A recognition method in holographic data storage system by using structural similarity

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Abstract

The holographic data storage system (HDSS) is a page-oriented storage system with advantages of great capacity and high speed. The page-oriented recording breaks the tradition of the optical storage of one-point recording. As the signal image is retrieved from the storage material in the HDSS, various noises influences the image and then the data retrieve will be difficultly from the image by using the thresholding method. For progressing on the thresholding method, a recognition method, based on the structural similarity, is proposed to replace the thresholding method in the HDSS. The recognition method is implemented that the image comparison between the receive image and reference image is performed by the structural similarity method to find the most similar reference image to the received image. In the experiment, by using recognition method, the bit error rate (BER) results in 26% decrease less than using the thresholding method in the HDSS. Owing to some strong effects, such as non-uniform intensity and strong speckle, still influencing on the received image, the recognition method is seemed to be slightly better than thresholding method. In the future, the strong effects would be reduced to improve the quality of the receive image and then the result of using the recognition method may be vastly better than the thresholding method.

Keywords: structural similarity, holographic data storage system, recognition method

1. Introduction

With the huge quantities of information increasing, the data storage requires more capacity to fill with the information. Then, the novel data storage, holographic data storage system (HDSS), is proposed to perform the task well. The striking difference between HDSS and the conventional data storage (compact disc) is that the binary point readout is replaced by the page-oriented image readout from a record point of the disc [1]. The carried information of the HDSS can be approached over 100 times the capacity of the compact disc for backing up huge data [2 3]. Although the capacity of the HDSS is increased substantially, several noises, including aberration [4], misalignment [5 6], scattering noise [7], speckle noise [8] and inter-pixel/page interference (IPI) [9-11], are also brought to affect the HDSS in the image data. Then, the image would be difficult to be returned to original data. Thus, preprocesses and post-processes are developed for obtaining clear image to determine the original data. The preprocesses and the

post-processes include encoding, image processing, and system structure improving and then build a series of the processing to reduce the noises on the HDSS.

As the cost of the HDSS is decreased, the precise optical elements would be removed from the HDSS and the noises would be enhanced to influence severely on the HDSS. Although the encoding and the perfect alignment can reduce the influences partially, the strong IPI, scattering noise, and speckle noise still buffet the HDSS to distort the image [12 13]. Then, the original data would be hard to be retrieved from the distorted image by using the thresholding method. The thresholding method is utilized a threshold to divide the grayscale pixels of the image into two groups, 0's and 1's, regarding as the binary data. As the groups of 0s and 1s of the binary data have a slight separation, low signal-to-noise ratio (SNR) in the HDSS, the part pixels of 0's/1's group would be demarcated into the 1's/0's group by the selected threshold. Thus, the determined binary data have errors to be different to the original data. For avoiding the issue, several studies aim to reduce the noises to be regarded as increasing the separation of the 1's and 0's groups [14 -17]. Owing to the human vision being able to discern the 0s and 1s in the image of slight separation faintly, the issue seems to be the thresholding method rather than the noise reduction. Therefore, the thresholding method should be improved at local comparison with a dynamic threshold.

In this paper, we propose that a recognition method with the local comparison by using the structural similarity (SSIM) method. The recognition method uses a set of the reference image to compare the distorted image locally and the threshold would be replace by the correlation coefficient.

2. Methodology

The image comparison can be completed by way of various correlation methods such as mean square error (MSE), Pearson correlation, Q factor, SSIM and complex wavelet SSIM (CWSSIM) [18-20]. MSE is a usual convention in the estimation and it is very simple to widely use under a clear physical meaning [20]. For the image fidelity, MSE fails in the comparison without the texture and it is unable to show the degree of the noise effect on the human vision system (HVS). Pearson correlation supplies an index, from -1 to 1, for simple estimating the similarity degree between two images but Pearson correlation would misestimate the similarity degree during the image comparison in the abnormal distribution [12]. Q factor is similar to the SSIM and the correlation indexes of both methods are determined from -1 to 1. The difference between Q factor and the SSIM is that the small constants are introduced into the SSIM to obtain a stable result [21]. CWSSIM is an excellent estimation of the image quality on the HVS and CWSSIM is performed in the wavelet domain. Owing to CWSSIM working on the frequency domain, the spatial influences, rotation, shift and zoom, are unable to impact significantly on the index. Considering the processing speed, the SSIM strikes a balance between the processing speed and image fidelity.

