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A hybrid method to improve the accuracy of multichannel volume holographic correlators

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Due to large database storage capacity and high speed multi-channel parallel correlation, volume holographic optical correlator (HOC) is a promising candidate for on-board real-time pattern recognition. The optical calculation accuracy is the bottleneck of this technology for practical applications. A hybrid method combined of standardizing and inter leaving images is proposed to improve the output accuracy of volume holographic correlators. The method equalizes the filling ratios of ON to ALL pixels in the processed images and redistributes the pixels inside images without changing the inner products. It can eliminate the impact of the correlation pattern difference on the accuracy of inner product calculation. Experimental tests shows that this method could acquire better calculation value.

1 Introduction

Because of fast multi-channel parallel process, high storage density, and content addressability, volume holographic optical correlators (HOC) are becoming increasingly important and generating more and more applications. It has been reported that 7,500 images can be multiplexed in one location of a crystal. Each stored image is corresponding to a channel. These images can serve as a library or matching filter for data searching [1-3], associative retrieval [4], fingerprint identification [5], scene matching [6-7], and so on.

Due to Bragg selectivity and medium defocusing, the output correlation pattern of the HOC is a set of suppressed correlation functions, whose central point represents the two-dimensional (2D) inner product [8-9]. Therefore, HOC is often used to calculate the 2D inner products between the input and stored images. It is crucial that the detected signal should only be determined by the inner product, but in practice it is not the case. That is, for an image with two blocks vertically separated, its theoretical autocorrelation does not change with the separation distance, but the measured autocorrelation changes with it. This shows that the detected signal also depends on the image patterns. The reason is as follows: As measuring the brightness of a "mathematical" center point is impossible, the correlation function over a small area covering the center point has to be integrated to approximate the inner product. However, the output correlation shapes strongly depend on the input and stored image patterns, thus the distribution in the integration area is also variable. As a result, the integration result depends not only on the inner product but also on the actual distribution of the correlation pattern. This implies that the results may be different even if the inner products are equal. This pattern-dependent behavior is serious when the images have differences in zero and low spatial frequencies, because the integration results are notably impacted by the profiles (the general shape) of the correlation functions, which mainly depends on the zero and low frequency components of the input and stored images.

If the integration area is small enough, the impact of the correlation pattern difference can be ignored. A diffuser placed in the path of object beam can suppress the sidelobe of the correlation pattern [10]. In theory, diffusers with large scattering angles will make the integration area small enough to reduce the impact of the correlation pattern difference to an undetectable level. However, in practical systems,

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diffusers with large scattering angles are not applicable for throughput considerations. As a result, the impact of the correlation pattern difference still exists after using the diffuser. In this work, we proposed a hybrid method combined of standardizing and interleaving images to reduce this effect further, improving the output accuracy of volume holographic correlators.

2 Hybrid method for improving output accuracy

Optical correlator based on single planar hologram is a kind of Van der Lugt correlator. The correlation result is the correlation of the input pattern and the stored patterns. For the volume holographic correlator, the correlation output function is written as,

$$g(x_c, y_c) \propto \sum_{p=1}^{P} \int \mathrm{d}\,x_0\, \mathrm{d}\,y_0 f_0(x_0, y_0) f_p^*(x_0+\xi, y_0+\eta) \times t\,\mathrm{sinc}\left\{\frac{t}{2\pi}\left[k_{pz} - k_{dz} + \frac{\pi}{\lambda}\frac{\xi(2x_0+\xi)+\eta(2y_0+\eta)}{f^2}\right]\right\}, \tag{1}$$

where t is the thickness of the volume hologram and sinc function represents the Bragg selectivity of the hologram. Due to the Bragg selectivity, the holograms can be multiplexed and the correlation output is shaped to a narrow vertical slice of the 2-D correlation function. There are some sidelobes around the peak which cause the crosstalk among different channels due to the sinc function. To avoid the crosstalk, the channels should be sparse enough, thus the number of the database is greatly limited. When using a diffuser to modify the function, the sidelobes are completely suppressed. The crosstalk is negligible and the correlation peak becomes a bright sharp spot. By using the speckle modulation, the recognition output is,

$$g(-x_m, -y_m) \propto \sum_{p=1}^{P} \iint dx_0 dy_0 f_0(x_0, y_0) f_p^*(x_0, y_0) \tag{2}$$

Thus, the output value at the correlation plane is now the inner product of the input and stored patterns.

