Information retrieval based on single-pixel optical imaging with quick-response code

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ABSTRACT

Quick-response (QR) code technique is combined with ghost imaging (GI) to recover original information with high quality. An image is first transformed into a QR code. Then the QR code is treated as an input image in the input plane of a ghost imaging setup. After measurements, traditional correlation algorithm of ghost imaging is utilized to reconstruct an image (QR code form) with low quality. With this low-quality image as an initial guess, a Gerchberg-Saxton-like algorithm is used to improve its contrast, which is actually a post processing. Taking advantage of high error correction capability of QR code, original information can be recovered with high quality. Compared to the previous method, our method can obtain a high-quality image with comparatively fewer measurements, which means that the time-consuming postprocessing procedure can be avoided to some extent. In addition, for conventional ghost imaging, the larger the image size is, the more measurements are needed. However, for our method, images with different sizes can be converted into QR code with the same small size by using a QR generator. Hence, for the larger-size images, the time required to recover original information with high quality will be dramatically reduced. Our method makes it easy to recover a color image in a ghost imaging setup, because it is not necessary to divide the color image into three channels and respectively recover them.

Keywords: QR code, ghost imaging, Gerchberg-Saxton-like algorithm.

1. INTRODUCTION

In two-arm ghost imaging (GI) setup, a laser beam goes through a 50-50 beam splitter to generate two beams respectively called reference and object light beams. Undergoing a paraxial diffraction over free-space with the same path length, the reference beam is captured by a spatially resolving sensor and the object light illuminating a transmission-mask is collected by a (single-pixel) bucket detector [1-3]. The single-arm computational setup of GI is also developed in recent years, in which the reference arm of the two-arm setup is removed and replaced by a precalculated intensity pattern stored in the computer memory [4]. However, the same principle is used in these two setups. Correlating the data captured by the sensor with spatial resolution and the bucket detector can reconstruct the object. Based on this basic ghost imaging technique, some advanced methods such as differential ghost imaging (DGI) [5] and normalized ghost imaging (NGI) [6] are further proposed to improve the signal-to-noise ratio (SNR). However, the improvement is limited. In Ref. [7], it is demonstrated that a Gerchberg-Saxton-like algorithm based on GI setup can improve the quality of recovered image greatly. This algorithm takes advantage of the integral property of Fourier transform and treats the captured data as constraints for image reconstruction, which results in a nonlinear growth of the SNR value with respect to the number of measurements. Hence, the improvement in SNR value will be obvious especially with a large amount of measurements. However, using many measurements to obtain a high-quality image in this algorithm is also time-consuming. Especially, for the larger size images, the measurements and time required to reconstruct a high-quality image also increase greatly. For color images in ghost imaging [8], they will be considered as three channels and the three channels are measured and respectively recovered, which is complex.

Quick-response (QR) code becomes more and more popular in our society, after it was invented. There are some remarkable advantages of QR code, including fast speed, large storage capacity and high error correction capability. The most important advantage is that this technique converts original information (such as text and image) into a binary twodimensional image which can be easily processed in various kinds of information processing. Ref. [9] is an example combining QR code and computational GI into optical encryption.

In this paper, QR code technique is introduced into the GI setup. The high error correction capability of QR code is utilized to obtain high-quality images with comparatively fewer measurements compared with the method in Ref. [7]. In our method, the larger size images do not mean a larger amount of measurements, because different size images can be transformed into the same small-size QR code. It is worth noting that the QR code is treated as the input and processed later, and original information will be extracted from the recovered QR code form. Contrast to the method in Ref. [8], when converted into QR code form firstly, color images can be recovered directly from the reconstructed QR codes.

