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High-Quality Object Reconstruction Based on Ghost Imaging

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Abstract— Ghost imaging (GI) becomes an attractive research topic in recent years, and has been developed for some years. Correlation algorithm is usually used to reconstruct object in the GI. However, due to a linear relationship between quality of the recovered objects and the number of measurements, it needs a large number of measurements to obtain a satisfied object reconstruction when conventional GI is applied. Although some improved algorithms, e.g., differential GI and normalized GI, are developed, they could still not be feasible for achieving high-quality object reconstruction in some cases. In this paper, a high-quality object reconstruction method is presented for the GI. The method takes advantage of the property of Hadamard transform. For a 2D matrix, after the Hadamard transform is applied to it, the first element of the Hadamard spectrum is equivalent to the sum of all matrix elements. In the measurement process of GI, single-pixel detector collects the total light intensity, i.e., the sum of transmitted light. Hence, the property of Hadamard transform corresponds to the single-pixel measurement process in the GI. As a result, it is possible to utilize the detected single-pixel values as constraints. An algorithm is presented in this paper to reduce the number of measurements dramatically in the GI and simultaneously achieve a high-quality object reconstruction. In the method, the signal-to-noise ratio (SNR) has a nonlinear growth with respect to the number of measurements, and it is different from conventional GI methods. Feasibility and effectiveness of the method are computationally demonstrated.

1. INTRODUCTION

Ghost imaging (GI) is first considered as quantum phenomenon, and it is subsequently demonstrated that the GI can be realized with classical thermal light [1–7]. Conventional GI setup contains two paths, i.e., reference beam path and object beam path. With a rapid development of optoelectronic devices, the reference beam path is removed when spatial light modulator (SLM) is used. In this case, computational GI (CGI) is developed which consists of only object beam path, and is easy to be conducted in practice [8,9]. In the CGI, a number of illumination patterns are generated by using SLM and are sequentially projected onto an object. A single-pixel detector without spatial resolution is used to collect the total light intensity. Using the illumination patterns and the collected single-pixel data, correlation algorithm is usually applied to recover the test object. However, there is a drawback in conventional GI methods, i.e., low quality (contrast) of reconstructed objects. In order to enhance the quality, it is necessary to conduct a large amount of measurements which are much larger than the Nyquist limit in conventional GI methods. Although some algorithms have been proposed to improve the performance of conventional correlation algorithms, such as differential GI (DGI) [10] and normalized GI (NGI) [11], they could still not be feasible in some cases.

In this paper, a high-quality object reconstruction method is presented for the GI. The method takes advantage of the property of Hadamard transform. In the measurement process of GI, patterns generated by using the SLM sequentially illuminate an object, and the total light intensity of transmitted light is sequentially collected by using a single-pixel detector which has no spatial resolution. From a mathematical view of point, if Hadamard transform is applied to the element-wise product between the illumination pattern and the object, the first value of Hadamard spectrum is equivalent to the corresponding value detected by the single-pixel detector [12,13]. This property can be utilized to improve quality of the recovered objects. When only a small number of measurements (i.e., lower than the Nyqusit limit) are obtained in the GI, the recorded single-pixel values can act as constraints to be utilized repeatedly. As a result, high-quality object reconstruction can be achieved. In the method, the number of measurements can be reduced dramatically to retrieve high-quality object compared with conventional methods. In addition, different from the linear growth of signal-to-noise ratio (SNR) with respect to the number of measurements in conventional GI methods, the method presented here can realize a nonlinear growth of SNR values corresponding to the number of measurements.

2. THEORETICAL ANALYSES

A schematic setup for the CGI [12,13] is shown in Fig. 1. A laser beam is expanded and collimated. The collimated laser beam is sequentially modulated by a series of illumination patterns embedded in the SLM. Then, the modulated beam is projected onto a target object by using a 4*f* system. A single-pixel detector without spatial resolution is used to collect the total light intensity of transmitted light. The measurement process can be described by [12–14]

$$B_i = \sum_x \sum_y P_i\left(x, y\right) O\left(x, y\right), \quad \left(i = 1, 2, 3, \ldots, M\right), \tag{1}$$

where B_i denotes the intensity value detected by single-pixel detector, $P_i(x,y)$ denotes the pattern sequentially embedded in the SLM, $O(x,y)$ represents a target object, and M represents the number of measurements.