The 2D random interleaving method redistributes the pixels inside the images by using the same pixel-shifting algorithm so that it eliminates the correlation pattern difference caused by the low frequency components and makes the correlation patterns similar to each other while keeping the inner product unaltered. Thereby the impact of the correlation pattern difference is reduced and the calculation accuracy is improved. But the interleaving method does not change the filling ratio (ratio of ON to ALL pixels) of image, which is the zero frequency component of image. Thus it can not eliminate the correlation pattern difference caused by the zero frequency components. If the filling ratios of images are different, the correlation pattern difference is still residual after applying the interleaving method. It can be illustrated by a brief example shown in Fig 1. The two input images have the same theoretical inner product with the stored image. But the filling ratios of the two input images are different. After applying the interleaved method, the two correlation patterns are still different. Although HOC can suppress the correlation to a “slice”, it can not totally get rid of the difference. Figure 1 shows the theoretical suppressed correlation in the vertical axis. The profile of input 2 is larger than that of input 1. Therefore, when the central area is integrated to approximate the inner product, the corresponding result of input 2 is larger than that of input 1, which makes the result inaccurate.

We propose a hybrid method to eliminate the impact of correlation pattern difference caused by both the zero frequency components and the low frequency components of images. This can be done by two steps: first, a standardizing method which adopts balance partition to eliminate the correlation pattern difference caused by the zero frequency components. It equalizes the filling ratios of images while keeping the inner products unaltered. Secondly, the 2D random interleaving method is used to eliminate the correlation pattern difference caused by the low frequency components. It redistributes the pixels inside the images while keeping the inner products unaltered. Therefore, the inner product calculation accuracy of HOC is improved.

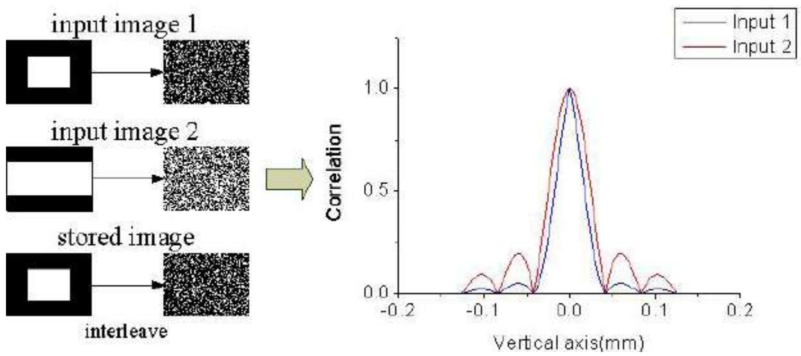


Fig 1. The theoretical correlation in the vertical axis when the images are only interleaved.

First, the original images are processed by a standardizing method to eliminate the correlation pattern difference caused by the zero frequency components of images. The kernel of the standardizing method is to equalize the filling ratios of the images while keeping the inner products unchanged. Both the input images and the stored images should be standardized.

To standardize the input images, a balance partition is divided in the input images and used to equalize the filling ratios of input images. However, the balance partition should not disturb the inner product calculation. In other words, in the calculation, it should be multiplied with zero. Thus a corresponding zero partition is divided in the stored images. To standardize the stored images, another pair of balance partition and zero partition is divided in stored images and input images, respectively. The division scheme is shown in Fig 2(a).

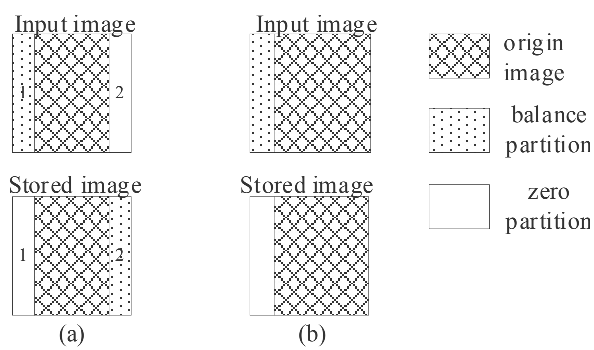


Fig 2. The division scheme of the patterns. (a) General; (b) special.

