Real-time Fringe Pattern Generation with High Quality

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Abstract: A hologram computation procedure and its GPU implementation are presented. The procedure is based on partitioning. Each segment has an approximate but simpler frequency domain representation. Quality of the results is comparable to Fresnel holograms.
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1. Introduction

As a consequence of typically large number of pixels in a hologram and the associated computational complexity, the computation time is a major issue in holographic video. The coherent holographic stereogram (CS) [1] is a fast method which significantly reduces the computational complexity. The main algorithm in this approach uses discrete spatial frequencies and the associated phases at those frequencies are also quantized. Modified and improved versions of the basic CS are reported in the literature [2, 3, 4, 5, 6]. Here we propose a further improved version of the basic CS; we call this new version "accurate compensated phase-added stereogram (ACPAS)". We used the term "accurate" to emphasize that reconstructed images are quite similar to the reconstructions from the Fresnel hologram. ACPAS has the advantages of both the CPAS [5] and the APAS [6]; furthermore, ACPAS is implemented on a multi GPU environment [7], and thus, a higher speed is achieved.

2. Quality improvements for coherent stereogram

Computational speed of the CS is much faster than that of the Fresnel hologram [1]. The main reason for the speed up is the initial partitioning of the output diffraction pattern (hologram) into segments, and then approximating the contribution of each object point to the hologram pattern over one segment as a single 2D complex sinusoid; an initial Fourier domain pattern is composed by writing the complex amplitude of each such complex sinusoid to their frequency locations, and a subsequent inverse fast Fourier transform (IFFT) completes the fringe pattern computation for a segment. Repeating this procedure for each segment completes the computation. The compensated phase-added stereogram (CPAS) and accurate phase-added stereogram (APAS) are quality improvements over the PAS as described below. The PAS uses the IFFT to generate a fringe pattern; since the locations of the allowed frequencies is discrete, the exact frequency components associated with the contributions of each object point have to be modified; this is done by moving the exact frequencies to their nearest allowed discrete frequency values without changing their complex amplitudes. This is a source of error (noise). An improvement is the CPAS where the phases of the complex amplitudes are compensated, in a manner to reduce the error, as the frequency components are moved. The phase compensation is computed from the differences between the spatial frequency values in the continuous and the discrete domains. As expected, the reconstructed image of the CPAS is better than that of the PAS. The calculation time is almost the same as the PAS. The fundamental frequency component of a fringe pattern in a segment, in cycles per unit length, is,

$$f_{BSF} = \frac{1}{T_{BP}} = \frac{1}{\Delta S} = \frac{1}{\Delta P N_S},\tag{1}$$

where T_{BP} is the fundamental period, ΔS is the segmentation size, ΔP is a pixel size, and N_s is the number of pixels along one direction of a segment. We take the number of pixels in a segment as $N_s \times N_s$. Accordingly, the coordinates of the spatial frequencies are $\xi_{int} = \text{integer}(f_{p\xi c}/f_{BSF\xi})$, and $\eta_{int} = \text{integer}(f_{p\eta c}/f_{BSF\eta})$, where $f_{p\xi c}$ and $f_{p\eta c}$ are sthe continuous spatial frequencies on ξ and η axes, and ξ_{int} and η_{int} are the corresponding horizontal and vertical discrete coordinates. Here the $\text{integer}(\cdot)$ refers to the "nearest integer" operator. The spatial frequencies $f_{p\xi c}$ and $f_{p\eta c}$ are determined as $(\sin\theta_{p\xi c} - \sin\theta_{\xi\text{ref}})/\lambda$ and $(\sin\theta_{p\eta c} - \sin\theta_{\eta\text{ref}})/\lambda$, where $\theta_{p\xi c}$ and $\theta_{\xi\text{ref}}$ are the incidence angles of the object and reference beams on ξ axis, and $\theta_{p\eta c}$ and $\theta_{\eta\text{ref}}$ are the incidence angles on η axis. The related frequency error compensations are $C_\xi = 2\pi\left(f_{p\xi c} - f_{BSF\xi}\right)$ and $C_\eta = 2\pi\left(f_{p\eta c} - f_{BSF\eta}\right)$, on the ξ and η axes, respectively.

