographic reconstruction.

The rest of this paper is organized as follows. In Section 2, we propose algorithm EDHIR. The experimental results are shown in Section 3. Finally, we conclude this paper in Section 4.

2. EFFICIENT DIGITAL HOLOGRAPHIC IMAGE RECONSTRUCTION

Digital holography image reconstruction is a critical problem for 3D visual applications on mobile devices. In view of this, we develop an Efficient Digital Holographic Image Reconstruction (EDHIR). Our algorithm includes two stages: the reduction of the number of FFT and the fast calculation of the exponential function in the Fresnel integral for the digital holography image reconstruction. We derive a formulation to mitigate the number of FFT in the Fresnel integral. In the fast calculation of the exponential function in the Fresnel integral, EDHIR equally separates the domain of the argument in the exponential function into several subintervals. EDHIR only uses a polynomial approximation to approximate the exponential function with the remaining argument belonging to a separated subinterval. The details are as follows.

2.1 Digital Holographic Image Reconstruction

Gabor [7] devised holography to record and reconstruct the amplitude and phase of a wave field in the real world. In this method, the reference wave (e.g., laser) interferes with the real object wave, and the interference patterns are recorded in the photographic plate. The recorded photography is called hologram that contains 3D information about the entire 3D wave field that shows the effects of perspective, illumination, and depth of focus. Lighting the hologram with the reference wave can reconstruct the object wave to represent a clear perception of the 3D scene for the human viewer. Therefore, the digital holographic image reconstruction is based on the diffraction of the light wave at the hologram, and such an optical diffraction is modeled as the Fresnel integral [12]. The Fresnel transformation gives high computational complexity such that it is difficult to reconstruct the digital holographic image in a mobile device with hardware restrictions.

2.2 Fast Fresnel Integral

We first model the diffraction of the reference wave over the digital hologram by using the Fresnel method [12]. Reference wave R is modeled as

$$R(x, y) = a_0 \frac{e^{-i\frac{2\pi}{\lambda}r + \theta_0}}{r}, \tag{1}$$

where λ is the wavelength of the reference wave, a_0 is the real-valued amplitude, r is the distance, and θ_0 is the initial phase. We can assume that a_0 is equal to 1 and θ_0 is equal to 0 for convenience. r can be obtained as

$$r = \sqrt{d^2 + (x - u)^2 + (y - v)^2}, \tag{2}$$

where (x, y) and (u, v) are defined as the spatial coordinates in the hologram and reconstructed plane respectively. d is the distance between the reconstructed virtual image appearing at the position of the original object and the real image. The diffraction of reference wave R over given digital hologram $H(x, y)$ is described by the Fresnel integral expressed as

$$D(u, v) = \frac{i}{\lambda} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [H(x, y)R(x, y)]dxdy, \tag{3}$$

where $D(u, v)$ is reconstructed holographic image in spatial domain.

To reduce this high computational complexity, traditional works [8] [9] efficiently implemented Eq. 3 in Fourier domain. Specifically, the digital holographic reconstruction can be viewed as a linear system. Since Eq. 3 expresses the spatial convolution between the digital hologram and the reference wave [9], Eq. 3 can be computed as

$$D(u, v) = \frac{i}{\lambda} e^{-i\frac{2\pi}{\lambda}d} F^{-1}\{F[H(x, y)]F[R(x, y)]\}, \tag{4}$$

where F and F^{-1} are defined as Fourier transformation and its inverse respectively. However, such convolution methods take too many calculations in the Fourier transformation.