The area proportion of the balance partition 1 to the whole input image, and the area proportion of the balance partition 2 to the whole stored image can be calculated respectively as follows:

$$P_1 = \frac{f_{i\max} - f_{i\min}}{f_{i\max} - f_{i\min} + f_{s\max} - f_{s\min} + 1}, \quad P_2 = \frac{f_{s\max} - f_{s\min}}{f_{i\max} - f_{i\min} + f_{s\max} - f_{s\min} + 1} \tag{3}$$

where $f_{i\max}$ is the maximal filling ratio of the original input images, and $f_{i\min}$ is the minimal one. $f_{s\max}$ is the maximal filling ratio of the original stored images, and $f_{s\min}$ is the minimal one. For each input image or stored image, the filling ratios of the balance partition 1 and 2 are

$$f_{ib} = \frac{f_{i\max} - f_{io}}{f_{i\max} - f_{i\min}}, \quad f_{sb} = \frac{f_{s\max} - f_{so}}{f_{s\max} - f_{s\min}} \tag{4}$$

where f_{io} is the filling ratio of the original input image, f_{so} is the filling ratio of the original stored image. Specially, if the filling ratios of the stored images are already the same ($f_{s\max} = f_{s\min}$), then $P_2 = 0$, only the input images should be standardized. Thereby the division scheme is reduced to Fig 2(b). And Eq (3), Eq (4) are reduced to Eq (5), Eq (6), respectively as follows:

$$P = \frac{f_{i\max} - f_{i\min}}{f_{i\max} - f_{i\min} + 1} \tag{5}$$

$$f_{ib} = \frac{f_{i\max} - f_{io}}{f_{i\max} - f_{i\min}} \tag{6}$$

For simplicity, the special situation is discussed in the following paragraphs. Extension to the general situation is straightforward. As an example, the standardizing method is used to encode the input images and the stored image in Fig 1. The filling ratios of the input images are from 25% to 50%, thus *P* is 1/5, which is calculated by Eq (3). The standardized input images and stored image are shown in Fig 3. The left 1/5 of the images are the balance partition / zero partition.

Secondly, the standardized images with balance partition are processed by the 2D random interleaved method to eliminate the correlation pattern difference caused by the low frequency components. The interleaved method redistributes the pixels inside the standardized images contained both original images and standardizing partitions by using the same pixel-shifting algorithm. After applying the hybrid method, the theoretical output correlations in the vertical axis are shown in Fig 3. It clearly shows that the two profiles become the same. When the central area is integrated to approximate the inner product, the impact of the correlation distributions on the inner product is the same for different input images. It means that the inaccuracy caused by the pattern-dependent behavior can be eliminated and the calculation accuracy of HOC is improved by the use of the hybrid method.

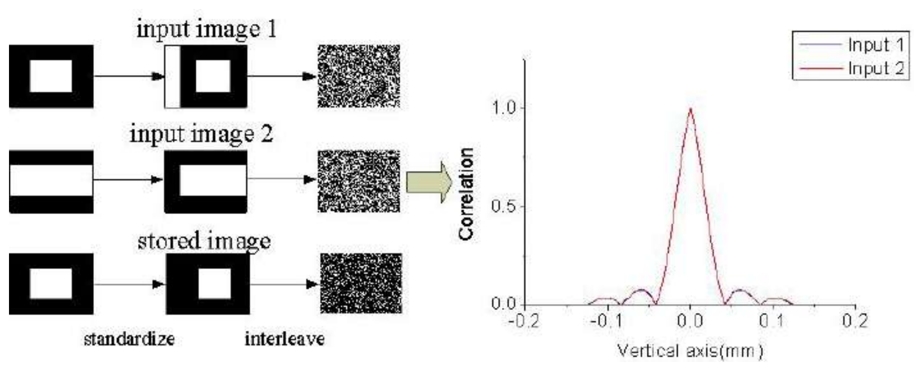


Fig 3. The theoretical correlation in the vertical axis when the images are standardized and interleaved.

3 Experiments

The experimental setup is shown in Fig 4. A diode-pumped solid-state laser (DPSSL, λ = 532nm) is the light source. A holographic diffuser of 0.2° scattering angle used as a speckle modulation device is inserted behind the SLM (CRL Opto VGA3). The holographic recording material is an $Fe:LiNbO_3$ crystal. A CCD camera (MINTRON MTV-1881EX) is used to detect the output.