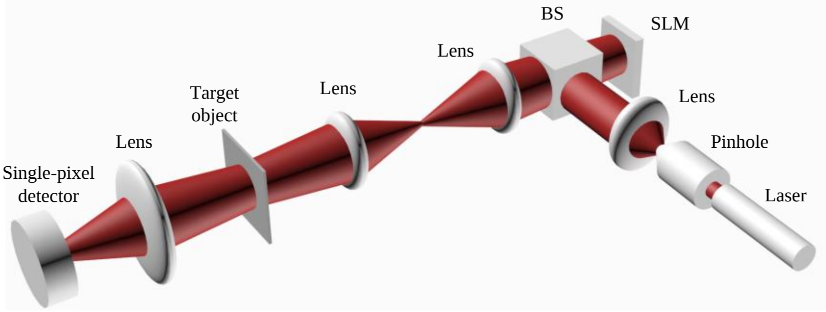


Figure 1: Schematic setup for the CGI, SLM: spatial light modulator, BS: beam splitter.

The correlation algorithm used to recover object can be expressed as [12–14]

$$R_{GI}\left(x, y\right) = \frac{1}{M} \sum_{i=1}^{M} \left(B_i - \left\langle B_i \right\rangle\right)\left(P_i - \left\langle P_i \right\rangle\right), \tag{2}$$

where $R_{GI}(x,y)$ denotes a recovered object, and $\langle \bullet \rangle = \sum_i \bullet / M$ denotes an ensemble average over M measurements.

The property of Hadarmard transform corresponding to the single-pixel measurement process, i.e., Eq. (1), is described in Fig. 2. In Fig. 2, a picture with white and black is used to represent a typical Hadamard pattern, and a picture with “ghost” is used to represent an object. In Fig. 2, $\odot$ represents element-wise product, and *H* represents Hadamard transform. When Hadamard transform is applied to the element-wise product between the two pictures, the first value of the generated Hadamard spectrum, i.e., $H\{P \odot O\}_{u=0,v=0}$, is equivalent to the correspondingly detected single-pixel intensity value.

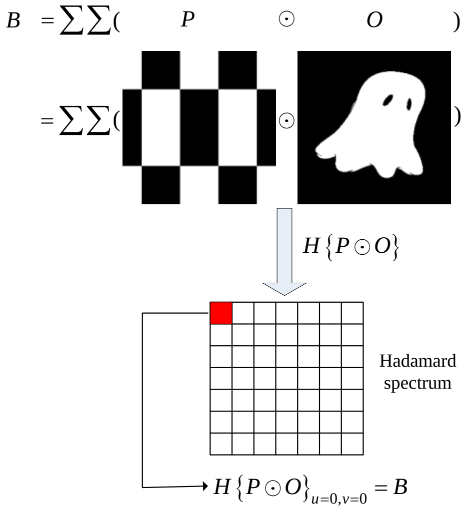


Figure 2: A schematic to illustrate the property of Hadamard transform.

Taking advantages of the above property [12,13], an algorithm for achieving high-quality object reconstruction is presented as follows:

(1) Equation (2) is used to obtain an initial guess R;

(2) Multiply the initial guess with an illumination pattern to be I_{tar};

(3) Apply Hadamard transform to I_{tar} and get its Hadamard spectrum $H(I_{tar})$;

(4) Use the detected value to replace the first component of $H(I_{tar})$ and get a new spectrum $H'(I_{tar})$;

(5) Do inverse Hadamard transform for $H'(I_{tar})$ to get an update I'_{tar};

(6) Further update the initial guess by

$$R'=R+\frac{P}{\max(P^2+\alpha)}\odot\left(I'_{tar}-I_{tar}\right), \tag{3}$$

where α denotes a parameter used to avoid zero value in the denominator.

