VIEWING ANGLE DEPENDENT CODING OF DIGITAL HOLOGRAMS

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ABSTRACT

In this work, an interactive digital hologram transmission algorithm is proposed based on the user's viewing direction. Digital hologram is a digital image yielding the depth information of 3D object, where a local region of sub-hologram is associated with a specific viewing direction to observe the 3D object. Therefore, in server-client communication environments, a client requests the viewing angles associated with a specific viewing direction, and the server adaptively transmits the sub-hologram data according to the client's request. In practice, since the digital hologram is generally a noise-like image, the object image is encoded instead which is numerically reconstructed from digital hologram. Moreover, H.264/AVC intra-only coding scheme is used to increase the coding gain of reconstructed images. It was shown that the proposed viewing angle dependent coding algorithm more effectively exploit the transmission bandwidth compared with the conventional viewing angle independent coding method.

1. INTRODUCTION

Digital holography is one of the techniques to represent 3D images by using the interference and diffraction of light waves [1]. In digital holography, a CCD (Charged Coupled Device) sensor captures the digital hologram which is the intensity image of interference pattern between the reference wave and the reflected wave from 3D object. The digital hologram can then be used to optically reconstruct a 3D image using spatial light modulator [2], or numerically compute an object image based on the mathematical modeling of light diffraction [1].

Digital hologram generally requires large storage space and high transmission bandwidth. Therefore, during the last decade, a lot of researches have been carried out to efficiently compress the digital holograms. Naughton et al. attempted the several coding techniques such as LZ77, LZW, Huffman, and Burrows-Wheeler transform coding, for lossless compression of digital holograms [3]. Shortt et al. introduced a wavelet transform method to analyze digital holograms, and encoded the quantized wavelet coefficients [4]. A non-uniform quantization scheme was also proposed based on the histogram of digital hologram [5]. Darakis et al. encoded the object image reconstructed from digital hologram, and showed that the reconstructed images yield better compression performances than the digital holograms [6, 7, 8].

Even though the previous compression methods can be used to store and transmit the digital holograms, we may need an interactive transmission technique for a server-client environment. In particular, a part of digital hologram is related to a specific viewing direction to observe the 3D object, and thus can be selectively compressed and transmitted according to the user's viewpoint [9]. In this paper, we develop a viewing angle dependent coding algorithm of digital holograms using the reconstructed images. A client first requests the viewing angles and the window size of the corresponding sub-hologram. Then the server adaptively encodes the object image reconstructed from the requested sub-hologram by using H.264/AVC intra-only coding scheme. The compressed bitstream is transmitted to the client, while the client's viewpoint is fixed. When the client's viewpoint is changed, new viewing angles are updated to the server and the object image reconstructed from the newly requested sub-hologram is transmitted. The overlapped region between the previously requested sub-hologram and the currently requested one is not encoded again to effectively use the transmission bandwidth. We show that the proposed algorithm yields a higher compression ratio and more reduces the transmission bandwidth than the conventional method.

The remainder of paper is organized as follows. Section 2 explains the digital holography and Section 3 describes the characteristics of digital hologram. Section 4 proposes the viewing angle dependent coding scheme in server-client environments. Experimental results are given in Section 5. Finally, we draw a conclusion in Section 6.

2. DIGITAL HOLOGRAPHY

Digital hologram is first recorded as a digital image having the depth information of 3D object. Then the object image is numerically reconstructed from the digital hologram and further processed for a better visual quality.