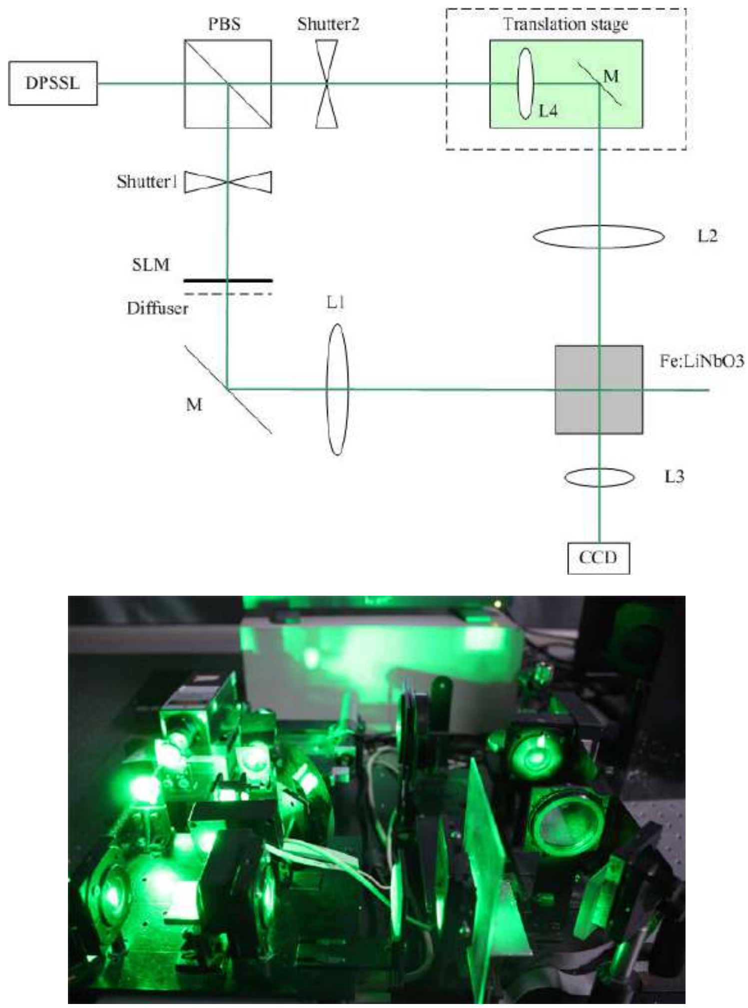
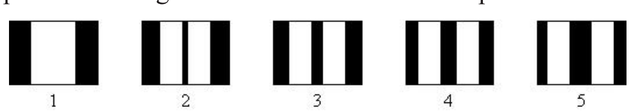
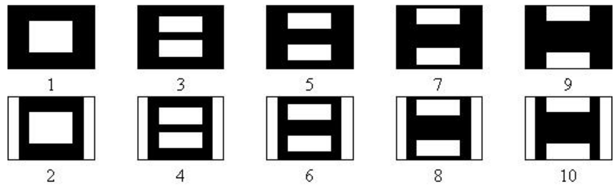


Fig 4. The experimental setup for testing the method.

In the first experiment, the three versions of images: raw, interleaved only, standardized-and-interleaved, are used to test the effect of the method. The raw images are shown in Fig 5. The filling ratio of inputs with odd serial number is 25%, and the filling ratio of inputs with even serial number is 50%. For each stored image, its inner products with all the input images are same. The five stored images were first stored in the crystal, forming a five-channel HOC. Then, the ten input images were input to the HOC one by one. For every input, the output consists of five correlation spots. Ten inputs generate 5×10 spots. Figure 6 gives the experimental results of the three versions, and each row of a version is 60×10 pixels. The five spots in one row are generated by one input image, taken with one CCD shot, corresponding to the response of five channels to a single input. The ten spots in one column are generated by ten input images, corresponding to the response of a single channel to ten different inputs.

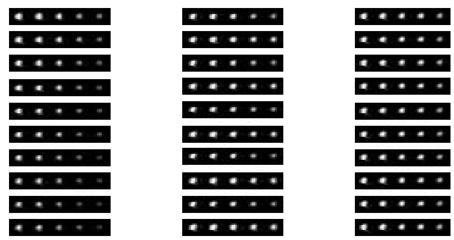


(a)



(b)

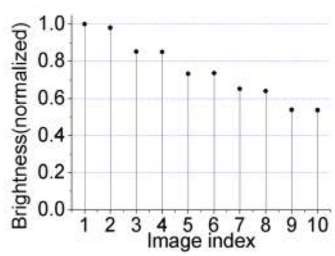
Fig 5. The raw images used to test the method. (a) stored images. (b) input images



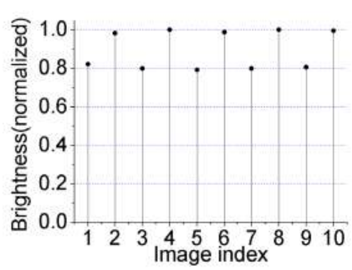
(a) (b) (c)

Fig 6. Output correlation spots. (a) raw; (b) interleaving only; (c) hybrid standardizing and interleaving method.