2. THEORETICAL ANALYSES

The single-arm ghost imaging setup used in our simulation is shown in Fig. 1. The speckle wave field illuminating the object is generated by a monochromatic laser modulated by a spatial light modulator (SLM). $\{I_i(x,y)\}_{i=1}^{M}$ is used to represent a sequence of the intensity distribution of the speckle fields. The total light intensity $\{B_i\}_{i=1}^{M}$ transmitting through the object $O(x,y)$ is collected by a bucket detector without spatial resolution. Then we have

$$B_i = \int dxdy I_i(x,y) O(x,y), \qquad (i = 1,2,3,...,M). \tag{1}$$

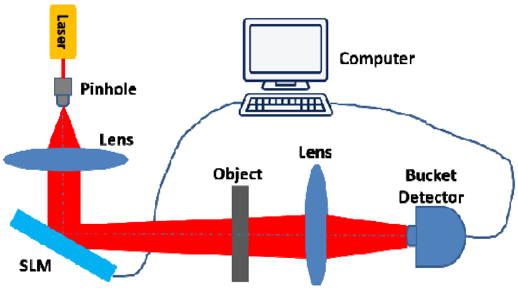

Figure 1. A schematic setup of a single-arm ghost imaging

Here, it should be noted that the object is a QR code form which contains the original image. With the data captured by the detector and the speckle patterns stored in the computer, a correlation algorithm can be used to reconstruct the QR code form image.

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

where $\langle \bullet \rangle = \frac{1}{M}\sum_i \bullet$ denotes an ensemble average over M measurements.

An initial guess can be obtained by Eq. (2), and a Gerchberg-Saxton-like algorithm introduced in Ref. [7] is used to further improve its contrast. This algorithm takes advantages of the property of Fourier transform and treats the data $\{B_i\}_{i=1}^{M}$ as constraints in the iterative procedures. A threshold (i.e., 10^{-10}) is set to break the iterative process. The contrast can be improved dramatically, especially for a large amount of measurements. To quantitatively describe quality of recovered results, SNR is used as a criterion which is defined as [10]

$$\mathrm{SNR} = \frac{\sum\left(O - \bar{O}\right)^2}{\sum\left(T - O\right)^2}, \tag{3}$$

where $\overline{O}$ denotes the mean of O, and T represents the recovered object.

3. RESULTS AND DISCUSSION

In Fig. 2, we give simulation results for an image with 64×64 pixels. Figure 2(a) shows an original image, and Fig. 2(e) is the QR code form image transformed from Fig. 2(a). When taking the Fig. 2(a) and Fig. 2(e) as the input image separately, we can obtain the corresponding recovered results Fig. 2(b) and Fig. 2(f) using traditional correlation algorithm. As shown in the Fig. 2, quality of these two results is bad. However, after processed by the Gerchberg-Saxton-Like algorithm, it can be seen from Figs. 2(c) and 2(g) that the contrast of these two images is significantly improved. For Fig. 2(g), the original image with high quality can be further extracted from it, as shown in Fig. 2(h).

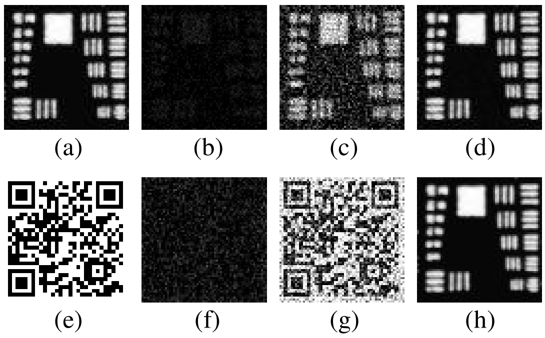

Figure 2. Results with 3000 measurements for image size of 64×64 pixels. The images of the first row are results of the method in Ref. [7]: (a) original image; (b) reconstruction by correlation algorithm; (c) quality improved by Gerchberg-Saxton-like algorithm; (d) qualtiy improved with 5000 measurements. The images of the second row are results by using QR code: (e) QR code transfromed from the original image; (f) reconstruction by correlation algorithm with 3000 measurements; (g) quality improved by the proposed method with QR code using 3000 measurements; (h) information extracted from (g).