2.1 Recording of Digital Hologram

Fig. 1 (a) shows the recording process of digital hologram. A linearly polarized laser with a unique wavelength is first split into the two parts by beam splitter. One is the reference wave, and another is the object wave which is reflected from 3D object and yields the deformed phase information. The complex amplitude of wave is composed of the real amplitude A and the phase φ. Hence the reference wave $E_{ref}(x,y)$

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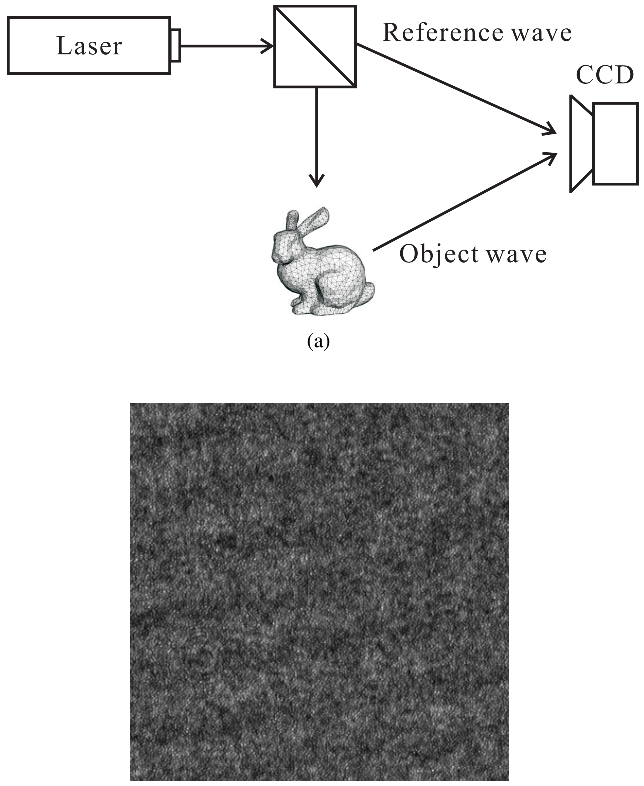


Figure 1: (a) Recording processes in digital holography. (b) The 'Brahms' digital hologram.

and the object wave $E_{obj}(x,y)$ can be represented by

$$\begin{aligned} E_{ref}(x,y) &= A_{ref}(x,y)e^{i\varphi_{ref}(x,y)} \\ E_{obj}(x,y) &= A_{obj}(x,y)e^{i\varphi_{obj}(x,y)}. \end{aligned} \quad (1)$$

$E_{ref}(x,y)$ interferes with $E_{obj}(x,y)$ in the plane of CCD sensor, and the intensity $h(x,y)$ of the interference pattern is stored as a digital hologram.

$$\begin{aligned} h(x,y) &= |E_{obj}(x,y) + E_{ref}(x,y)|^2 \\ &= |E_{obj}|^2 + |E_{ref}|^2 + 2A_{obj}A_{ref}\cos[\Delta\varphi(x,y)] \end{aligned} \quad (2)$$

where $\Delta\varphi(x,y) = \varphi_{obj}(x,y) - \varphi_{ref}(x,y)$ means the difference of optical paths between the reference wave and the object wave, which is related to the depth information of 3D object. Fig. 1 (b) shows the digital hologram of the 'Brahms' model.

2.2 Reconstruction of Object Image

When the reference wave illuminates the digital hologram again, the 3D object image can be optically reconstructed by using spatial light modulator, as shown in Fig. 2. However, we can also numerically compute an object image $H(x',y')$ from digital hologram $h(x,y)$ based on the unitary Fresnel transform [10] defined by

$$H(x',y') = \frac{e^{ikd}}{i\lambda d} \iint h(x,y) e^{\frac{i\pi}{\lambda d}[(x-x')^2+(y-y')^2]} dxdy. \quad (3)$$

k is a constant, d means the distance from the captured object to the hologram plane, and λ is the wavelength of light

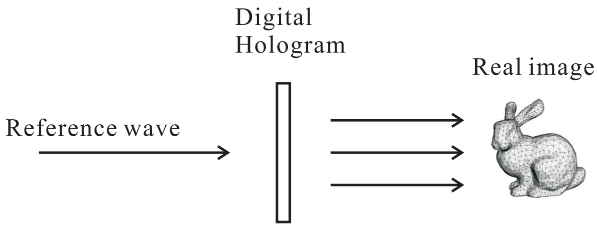


Figure 2: Optical reconstruction process in digital holography.