The development of the recognition method is based on the image quality estimation, SSIM, and the image quality estimation is to be corresponding to the image comparison. The recognition method uses a set of the reference image to compare the distorted image locally and the determined correlation coefficients can represent the similarity degree between the reference and distorted images. As the maximal correlation coefficient is determined from the result of

the image comparison between one of the reference images and the distorted image, the data of the reference image can be replaced the data of the distorted image. Therefore, the recognition method can avoid the issue of the threshold selection in the thresholding method.

The prime aim of the SSIM is to estimate the image quality on the display and the idea is proposed by Wang and *et al.* [18]. The SSIM formula takes into account three factors, luminance, contrast, and structure, and the three factors are also the primary elements of the grayscale image. Each factor can be defined as a formula and integrated into the SSIM formula as

$$\text{SSIM}(r,t) = \frac{\left(2\mu_r\mu_t + C_1\right)}{\left(\mu_r^2 + \mu_t^2 + C_1\right)} \times \frac{\left(2\sigma_{rt} + C_2\right)}{\left(\sigma_r^2 + \sigma_t^2 + C_2\right)} \tag{1}$$

where the subscripts r and t represent the reference and distorted images; μ_r and μ_t denote the mean values of r and t; σ_r^2 and σ_t^2 refer to the variance; σ_{rt} is the covariance between the two compared images; and C_1 and C_2 represent both two small constants used to adjust the weighting of the three factors.

Owing to the perception of human vision involved to the SSIM, the noise influences, such as speckle noise, Gaussian noise and pepper noise, can be reduced substantially in the image comparison.

The implementation of the recognition method requires a database which owns a set of reference images as Fig. 1. The gray level of the reference images created is referred to the system performance and the size of the reference image is determined by the unit of the matrix in the distorted image. The unit of the compared image is limited to a minimal size of 2 by 2 bits and the number of the reference images is determined as $2^{\text{total bits}}$. When the database of the reference images has been built, the part distorted image is produced by the gray level around the fiducial points in the distorted image and the part distorted image would be compared with all reference images to find out the reference image which has the maximal correlation coefficient. The area, surrounding the fiducial point (Fig. 2), is according to how much the pixels owned as a bit and the size of the area can be reduced slightly to cancel the influence of the specific aberration.
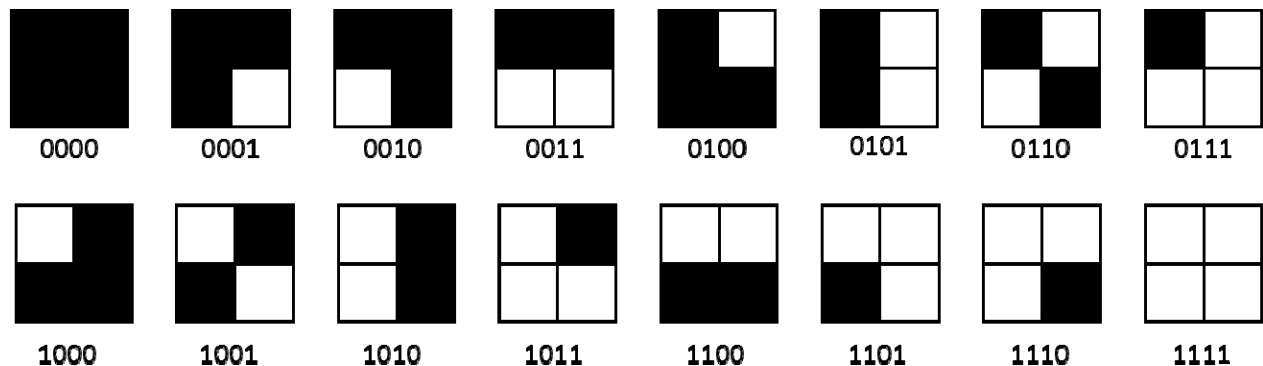

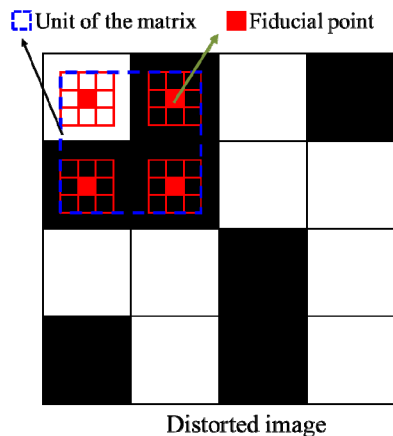Fig. 1. The instance of the reference images with the size of 2 by 2 bits.