The spatial frequency and the phase at the center of a segment are used to calculate the PAS of the segment. Then the error due to discretization of the spatial frequencies is reduced by adding the error compensations to the phases. Consequently, the compensated PAS is computed as [5],

$$\mathbf{I}_{CPAS}(\xi, \eta) = \sum_{p=1}^{N} \frac{a_p}{r_p} \cos \left\{ 2\pi \left[(\xi - \xi_c) f_{p\xi\text{cint}} + (\eta - \eta_c) f_{p\eta\text{cint}} \right] + k r_p + C_\xi + C_\eta \right\}. \tag{2}$$

where N is the number of object points. The wave number k is $2\pi/\lambda$, where λ is the free-space wavelength of the coherent light. The oblique distance r_p between the p-th object point and the point (ξ, η) on the hologram is $\left[(\xi - x_p)^2 + (\eta - y_p)^2 + z_p^2 \right]^{1/2}$. Spatial frequencies $f_{p\xi\text{cint}}$ and $f_{p\eta\text{cint}}$ are determined as $f_{p\xi\text{cint}} = \xi_{\text{int}} f_{BSF\xi}$, and $f_{p\eta\text{cint}} = \eta_{\text{int}} f_{BSF\eta}$, respectively.

There associated sampling issues must be carefully considered since there is a trade-off. If the segment size gets smaller, and if the IFFT size is taken to be equal to the segment size (as in PAS), the discretization of the frequencies gets coarser; therefore, the noise over the reconstructed image increases, too. On the other hand, if the segment size gets larger, the approximation error which assumes a single frequency contribution from each object point also gets larger. Consequently, there is an optimal choice of the segment size to minimize the overall error in the reconstructed image. The APAS uses a larger FFT size per each segment, and thus reduces the error due to discretized spatial frequency domain. In this case, the hologram segment is obtained by truncating the large-size IFFT output properly. The quality of the reconstructed image using the APAS is close to the continuous-frequency PAS. The calculation time of the APAS longer than the discrete-frequency PAS due to larger size IFFT computations.

3. Accurate compensated phase-added stereogram

The fringe generation methods of the CPAS and APAS can be combined to get a higher quality reconstructed image; we call this method better compensated phase-added stereogram (ACPAS). The generation method of the ACPAS is the same as in the previous sections. This proposed method generates more accurate results which closely resembles the Fresnel hologram. The results of a typical case is presented below.

The perspective image of a point-cloud (vertices-only, sparse) 3D model is shown in Fig. 1(a). The dense 3D object points, which are extracted from the 3D model assuming a triangular mesh structure with the given vertices, are used to generate hologram patterns using the Fresnel hologram and the ACPAS algorithm, for comparison. The reconstructed images are shown in Fig. 1(b) and 1(c). The used 3D object consisted of about 3,000 vertices, and therefore, the rendered images are photorealistic. As seen in Fig. 1, the quality of the reconstructed images using ACPAS and the unapproximated Fresnel holograms are similar.
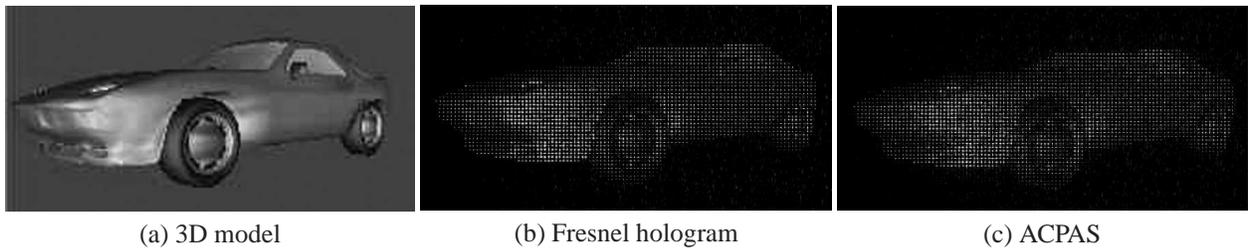

(a) 3D model   (b) Fresnel hologram   (c) ACPAS

Fig. 1. A perspective image of the used 3D model and reconstructed images.