To reduce the number of the Fourier transformation, we have to deal with Eq. 3 in discreted domain. By substituting Eq. 1 and Eq. 2 into Eq. 3, we obtain

$$\begin{aligned} D(u, v) \quad = \quad & \frac{i}{\lambda} e^{-i\frac{2\pi}{\lambda}d} e^{-i\frac{\pi}{\lambda d}(u^2+v^2)} \times \\ & \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [H(x, y) e^{i\frac{\pi}{\lambda d}(x^2+y^2)} \times \\ & e^{-i\frac{2\pi}{\lambda d}(xu+yv)}]dxdy. \end{aligned} \tag{5}$$

For the digital hologram, $H(x, y)$ is discreted to $M \times N$ samples at periods $\triangle x$ and $\triangle y$ in the x and y directions respectively. Therefore, x is equal to $k\triangle x$, and y is equal to $l\triangle y$, where k and l are integer numbers. Similarly, we obtain digital reconstructed image $D(n\triangle u, m\triangle v)$ with size $N\times M$. In other words, $D(u,v)$ is discreted to $M\times N$ samples at periods $\triangle u$ and $\triangle v$ in the u and v directions respectively. Therefore, u is equal to $n\triangle u$, and v is equal to $m\triangle v$, where n and m are integer numbers. In Eq. 5, we replace the integral and the continuous coordinates with summations and discreted coordinates respectively. Therefore, we can obtain

$$\begin{aligned} D(n\triangle u, m\triangle v) &= \frac{i}{\lambda}e^{-i\frac{2\pi}{\lambda}d}e^{-i\frac{\pi}{\lambda d}(n^2\triangle u^2+m^2\triangle v^2)}\times \\ & \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1}\sum_{l=-\frac{M}{2}}^{\frac{M}{2}-1}[H(k\triangle x, l\triangle y)\times \\ & e^{i\frac{\pi}{\lambda d}(k^2\triangle x^2+l^2\triangle y^2)}\times \\ & e^{-i\frac{2\pi}{\lambda d}(k\triangle xn\triangle u+l\triangle ym\triangle v)}]. \qquad (6) \end{aligned}$$

The direct computation of Eq. 6 is $O(MN)$. To reduce this high complexity, we further re-formulate Eq. 6 to

$$\begin{aligned} D(n\triangle u, m\triangle v) &= \frac{i}{\lambda}e^{-i\frac{2\pi}{\lambda}d}e^{-i\frac{\pi}{\lambda d}(n^2\triangle u^2+m^2\triangle v^2)}\times \\ & FFT[H(k\triangle x, l\triangle y)\times \\ & e^{i\frac{\pi}{\lambda d}(k^2\triangle x^2+l^2\triangle y^2)}]. \qquad (7) \end{aligned}$$

Eq. 4 shows that the computational complexity of the digital holographic reconstruction can be reduced to $O(3MlogN)$ by using Fast Fourier Transform (FFT). Compared to the convolution methods [8] [9], Eq. 7 demonstrates that we merely take one FFT in $O(MlogN)$ complexity to reconstruct the digital holographic image.

2.3 Fast Exponential Function

To further speed up the exponential function in Eq. 7, EDHIR adopts a polynomial approximation [14] collaborating with a lookup table. Since the argument of the exponential function is a complex number, we transform e^{ix} into $cos(x) + isin(x)$, where i is equal to $\sqrt{-1}$. Therefore, we focus on fast sine and cosine functions with argument x. The approximation of the sine and cosine functions gives large domain by merely using polynomial or rational functions with large degrees. This leads to large computational complexity, and also makes the numerical error. We thereby split the argument domain into several smaller subintervals, and then store the solutions of the subinterval boundaries in a table. Such a way results in fewer memory sizes than the stored solutions in the whole argument domain. For each small subinterval, the coefficients of a low-degree polynomial approximation are sufficient for the high quality of digital holography image reconstruction. This can also dramatically reduce the expensive computation.

2.3.1 Argument Domain Separation

EDHIR accelerates sine and cosine functions by equally separating the domain of argument x into 2^n small subintervals, where n is a positive integer. Then, EDHIR finds a close subinterval boundary point p to x. Finally, remaining argument r is defined as $x - p$. In other words, EDHIR decomposes x to $p + r$ because p is a most significant argument to affect the solutions of the sine and cosine functions with argument x. On the other hand, remaining argument r is a least significant argument to affect those. The goal of the argument domain separation is to reduce the large argument to small one such that the polynomial approximation can fast converge. In contrast to traditional methods [6], such an argument domain separation is flexible and efficient since the subintervals can be dependent on precision for the sine and cosine functions.