Fig. 2. The diagram of the compared image creation from the surrounding the fiducial point in the distorted image.

3. Experiment and results

The testbed is a coaxial HDSS with a reflective storage material as depicted in Fig. 3. The form of the reference beam is designed as a ring pattern and the pattern is embedded in the signal image for the recording in the storage material. The signal image is built by 25 by 25 bits and each bit is constructed of 4 by 4 pixels in the spatial light modulator as shown in Fig. 4. As the signal image read out from the storage material, the non-uniform intensity, strong speckle effect, and noisy fringe are present at the received image as Fig. 5(a). The received image would be hard to retrieve the data by using the thresholding method and the histogram of the intensity distribution is illustrated as Fig. 6(a). The intensity distribution has an apparent convergence in the low gray level and the valley between the distributions of 0 and 1 is concealed in the convergence. An attempt by enhancing the contrast and brightness of the image to alter the distribution towards separation is difficulty and the enhanced image and the histogram are shown in Fig. 5(b) and Fig. 6(b), respectively. The valley is still concealed in the convergence but the enhanced image is seemed to be better than the previous image. However, both images are made attempts to be retrieved original data.
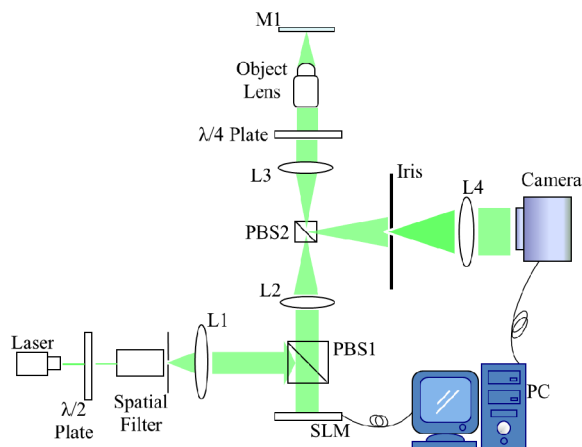

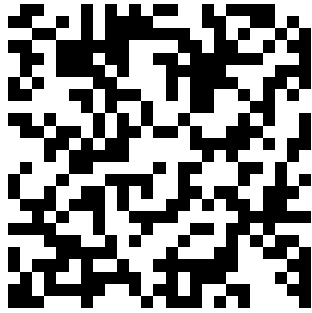
Fig. 3. The sketch of the HDSS testbed.

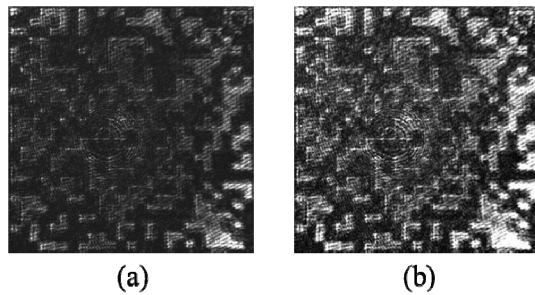Fig. 4. The signal image constructed of 25 by 25 bits.

Fig. 5. The reconstructed image (a) without image preprocessing (b) with image preprocessing (contrast and brightness enhanced).
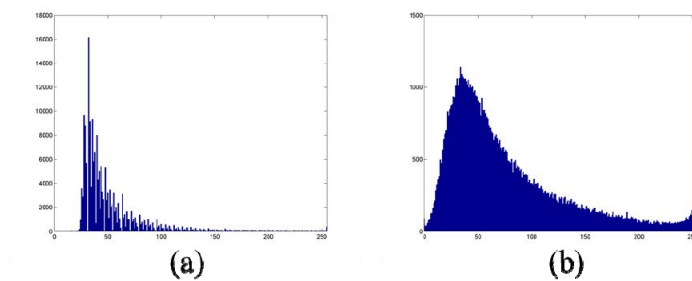

Fig. 6. The histogram of the reconstructed image (a) without image preprocessing (b) with image preprocessing (contrast and brightness enhanced).