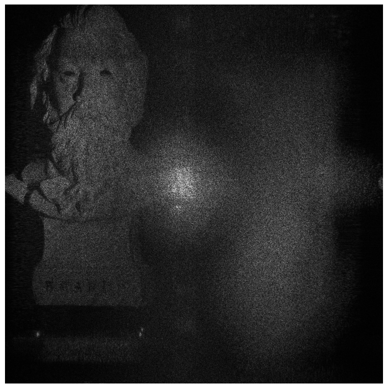


Figure 3: Numerically reconstructed image of the 'Brahms' digital hologram with an off-axis setup.

waves. Fig. 3 represents the image numerically reconstructed from the 'Brahms' digital hologram.

However, the quality of reconstructed image may be degraded by zero-order diffraction and conjugate image [1, 11]. Zero-order diffraction denotes the bright region appeared in the center of image, which is caused by the reference wave penetrating the digital hologram. Conjugate image is a replica of the object image, which is derived from the complex conjugate of object wave. Therefore, there have been some approaches to overcome these drawbacks [11, 12]. An off-axis setup was basically designed by illuminating the reference wave to digital hologram along the oblique direction to the axis of CCD sensor. Then the positions of the zero-order diffraction and conjugate image can be separated from that of the desired object image, as shown in Fig. 3. The complex bandpass filter was additionaly applied to digital hologram in frequency domain, to remove these artifacts [11]. Phase-shifting digital hologram is another approach [12], where three or more holograms, called interferograms, are generated with the reference waves of different phases. By using multiple interferograms, the amplitude and phase of the object wave can be directly calculated without any artifacts.

3. PROPERTY OF DIGITAL HOLOGRAM

Digital hologram is inherently a captured image by CCD sensor, and therefore each pixel of digital hologram records the reflected light observed from a particular viewing direction. It means that the digital hologram has the information of

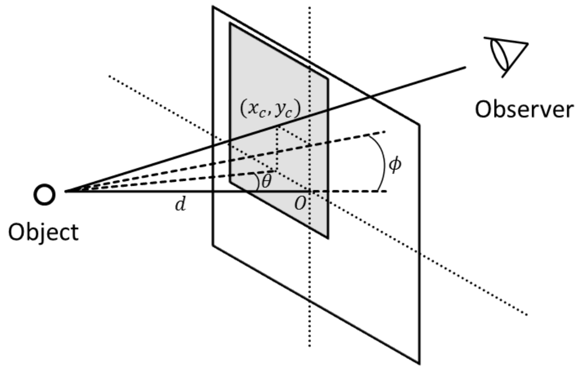


Figure 4: The local region of digital hologram corresponds to a specific viewing direction.

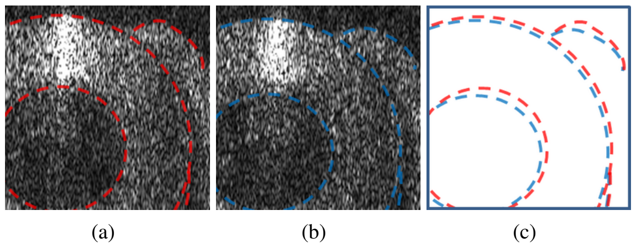


Figure 5: The reconstructed images using the partial 400 × 400 sub-holograms of the 'Screw' data, where the corresponding viewing angles (θ, ϕ) are (a) $(-0.366°, 0.366°)$ and (b) $(0.366°, -0.366°)$, respectively. (c) Overlapped boundaries of the two images.

multi-perspective views. Furthermore, the reconstructed image is also a superposition of the multiple images associated with multiple viewpoints, since the object image is reconstructed from digital hologram using Eq. (3), which is similar to the Fourier transform. Therefore, if a local region of digital hologram is employed to the reconstruction process, we can get an object image seen from a particular viewing direction.

