High-resolution Mesh-based Computer-generated Hologram Synthesis using Valid Frequency Domain and Fast Fourier Transform with Graphics Processing Unit

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ABSTRACT

To reduce the calculation time of synthesizing high-resolution mesh-based computer-generated hologram (CGH), we define a valid frequency domain in off-axis condition which makes different path of DC and three-dimensional (3D) object. Also, we propose a graphics processing unit (GPU) based fast Fourier transform (FFT) method for calculating angular spectrum of mesh-based CGH.

1 INTRODUCTION

Computer-generated hologram (CGH) is a technique to calculate an optical filed of three-dimensional (3D) object. Among the CGH synthesis methods, a mesh-based method is effective for synthesizing large objects [1-3]. Because the mesh-based CGH assumes plane wave incident on the triangle aperture, it has a very narrow viewing angle. To enlarge the viewing angle, each mesh is divided and applied with different phases [1]. However, those mesh dividing procedures take a lot of calculation time. In an analytic method, instead of dividing meshes, a convolution is used to approximate the random phase to reduce the calculation time [2]. In a non-analytic method, it is applied by multiplying random phase in the local spatial domain [3]. While the analytic method uses one convolution replaced with two times of FFT, the non-analytic method contains single FFT which calculates global angular spectrums from local angular spectrums. In these cases, the FFT operation, occurring in each mesh, takes the largest time in the synthesis of the mesh-based CGH. In this paper, we explain how to reduce the calculation time of FFT which is a significant issue especially for a high-resolution hologram.

2 PROPOSED METHOD

2.1 Valid Frequency Domain

When the amplitude hologram is reconstructed, conjugate image and DC component disturb the observer. To solve these issues, the off-axis hologram which divide the path of DC component and 3D object by multiplying uniform plane wave having certain angle is usually applied. And, the calculation of multiplying uniform plane wave having certain angle is the shifting process in the frequency domain.

$$u(x)\exp(i2\pi f_0 x) \Leftrightarrow U(f-f_o)$$

$u(x)$ and $U(f)$ are hologram and angular spectrum domain with one-dimension respectively and $\Leftrightarrow$ denote the Fourier transform. The exponential term is the plane wave having angle of $\sin^{-1}(f_0\lambda)$ with wavelength of λ and it shifts the angular spectrum domain by f_o.

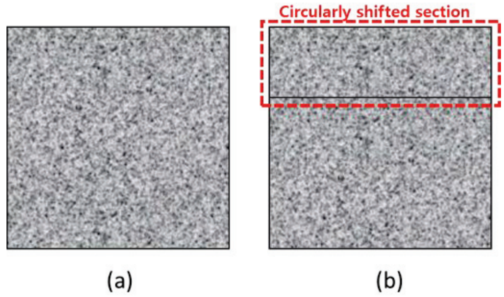

Fig. 1 Angular Spectrum
(a) before off-axis, (b) after off-axis

In the angular spectrum domain, the grid step is defined by the pixel pitch of hologram and the range is limited by the resolution of hologram. For these reasons if the angle of off-axis is set to y-direction, after shifting, the angular spectrum is shifted circularly as shown in Fig 1. Therefore, the circularly shifted section reconstructs the 3D object in undesired position.

Fig. 2 Angular Spectrum with Circularly Shifted Section Replaced by Zero

To avoid this problem, the circularly shifted section should be replaced by zero as shown in Fig. 2. In this paper, for preliminary processing of zero padding caused by off-axis, we calculate the range of the circularly shifted section before synthesizing the angular spectrum of hologram and propose calculating only the valid region to reduce the calculation time.

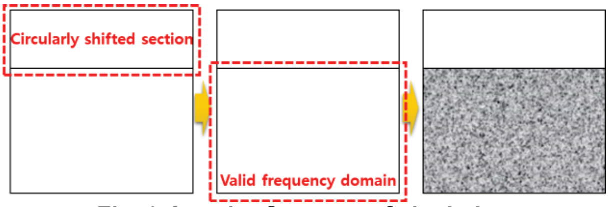

Fig. 3 Angular Spectrum Calculation using Valid Frequency Domain

In mesh-based CGH, the angular spectrum domain is pre-calculated, and it is transformed to hologram domain by Fourier transform. Because the angular spectrum is calculated from the index of frequency domain, by setting the index we want to know, we can calculate the angular spectrum of any range. And, as we know the propagation angle of plane wave used for off-axis, we can easily find the circularly shifted section. Figure 3 shows the calculation step using the valid frequency domain. At first, the circularly shifted section is calculated from off-axis plane wave. And then, the valid frequency domain is set. Finally, the angular spectrum is calculated.