Owing to the alignment method declined to be applied, the size of the received image is rescaled from 436 by 436 pixels to 400 by 400 pixels and each bit contains a size of 16 by 16 pixels in the rescaled image. By using the thresholding method to retrieve the data, the average of the gray levels of the pixels, in the extent of a bit, is determined as either 0 or 1 by the threshold. Owing to the valley concealed in the distribution, the threshold is found by trial and error as the minimal number of the errors is obtained. In the recognition method, the size of the reference images is constructed of 2 by 2 bits, a bit containing 16 by 16 pixels, to be compared with the part received image. The results of the data accuracy determined by the two methods are shown in table 1 and Fig. 7.

Table 1 presents the results, bit error rate (BER) and the number of the error and total bits, for the data accuracy. As the received image is enhanced by the contrast and brightness, the number of the error bits is reduced from 38/28 to 35/26 to induce 7.9% / 7.1% decreasing in the BER by using thresholding / recognition method. In the comparison of the methods, the recognition method significantly reduces the number of the error bits, approximately 10 bits, to result 26% decrease in the BER. Therefore, the recognition method indeed can reduce the BER better than the thresholding method in the HDSS.

Table 1. The results of the BER, error bits, and method comparison.

Results Methods	Error bits/total bits/BER	
	Without image preprocessing	With image preprocessing
Thresholding method	$38/625/6.08 \times 10^{-2}$	$35/625/5.6 \times 10^{-2}$
Recognition method	$28/625/4.48 \times 10^{-2}$	$26/625/4.16 \times 10^{-2}$

The results of the error maps are figured as Fig. 7. When the received image is enhanced to increase the threshold from 42 to 66 for determining the minimal number of the error bits, the number of the error bits can be slightly decreased but some errors might be induced to the location of none error in the image center (Fig. 7 (a) and (b)). The error map determined by the recognition method also has the status of the causing other error bits, too. The reason might be the contrast enhanced in the image preprocessing because the contrast enhanced requires a turning point to increase/decrease the gray level of white/black. Most error bits occurring at the same location are cause of the non-uniform intensity in Fig. 5.
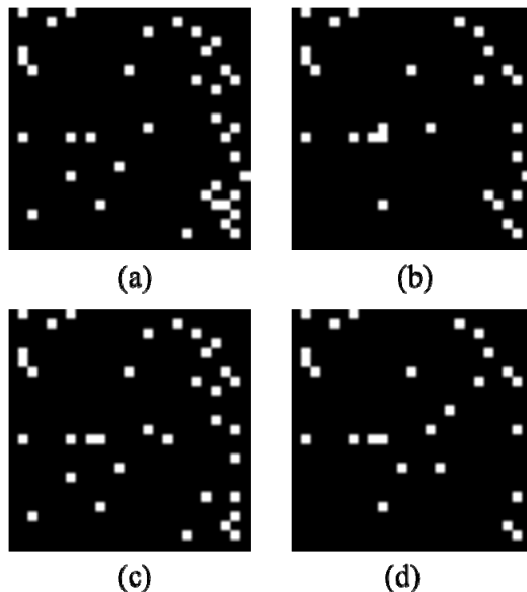

(a)

(b)

(c)

(d)

Fig. 7. The error maps determined by the subtraction of the signal image from the retrieved image. (a) without the image preprocessing and retrieved by the thresholding method, (b) with the image preprocessing and retrieved by the thresholding

method, (c) without the image preprocessing and retrieved by the recognition method, (d) with the image preprocessing and retrieved by the recognition method.

4. Conclusions

In this study, a novel method is proposed to improve the thresholding method in the HDSS. A recognition method based on the structural similarity method is an appropriate way to retrieve the original data from the distorted image in the page-oriented HDSS. The benefit of the structural similarity method offers the human vision, high sensitivity to the image structure, and therefore the recognition method can give a better result than thresholding method in the BER. The high sensitivity of the image structure can increase the successful outcome in the image comparison. In the experiment, the optimal BER is determined by trial and error in the gray level of the reference image as the minimum errors occur. The result shows that the BER of using the recognition method is able to have 26% decrease less than using the thresholding method. The idea of using the estimation of the image quality in the recognition method gives us a great impression on the BER result. In the future, the gray level of the reference image would be defined according to SNR and the dynamic threshold may be introduced into the recognition method.