To be specific, the local grey region of digital hologram in Fig. 4 is centered at (x_c, y_c) and yields the information seen from the viewpoint of observer. θ and ϕ are the viewing angles associated with the viewing direction, where $\theta = \tan^{-1}(x_c/d)$ and $\phi = \tan^{-1}(y_c/d)$, respectively. By changing (θ, ϕ), we can select the proper region of sub-hologram to reconstruct an object image corresponding to a specific viewing direction. For example, Fig. 5 shows the reconstructed images of the 'Screw' digital hologram according to the change of (θ, ϕ). The object images reconstructed from the partial 400 × 400 sub-holograms corresponding to $(-0.366°, 0.366°)$ and $(0.366°, -0.366°)$, are shown in Fig. 5 (a) and (b), respectively. As observed in Fig. 5 (c), slightly different images are exhibited with the change of viewing angles. Note that, due to the loss of information, each image reconstructed from a sub-hologram yields a relatively lower quality compared with the original one reconstructed from the entire hologram.

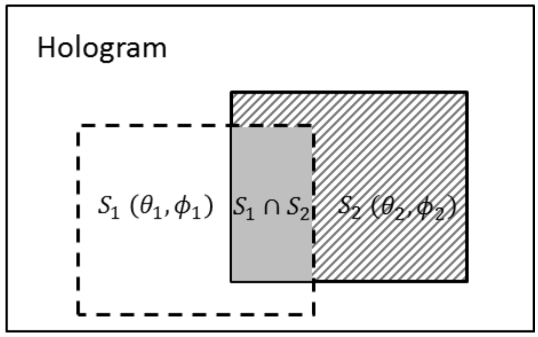


Figure 6: Sub-holograms associated with the viewing angles. S_1 is the previously transmitted sub-hologram corresponding to the viewing angle (θ_1, ϕ_1), and S_2 is the sub-hologram corresponding to the newly requested viewing angle (θ_2, ϕ_2). The grey region denotes the overlapped region between S_1 and S_2.

4. VIEWING ANGLE DEPENDENT CODING

As mentioned above, multi-perspective images can be reconstructed from a digital hologram. Based on this property, we propose a viewing angle dependent compression and transmission algorithm of digital holograms for server-client interactive applications.

4.1 Basic Coding Scheme

H.264/AVC is the latest video coding standard which uses the intra and inter prediction methods to reduce the spatial and temporal redundancies in a video sequence, and was also applied to directly compress a sequence of digital holograms [14]. However there was no trial to use it to encode the reconstructed object images. Moreover, H.264/AVC can also be used to compress a still image by using the intra-only coding mode, and it was reported that the compression performance of H.264/AVC intra-only coding is better than that of JPEG2000 [13].

The reconstructed image of digital hologram is inherently a complex wave field, and hence composed of the real and imaginary part images. We observe that the correlation between the two images is close to zero. Therefore, H.264/AVC intra-only coding scheme is separately applied to compress the real and imaginary part images, and provides a even higher coding gain than the inter prediction method for the two images. It is also found that the background region of object image generally exhibits smaller pixel values. Hence the DC prediction mode in H.264/AVC intra-only coding scheme is most frequently selected in such region.

4.2 Viewing Angle Dependent Transmission

We consider a server-client environment for interactive transmission of digital holograms over wired/wireless communication networks. The server has a large database of digital holograms. A client first requests an interested digital hologram with the specific viewing angles (θ_1, ϕ_1) and the window size of sub-hologram. Then the server retrieves the sub-hologram S_1 associated with the requested (θ_1, ϕ_1), and reconstructs the object image from S_1. The reconstructed object image is encoded by H.264/AVC intra-only coding scheme and transmitted to the client. The client decodes the

(a) (b) (c)

Figure 7: Reconstructed images of digital holograms. (a) Dice (courtesy of Dr. U. Schnars). (b) Brahms (courtesy of the HoloVision project). (c) Screw (courtesy of Dr. F. Zhang).