4. ACPAS acceleration on GPU

The graphics processor unit (GPU) is a dedicated graphics rendering device for personal computers. The highly parallel structures of modern GPUs improve computation times of a range of complicated algorithms significantly compared to typical CPUs. Since the algorithm of the CS can be easily mapped to a single instruction multiple data architecture, the ACPAS computing can significantly benefit from GPU based implementations.

An experimental code to compute the ACPAS on multi-GPU has been implemented. The software has three GPU kernel functions: calculation of spatial frequencies and phases in each segment, IFFT corresponding to each segment, and normalization of the complex fringe pattern. All three kernel functions are processed in the GPU, and a computer

main processor, CPU, just manages the algorithm and data flow. Computation times corresponding to the CGH generation algorithms for different number of object points are shown in Fig. 2. We could achieve up to 300 times faster computation using GPU-based ACPAS compared to a typical CPU-based implementation. One mega-pixel frame size full color holograms can be generated at a rate of 30 frames per second for objects with more than 10,000 points. Comparative results for CPAS on a GPU and ACPAS on three GPUs are shown in Fig. 2. The used parameters in this experiment are as follow: the hologram size is $1K \times 1K$ pixels; the IFFT size is 64×64 pixels and the corresponding segment size is 32×32 pixels. The computing system has two Intel(R) Xeon(R) CPU 2GHz, 8-GByte memory and three NVIDIA GeForce GTX 280 video cards.
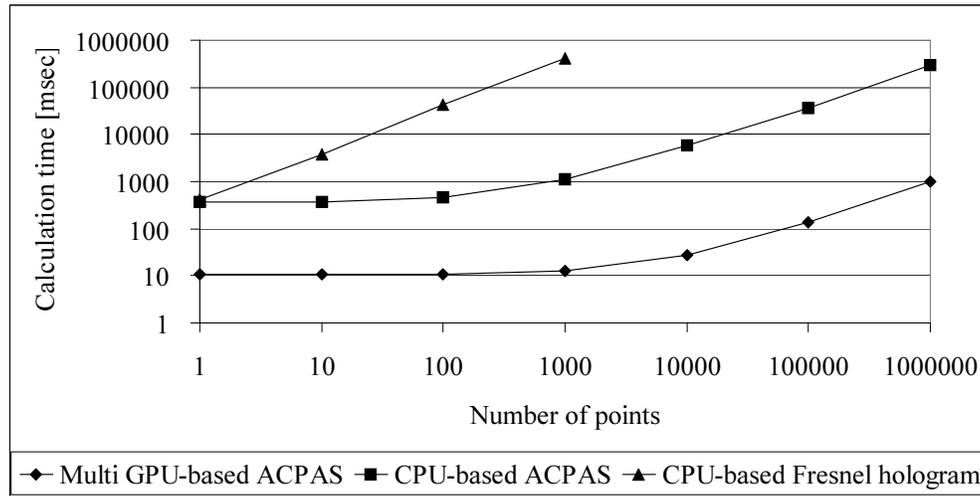

Fig. 2. Calculation-time comparison between CPU-based and GPU-based implementations.

5. Conclusion

We have proposed the ACPAS, which has two quality improvement methods over the CS. These improvements are due to phase compensation and reduction of frequency discretization step-size. The quality of reconstructed image is similar to the Fresnel hologram. In addition, the speed up due to multi-GPU implemented ACPAS is discussed. We can generate high quality hologram patterns in real-time as a consequence of a speed up factor of about 300 compared to CPU-based implementations. The digital holograms generated by the ACPAS can be computed and displayed at a rate of 30 fps for photorealistic scenes represented by ten thousands of object points.

Acknowledgments

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