Acknowledgments

References

[1]   N. B. Karahanoglu and M. Keskinoz, "Multistage adaptive filtering for identification of page-oriented volume holographic memories," Optical Engineering 49(2),

[2]   G. W. Burr, C. M. Jefferson, H. Coufal, M. Jurich, J. A. Hoffnagle, R. M. Macfarlane and R. M. Shelby, "Volume holographic data storage at areal density of 250 gigapixels/in.(2)," Optics Letters 26(7), 444-446 (2001).

[3]   J. H. Hong, I. McMichael, T. Y. Chang, W. Christian and E. G. Paek, "Volume Holographic Memory-Systems - Techniques and Architectures," Optical Engineering 34(8), 2193-2203 (1995).

[4]   O.-Y. Mang and C. Yu-Ta, "A Gray Level Weighting Method to Reduce Optical Aberration Effect in Holographic Data Storage System," IEEE Transactions on Magnetics 47(3), 546-550 (2011).

[5]   G. W. Burr and T. Weiss, "Compensation for pixel misregistration in volume holographic data storage," Optics Letters 26(8), 542-544 (2001).

[6]   G. W. Burr, "Holographic data storage with arbitrarily misaligned data pages," Optics Letters 27(7), 542-544 (2002).

[7]   M. Ayres, A. Hoskins and K. Curtis, "Image oversampling for page-oriented optical data storage," Applied Optics 45(11), 2459-2464 (2006).

[8]   S. S. Orlov, W. Phillips, E. Bjornson, Y. Takashima, P. Sundaram, L. Hesselink, R. Okas, D. Kwan and R. Snyder, "High-transfer-rate high-capacity holographic disk data-storage system," Applied Optics 43(25), 4902-4914 (2004).

[9]   J. F. Heanue, K. Gurkan and L. Hesselink, "Signal detection for page-access optical memories with intersymbol interference," Applied Optics 35(14), 2431-2438 (1996).

[10] M. A. Neifeld and M. McDonald, "Technique for controlling cross-talk noise in volume holography," Optics Letters 21(16), 1298-1300 (1996).

[11] W. C. Chou and M. A. Neifeld, "Interleaving and error correction in volume holographic memory systems," Applied Optics 37(29), 6951-6968 (1998).

[12] Y.-T. Chen, M. Ou-Yang and C.-C. Lee, "Improvement of bit error rate and page alignment in the holographic data storage system by using the structural similarity method," Applied Optics 51(16), 3660-3669 (2012).

[13] M. Keskinoz and B. Kumar, "Application of linear minimum mean-squared-error equalization for volume holographic data storage," Applied Optics 38(20), 4387-4393 (1999).

[14] J. W. Yang, L. M. Bernardo and Y. S. Bae, "Improving holographic data storage by use of an optimized phase mask," Applied Optics 38(26), 5641-5645 (1999).

[15] G. W. Burr, H. Coufal, R. K. Grygier, J. A. Hoffnagle and C. M. Jefferson, "Noise reduction of page-oriented data storage by inverse filtering during recording," Optics Letters 23(4), 289-291 (1998).

[16] S. Yasuda, Y. Ogasawara, J. Minabe, K. Kawano, M. Furuki, K. Hayashi, K. Haga and H. Yoshizawa, "Optical noise reduction by reconstructing positive and negative images from Fourier holograms in coaxial holographic storage systems," Optics Letters 31(11), 1639-1641 (2006).

[17] S. Yasuda, J. Minabe and K. Kawano, "Optical noise reduction for dc-removed coaxial holographic data storage," Optics Letters 32(2), 160-162 (2007).

[18] Z. Wang and A. C. Bovik, "A universal image quality index," IEEE Signal Processing Letters 9(3), 81-84 (2002).

[19] M. P. Sampat, Z. Wang, S. Gupta, A. C. Bovik and M. K. Markey, "Complex Wavelet Structural Similarity: A New Image Similarity Index," IEEE Transactions on Image Processing 18(11), 2385-2401 (2009).

[20] W. Zhou and A. C. Bovik, "Mean squared error: Love it or leave it? A new look at Signal Fidelity Measures," Signal Processing Magazine, IEEE 26(1), 98-117 (2009).

[21] Z. Wang, A. C. Bovik, H. R. Sheikh and E. P. Simoncelli, "Image quality assessment: From error visibility to structural similarity," IEEE Transactions on Image Processing 13(4), 600-612 (2004).