In this method, the computation time reduction is proportional to the absolute value of off-axis angle because the circularly shifted section is widened as the absolute value of off-axis angle is enlarged. Table. 1 compares the calculation time of the conventional method and proposed method using the valid frequency domain. In the comparison experiment, the pixel pitch and resolution of hologram are 3.74um and 3840 × 2160 respectively. The wavelength of 532nm is used, the depth of 3D object is 10cm. The cube with 24-mesh is used for the 3D model. By the pixel pitch of the hologram and the wavelength, the range of angular spectrum domain is set to -4.07° ~ +4.07°. As shown in Table. 1, increasing the angle of off-axis, the calculation time is reduced. Figure. 4 shows the angular spectrum and the numerical reconstruction of Table. 1. It is confirmed that the DC component goes away from the 3D object as the angle of off-axis increases while the 3D object is maintained in proposed method using the valid frequency domain.

2.2 GPU based FFT for Calculating Angular Spectrum

In this study, we use the non-analytic mesh-based CGH that contains single FFT [3] for each mesh. Figure 5. (a) and (b) show the flowcharts of the conventional and proposed mesh-based hologram synthesis method respectively. The conventional CGH is generated by sampling the angular spectrum from the local domain to the global domain by the first FFT for each mesh. And it is converted from angular spectrum to hologram through the second FFT. When the size of a two-dimensional (2D) matrix, which is going to be calculated FFT, is much larger than the GPU memory, it needs to be computed by the central processing unit (CPU) causing time-consuming problems. To overcome these problems, we propose a method described in the flowchart shown in Fig. 5 (b).

First, we split the 2D matrix of angular spectrum to the maximum size which can be computed in the GPU memory. Note that it is the same process setting the valid frequency domain of angular spectrum mentioned in Section 2.1 although the purpose is different. Second, we calculate the angular spectrum for all the meshes in the segmented matrix into GPU memory and store them. Finally, the FFT of integration of segmented angular spectrum is calculated in the CPU.

Table. 1 Computation Time Comparison of Conventional Method and Proposed Method using Valid Frequency Domain

Angle of off-axis	Conventional method	Proposed method
0°	15.5s	15.7s
1°	15.3s	13.8s
2°	15.4s	12.1s
3°	15.3s	10.0s

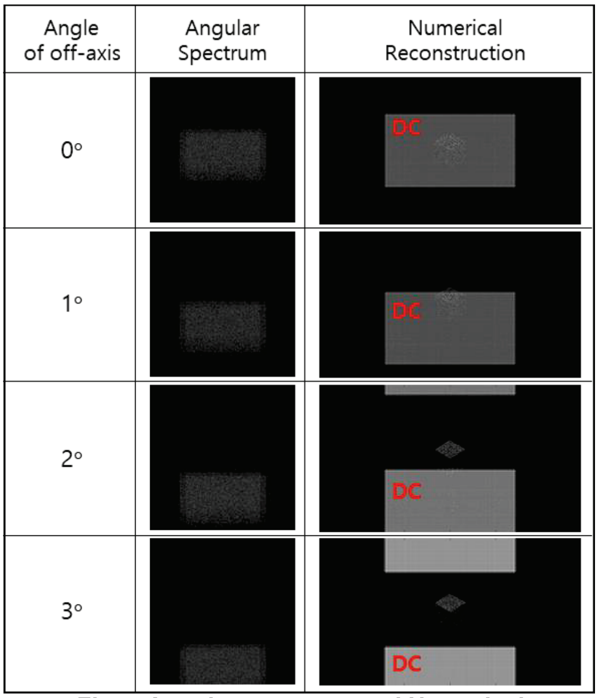

Fig. 4 Angular spectrum and Numerical Reconstruction of Proposed method using the valid frequency domain

To verify that the proposed method is faster than the conventional method, we compare the computation time of both methods. The synthesis was performed with a single mesh object and hologram resolution of 40K×40K. Computation was executed using a PC with Intel(R) i7-9700K (3.60 GHz) CPU, 64 GB of memory with 512 GB of virtual memory and NVIDIA GeForce RTX 2060 (6 GB) GPU.

The results of the computation time are shown in Table 2. In the experimental condition, the maximum size of FFT which can be performed in GPU is calculated to 4K×4K, so the total number of segments is 10×10 in the proposed method. Although the proposed algorithm is more complicated, the calculation time is reduced by more than half compared to the conventional method as shown in Table 2.