(7) Repeat the above steps for all measurements until a criterion is satisfied, and the criterion is defined as mean squared error calculated between R at the nth iteration and R' at the $(n+1)$th iteration.

A flow chart for the algorithm is further shown in Fig. 3.

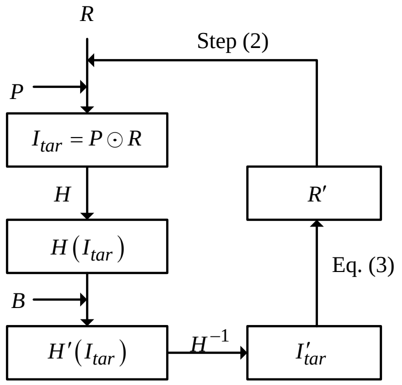


Figure 3: Flow chart for the reconstruction algorithm.

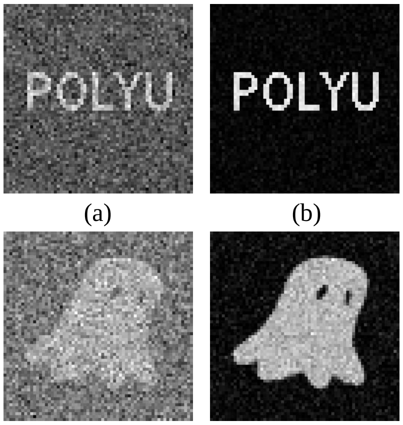
Here, the SNR is defined as [12–15]

$$\mathrm{SNR} = \frac{\sum\left(O-\bar{O}\right)^2}{\sum\left(R-O\right)^2}, \tag{4}$$

where $\bar{O}$ denotes the mean of O, and R denotes the recovered image.

3. RESULTS AND DISCUSSION

Figures 4(a)–4(d) show typical results respectively obtained by using conventional GI method and the proposed method. As shown in Figs. 4(a) and 4(c), quality of recovered objects based on conventional GI method is low, and there is much noise in the recovered objects. The SNR values for Figs. 4(a) and 4(c) are 1.79 and 1.31, respectively. The method presented here can extract high-quality objects, which can be seen in Figs. 4(b) and 4(d). The SNR values for Figs. 4(b) and 4(d) are 22.51 and 19.85, respectively.



(a) (b)

(c) (d)

Figure 4: Object reconstruction using 4000 measurements for the objects with 64×64 pixels. (a) and (c) two objects reconstructed by using conventional GI method, and (b) and (d) two recovered objects obtained by using the proposed method.

In the method presented here, the SNR values have a nonlinear growth with respect to the number of measurements. However, conventional method can only realize a linear relationship. A typical comparison is further illustrated in Fig. 5.

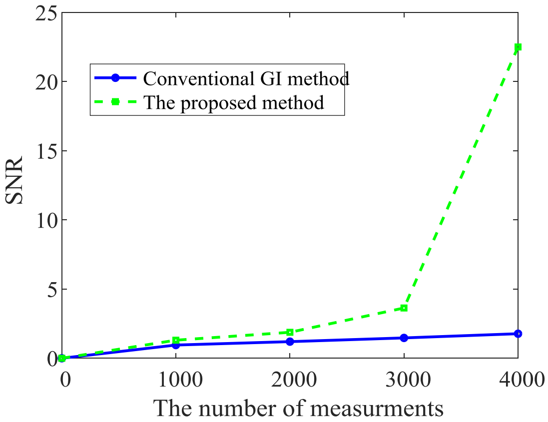


Figure 5: The SNR values versus the number of measurements.

4. CONCLUSIONS

A high-quality object reconstruction method is presented for the GI. By taking advantage of the property of Hadamard transform, an algorithm is presented which can lead to a nonlinear growth in the SNR values corresponding to the number of measurements. The method can reduce the number of measurements dramatically, and can facilitate the reconstruction to retrieve the objects with high SNR values. Feasibility and effectiveness of the method are validated by using numerical results and theoretical analyses.

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