Table 1: The parameters for digital holograms

Object	Dice	Brahms	Screw
Distance (m)	1.054	1.290	0.285
Wavelength (nm)	632.8	632.8	830
Resolution	1024×1024	1024×1024	1024×1024
Pixel pitch (μm)	6.8	6.8	6.45

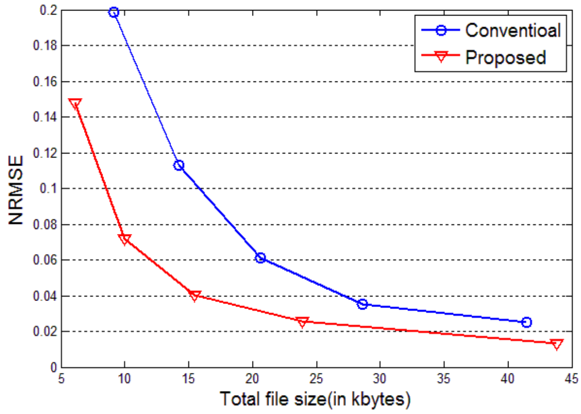
received bitstream and displays the object image corresponding to the requested viewing angles.

When the client changes the viewing direction, new viewing angles (θ_2, ϕ_2) are requested again to the server. Then the server finds the corresponding sub-hologram S_2, and transmits the object image of S_2 to the client. However, as shown in Fig. 6, some part of the new sub-hologram S_2 may be overlapped with the previously transmitted S_1, when the difference between (θ_1, ϕ_1) and (θ_2, ϕ_2) is not too large. In such case, the overlapped region $S_1 \bigcap S_2$ is specified, and the server only transmits the object image reconstructed from the newly added sub-hologram, i.e. $S_1^c \bigcap S_2$. The client can also reuse the information in $S_1 \bigcap S_2$ by back propagating the previously transmitted object image to the hologram plane via inverse Fresnel transform. Thus the exact object image corresponding to (θ_2, ϕ_2) can be reconstructed at the client side by combining the newly transmitted information with the already received one.

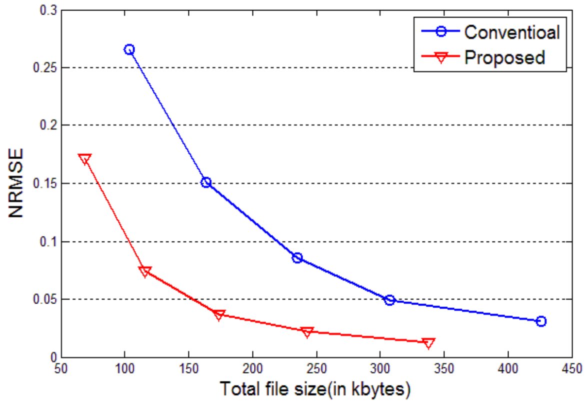
5. EXPERIMENTAL RESULTS

Fig. 7 shows the reconstructed images of the digital holograms used in our experiments. The 'Dice' and the 'Brahms' are classic digital holograms with the complex bandpass filtering [11], and the 'Screw' is a phase-shifting digital hologram [12]. Table 1 describes the parameters used to record the digital holograms. From the parameters in Table 1, the ranges of viewing angle θ or ϕ are calculated as $[-0.189, 0.189]$, $[-0.155, 0.155]$ and $[-0.601, 0.601]$ for the 'Dice', 'Brahms' and 'Screw' holograms, respectively. The distortion of reconstructed image is measured by the normalized root mean square error (NRMSE) [8]

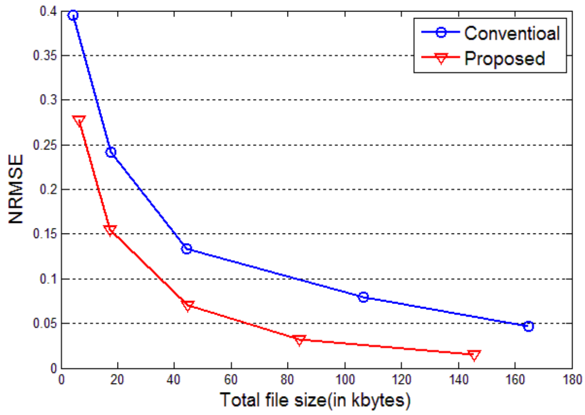
$$\sqrt{\frac{\sum_x \sum_y \left(|H(x,y)|^2 - |\hat{H}(x,y)|^2\right)^2}{\sum_x \sum_y \left(|H(x,y)|^2\right)^2}} \quad (4)$$