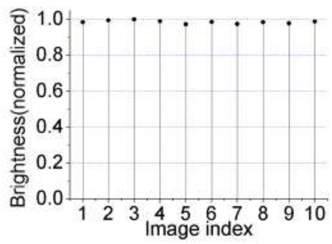
A window of 4×3 pixels is used to accumulate signals. Figure 7 shows the spots' intensities of the third column of each version in Fig 6. The theoretical inner products of the ten input images with the third stored image are same, thus the theoretical spots' intensities should be same. For the raw version, the intensity decreases inversely with the vertical distance between the two white blocks. It clearly shows the impact of the pattern-dependent behavior, which makes the results incorrect. For the interleaved only, the results are much better, but are still different. The intensity of inputs with odd serial number is less than that of inputs with even serial number. It shows that the impact of pattern-dependent behavior caused by the different filling ratios still exists. For the standardized and interleaved version, the experimental results are consistent very well. It shows that the impact of pattern-dependent behavior is eliminated by the hybrid method. The experimental results of the three versions accord with the theoretical prediction.



(a)



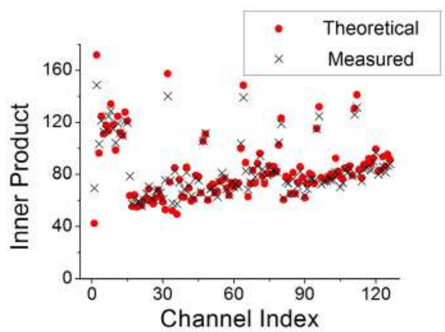
(b)



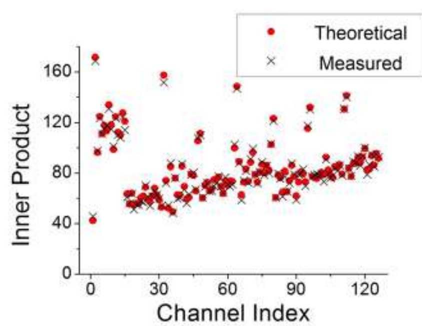
(c)

Fig 7. The intenstiy of the correlation peaks of the third column in Fig 6. (a) raw; (b) interleaving only; (c) hybrid standardizing and interleaving method

In the second experiment, a group of templates are used to further compare the effect of the interleaving method and the hybrid method. The raw template consists of 32×32 blocks, and each block represents a value within a range from 0 to 1. The 128 templates were first stored in the crystal, forming a 128-channel HOC. Then the interrogating templates were input to HOC. Figure 8 gives the plots of calculation results of one input for the interleaved only version and the standardized-and-interleaved version. In Fig 8 (a) the standard error is 6.13 and the error divided by the average inner product is 0.0864, while in Fig 8 (b) the standard error is 3.01 and the error divided by the average inner product is 0.0424. Multiple interrogating templates are input to HOC to get the statistical results. The average standard error of the interleaved only version is 6.53, while the average standard error of the standardized-and-interleaved version is 3.04. It clearly shows that the latter has better accuracy.



(a)



(b)

Fig 8. Calculated inner products between one input template and 128 stored templates (a) Interleaving method only (b) Hybrid standardizing and interleaving method

4 Conclusion

The pattern-dependent behavior in the inner product calculation performed by HOC is mainly caused by the different zero and low frequency components of images, which makes the results inaccurate. The interleaving method can only eliminate the impact of different low frequency components. Thus after applying it, the impact of the pattern-dependent behavior still exists. The proposed hybrid method, which combines the standardizing method and the interleaving method, is proposed to eliminate the impact of both zero frequency components and low frequency components. Experimental results show that the inner product calculation accuracy of HOC is remarkably improved by the use of the hybrid method. Both the accuracy and parallelism are greatly improved thanks to the proposed method. The tremendous advantages of the high computing speed of HOC over that of the electronic microprocessors will lead to some key applications. Although the optical computing based on HOC is limited to the inner product computing, the HOC system would help electronic computers to solve some impossible missions as a special-purpose functional unit in the near future.

Acknowledgements

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