2.3.2 Polynomial Approximation and Lookup Table

In light of trigonometric addition formulas, the $sin(p + r)$ and $cos(p + r)$ become $sin(p)cos(r) + cos(p)sin(r)$ and $cos(p)cos(r) - sin(p)sin(r)$ respectively. EDHIR stores $sin(p)$ and $cos(p)$ values in tables $TS(p)$ and $TC(p)$ with argument p respectively, and each table has 2^n entries. Next, EDHIR adopts a polynomial approximation to approximate the sine and cosine functions with the remaining argument r. That is, $S(r)$ approximates $sin(r)$ expressed as

$$S(r) = a_0 + a_1 r + a_2 r^2 + a_3 r^3. \qquad (8)$$

On the other hand, $C(r)$ approximates $cos(r)$ modeled as

$$C(r) = b_0 + b_1 r + b_2 r^2 + b_3 r^3. \qquad (9)$$

Coefficients a_i and b_i can be obtained from Remez's Algorithm [14], where $0 \le i \le 3$.

Although Taylor expansion is easy to use, it is much worse and less efficient than the other approximations [10]. This is because Taylor expansion only provides local approximations rather than global approximations. On the other hand, the computation of rational approximation [14] is more expensive than the polynomial approximation due to lots of dividers. Compared to these approximations, the polynomial approximation gives more accurate and efficient in the digital holography image reconstruction. We give an example for the above procedure.

Example: We approximate the sine function with argument $3\pi/16$ in [0, $\pi/4$]. EDHIR first equally separates the domain into two intervals [0, $\pi/8$] and [$\pi/8$, $\pi/4$], where n is 1. Since $3\pi/16$ is in [$\pi/8$, $\pi/4$], we decompose $3\pi/16$ to $\pi/8 + \pi/16$ (i.e., $p = \pi/8$ and $r = \pi/16$). $sin(3\pi/16)$ can be rewritten as $sin(\pi/8 + \pi/16)$ that is equal to $sin(\pi/8) \times cos(\pi/16) + cos(\pi/8) \times sin(\pi/16)$. Next, EDHIR stores the solutions of the sine and cosine functions among the subinterval boundaries, i.e., $sin(0)$, $sin(\pi/8)$, $sin(\pi/4)$, $cos(0)$, $cos(\pi/8)$, and $cos(\pi/4)$, in tables TS and TC respectively. EDHIR then uses the polynomial approximation to approximate the solutions of the sine and cosine functions with the remaining argument $\pi/16$, i.e., $sin(\pi/16)$ and $cos(\pi/16)$. With the polynomial approximation, $sin(\pi/16)$, i.e., $S(\pi/16)$, is equal to $a_0+a_1(\pi/16)+a_2(\pi/16)^2+a_3(\pi/16)^3$, and $cos(\pi/16)$, i.e., $C(\pi/16)$ is equal to $b_0 + b_1(\pi/16) + b_2(\pi/16)^2 + b_3(\pi/16)^3$. Coefficients $\{a_i\}$ are $\{0, 1, -0.0001, -0.1658\}$, and $\{b_i\}$ are $\{1, 0.0001, -0.5020, 0.0163\}$ both obtained from Remez's Algorithm [14], where $0 \le i \le 3$. Finally, we can obtain $sin(3\pi/16)$ as $TS(\pi/8)\times S(\pi/16)+TC(\pi/8)\times C(\pi/16)$ that is equal to 0.5556, where $TS(\pi/8)$ is equal to 0.3827, and $TC(\pi/8)$ is equal to 0.9239. ■

3. EXPERIMENTAL RESULTS

3.1 Experimental Environment

In this section, we conduct several experiments to evaluate the performance of algorithm EDHIR. We compare our