(a)



(b)



(c)

Figure 8: Comparison of the rate-distortion compression performances between the proposed algorithm and the conventional method. (a) Dice. (b) Brahms. (c) Screw.

where $H(x,y)$ and $\hat{H}(x,y)$ are the original and the decoded object images, respectively.

In Fig. 8, we first compare the rate-distortion compression performance of the proposed algorithm with that of the conventional method [7], when arbitrary viewing

Table 2: The comparison of NRMSE and compressed file size between the conventional method (Conv.) and proposed algorithm (Prop.), according to the change of client's viewing angles.

	Viewing angle (θ, ϕ)	NRMSE		FileSize (kB)	
		Conv.	Prop.	Conv.	Prop.
Dice	$(-0.064°, 0.061°)$	0.035	0.026	28.6	23.9
	$(0.026°, -0.024°)$	0.044	0.031	28.6	26.3
	$(0.098°, 0.065°)$	0.045	0.025	28.6	30.3
Brahms	$(-0.010°, -0.102°)$	0.049	0.022	307.3	243.1
	$(0.057°, 0.041°)$	0.052	0.023	307.3	250.4
	$(0.020°, -0.007°)$	0.050	0.023	307.3	247.1
Screw	$(0.364°, 0.169°)$	0.079	0.032	106.6	83.9
	$(0.082°, -0.016°)$	0.068	0.030	106.6	78.9
	$(-0.157°, 0.207°)$	0.087	0.039	106.6	72.3

angles of client are given. The selected viewing angles (θ, ϕ) are $(-0.064°, 0.061°)$, $(-0.010°, -0.102°)$ and $(0.364°, 0.169°)$, in Fig. 8 (a), (b) and (c), respectively. The window size of sub-hologram is assumed to be 256×256 in our experiments. But the quality of reconstructed image generally depends on the window size. Five quantization parameters of (32, 27, 22, 17, 12) are employed for H.264/AVC intra-only coding. It is observed that the proposed algorithm achieves the better compression performance than the conventional method, in which the server transmits the reconstructed image from the original digital hologram without taking into account the client's viewing angles, and the client selects the sub-hologram to display the reconstructed image. However, the proposed algorithm effectively uses the bitrate by only encoding the object image reconstructed from the requested sub-hologram.

We also evaluate the viewing angle dependent coding algorithm in Table 2, when the client's viewing angles are changing. The fixed quantization parameter of 17 is used for H.264/AVC intra-only coding. The proposed algorithm yields the much lower NRMSE as well as the less compressed file size than the conventional method. Note that the conventional method always encodes the whole digital hologram, and thus provides the fixed file size regardless of the change of viewing angles. In contrary, the proposed method yields a different size of compressed bitstream according to the client's viewing angles.

6. CONCLUSION

We proposed a viewing angle dependent transmission algorithm of digital holograms for server-client interactive communications. The server basically encodes the reconstructed image of the sub-hologram which is dependent on the viewing angles requested by client. If the client requests the new sub-hologram again associated with different viewing angles, the corresponding object image is newly computed and transmitted. We applied H.264/AVC intra-only coding scheme to encode the reconstructed image which is free from the zero-order diffraction and conjugate image. The experimental results showed that the proposed viewing angle dependant coding algorithm more effectively use the transmission bandwidth compared with the viewing angle independent coding method. As a future work, we will expand the viewing angle dependent coding algorithm to the multiple digital holograms which support the wider range of viewing angles.

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