To the best of my knowledge, in the conventional high-resolution mesh-based CGH, the algorithm for accelerating hologram synthesis uses only the multi-CPU with parallel processing [3]. In the proposed method, on the other hand, mesh-based CGH is generated by using GPU and the calculation time reduction is confirmed by experiments.

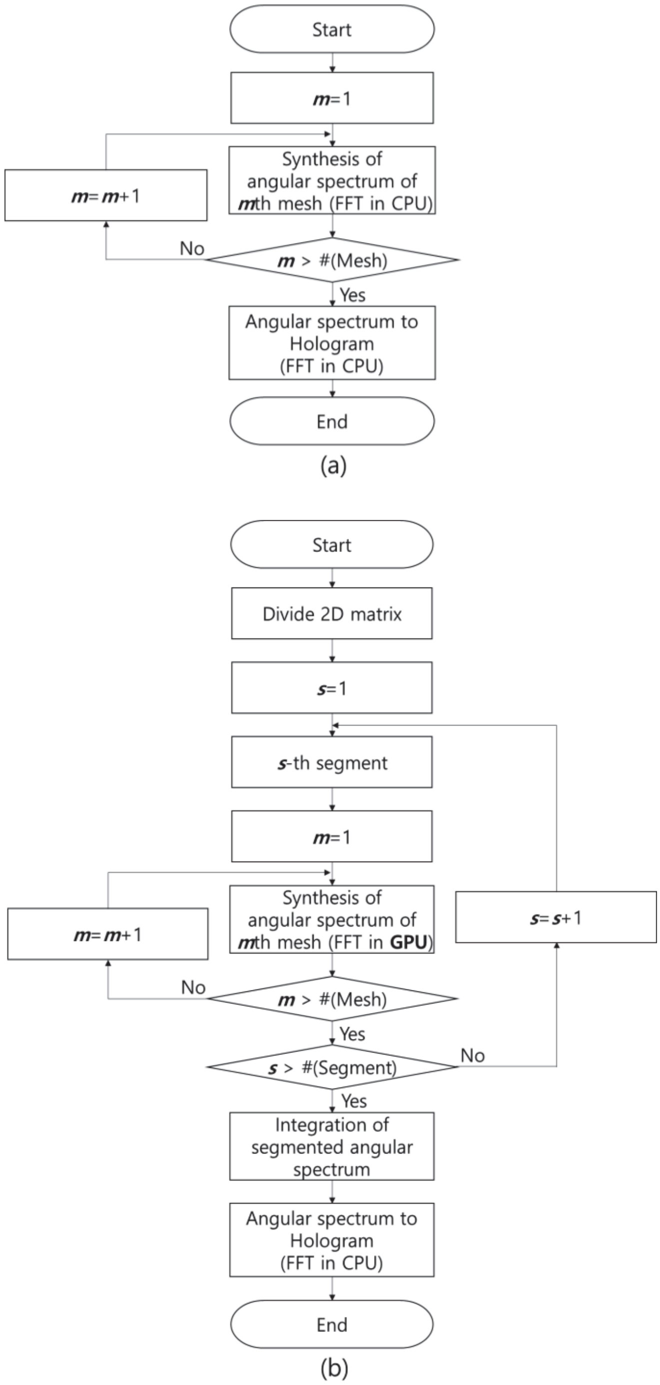

Fig. 5 Flowcharts of (a)conventional and (b)GPU based method

Table. 2 Computation time

Step	Conventional method	GPU based method
Synthesis of angular spectrum	1893.7s	668.3s
Integration of segmented images	-	145.8s
Angular spectrum to hologram	136.3s	135.2s
Total time	2030.0s	949.3s

3 CONCLUSION

In this paper, we propose the angular spectrum calculation algorithm using the valid frequency domain for reducing the calculation time. It is possible as we know the plane wave for off-axis and the angular spectrum can be calculated with arbitrary index we want to know. Also, we propose GPU based FFT for calculating angular spectrum. If the size of 2D matrix is larger than GPU memory, we can divide the matrix so that it is loaded into GPU memory. These two approaches can speed up high-resolution mesh-based CGH synthesis.

As the technology develops, the resolution of the holographic display panel will be increased, and it is necessary to develop a high-speed CGH algorithm to follow it. The proposed method can be one solution to accelerate the CGH calculation algorithm.

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