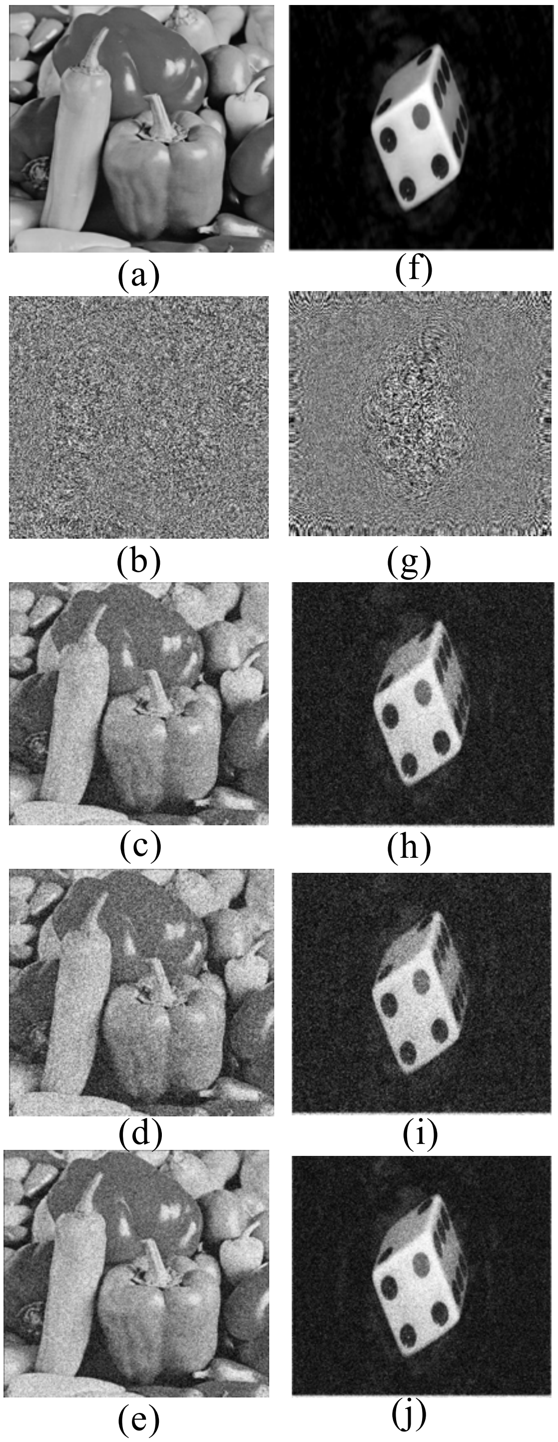

Figure 1: Results of digital holographic image reconstruction under each algorithm (a) original object (b) hologram of (a) (c) reconstructed image from (b) under THIR (d) reconstructed image from (b) under HHIR (e) reconstructed image from (b) under EDHIR (f) original object (g) hologram of (f) (h) reconstructed image from (g) under THIR (i) reconstructed image from (g) under HHIR (j) reconstructed image from (g) under EDHIR

Figure 2: Digital holographic image reconstruction under EDHIR on ASUS Transformer Pad

algorithm with Hardware-based Holographic Image Reconstruction (HHIR) [13] and Traditional Holographic Image Reconstruction (THIR) [16]. HHIR proposes a hardware-based method to speed up the computation in Fast Fourier transform for the reconstruction of digital holographic images. For the GPU dependent components of HHIR, HHIR is implemented by using CUDA with AndroidWorks for Android Development [4] that is native to the NVidia GeForce hardware platform in the android devices. On the other hand, THIR is a convolution method to accelerate the reconstruction of digital holographic images.

We implement our algorithm on a ASUS Transformer Pad (TF701T) Android Pad with Quad-core 1.9 GHz Cortex-A15, Chipset Nvidia Tegra 4 T40X, 3GB RAM, ULP GeForce GPU processor, Android 4.2, 2560×1600 pixels Super IPS+L CD display, and 5M pixels camera. Fig. 2 shows an example of running EDHIR on the ASUS Transformer Android Pad. Note that our program can be installed and runs on any Android devices.