The SNR values of Figs. 2(b) and 2(f) are 0.72 and 0.51, respectively. After improvement, the SNR value of Fig. 2(c) is 3.48, and SNR value of Fig. 2(g) is 3.56. If we want to obtain a high-quality recovered image using the method in Ref. [7], more measurements are necessary. For example, Fig. 2(d) shows the result using 5000 measurements. The SNR value can rise to 80.84. This is a time-consuming process. However, Fig. 2(h) extracted from Fig. 2(g) has a SNR value of 329.81, when only 3000 measurements are used in the proposed method.

Next, the effectiveness of our method is further illustrated for the larger size images. Here, 128×128, 256×256 and 512×512 images are used as examples.

As shown in Fig. 3, high-quality reconstruction can be obtained for the larger size images, when 3000 measurements are used. However, in traditional GI, for an image with 128×128 pixels, at least 10000 measurements are needed. In order to reconstruct high-quality images, the reconstruction for initial guess and postprocessing by using conventional Gerchberg-Saxton-like algorithm will take serveral hours or more which is slower compared with our method.

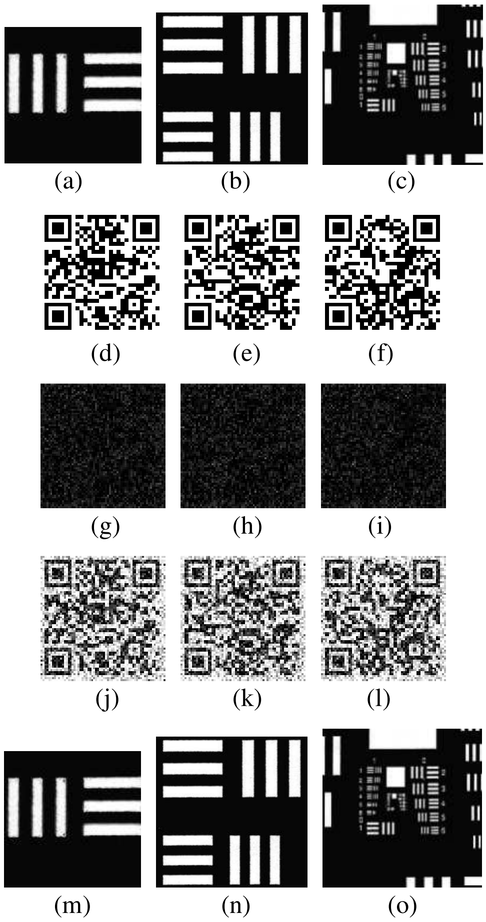

Figure 3. Results for three different size images with 3000 measurements. (a), (b) and (c) original images with 128×128, 256×256 and 512×512 pixels; (d), (e) and (f) the corresponding QR code forms; (g), (h) and (i) initial guesses recovered by GI technique; (j), (k) and (l) the improved results based on (g), (h) and (i) using the proposed method with QR code; (m), (n) and (o) respectively extracted from (j), (k) and (l).

It is further shown that it is also easy to recover a color image, when QR code technique is introduced into GI. In Fig. 4, it is illustrated that the proposed method is effective for extracting high-quality color images. Here, only 3000 measurements are used for the color image with 512×512 size.

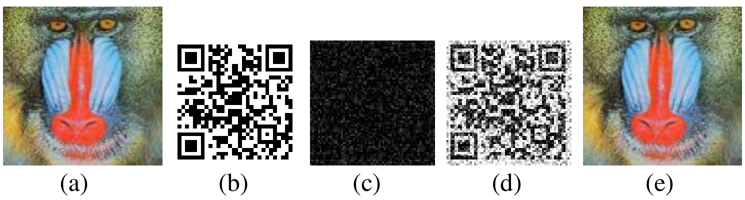

Figure 4. Results for color image with 512×512 piexels: (a) original image; (b) QR code transformed from the original image; (c) reconstruction by correlation algorithm; (d) quality improved by using the proposed method with QR code; (e) information extracted from (d).

4. CONCLUSIONS

In this paper, QR code technique has been introduced into computational GI setup. The original image is firstly transformed into a QR code form which is treated as the input image. Such a transformation can dramatically reduce the measurement time, especially for the larger size images. In addition, this method is also suitable for extracting high-quality color images.

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