Before evaluating the performance of our algorithm, we describe our data set and set up parameters as follows. Experimental images are from the USC-SIPI and European research center databases at http://sipi.usc.edu/database/ and http://www.erc-interfere.eu/downloads.html respectivel y. We generate synthetic holograms with size 512×512 and their corresponding parameters. We follow traditional setting for each hologram where all samples can be used for holography reconstruction. We normalize the spatial-domain amplitude and phase values of each hologram to [0,1] and $[0, \pi]$, respectively. The parameters for the hologram generation correspond to an off-axis configuration as $\lambda = 517{\times}10^{-9}$, $\triangle x = \triangle y = 6{\times}10^{-6}$, and $d{=}63{\times}10^{-2}$. In the following, we compare the execution time of each algorithm and the quality for different algorithms with respect to different factors on the mobile device.

3.2 Performance Analysis

The performance of the proposed algorithm is evaluated using the two objects, ‘Peppers’ and ‘Dice’, whose reconstructed images are shown in Figs. 1. The distortion of the reconstructed image is measured by peak-signal-to-noise ratio (PSNR). The mean squared error (MSE) for reconstructed image $D(n, m)$ and original image $O(n, m)$ with size $N \times M$ is given as

$$MSE = \frac{1}{N \times M} \sum_{n} \sum_{m} [D(n, m) - O(n, m)]^2. \qquad (10)$$

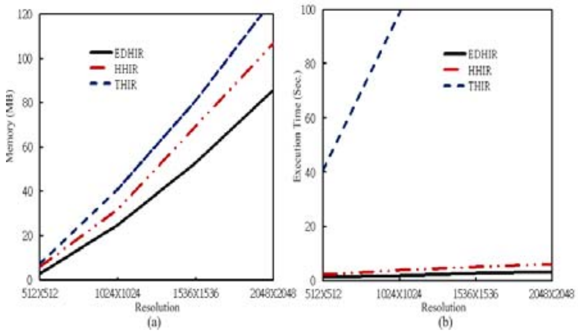

Figure 3: Comparisons of the hardware performance under each algorithm (a) memory consumption (b) execution time

The PSNR is expressed as

$$PSNR = 10log\frac{255^2}{MSE}. \quad (11)$$

Figs. 1 show that EDHIR with the average PSNR of 21.74dB is superior to THIR of 15.95dB and HHIR of 14.26dB. This is because EDHIR can achieve high accuracy for the numerical reconstruction of the holographic image in the exponential functions. Specifically, the accuracy of EDHIR overpasses that of HHIR and THIR by storing the high-precision results of the significant arguments. However, THIR and HHIR perform worse since they approximate these arithmetic results by merely using polynomial algorithms [17].

Fig. 3(a) shows that the memory sizes of EDHIR are smaller than HHIR and THIR since EDHIR effectively adopts the lookup table to store the solutions for more significant arguments rather than those of whole arguments. However, HHIR and THIR still cannot effectively save the memory since the 2D FFT is quite memory demanding. We observe that the 2D FFT allocates almost two times the hologram size of additional memory. Although EDHIR mainly stores the results of the significant arguments, EDHIR with one FFT can also conserve more memory sizes as compared to the traditional methods.

3.3 Efficiency Analysis

In this section, Fig. 3(b) shows that our algorithm is efficient and very feasible for the digital holographic image reconstruction on mobile devices. The computational time of the digital holographic image reconstruction on EDHIR is close to HHIR since EDHIR combines a lookup table and a polynomial approximation to fast calculate the exponential functions. Specifically, EDHIR needs fewer adders and multipliers accepted by a general-purpose CPU to execute the sum and product for the least significant arguments. GPU is very efficient for scientific computing since its high parallel structure is faster than the general-purpose CPU for FFTs and exponential functions. Although HHIR adopts GPU to speed up the Fresnel integral, it needs lots of dividers, multipliers, and memory sizes to burden the performance of HHIR. THIR performs worst since lots of FFTs yield heavy load in computation.

4. CONCLUSION

With the rapid advanced digital holographic visual technologies for mobile devices, the holographic image reconstruction in the mobile devices has become indispensable. However, the previous works are infeasible for the current mobile devices due to unacceptable computational complexity. In this paper, we have proposed an efficient and effective algorithm to reconstruct the digital holographic images. The experimental results have shown that our approach is not only of smaller running time but for higher quality of the digital holographic image reconstruction as compared to the existing works on the mobile devices.

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