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Image reconstruction using single-pixel color ghost imaging

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Abstract: A simple method is proposed to recover color image by using single-pixel ghost imaging (GI) technique. A color image (RGB format) is firstly converted to its indexed image format before it is measured, and conventional GI technique is used to measure and recover this indexed image. Quality of the recovered image using conventional correlation algorithm of GI is low even using a large amount of measurements. It is difficult to convert the low-quality indexed image back to the RGB image. To reconstruct color image with high quality, a Gerchberg-Saxton-like algorithm is used to further improve contrast of the recovered indexed image. This algorithm can lead to a nonlinear growth of signal-to-noise ratio (SNR) value with respect to the number of measurements. Hence, after a dramatic improvement, a large SNR value of the indexed image can be achieved and a comparatively high-quality color image can be obtained from the improved indexed image. Compared to traditional method in GI which treats a color image as three independent channels (i.e., red, green and blue), the proposed method is simpler, because it reduces the complexity by converting original three channels into a single channel. Besides, since the recovered indexed image is processed by a Gerchberg-Saxton-like algorithm, high-quality color images can be obtained. It is worth noting that the proposed method uses a post-processing strategy, and it does not add the complexity. Some computational results are presented to prove that the proposed method is feasible and effective.

1. INTRODUCTION

A color image is more meaningful than a monochromatic one at most times, because it can provide more useful information. In computer displays, a color image is commonly treated as a RGB format, i.e., red channel, green channel and blue channel. When taking into account a color image in image processing, the simplest way is to process the three channels independently. However, processing three channels is time-consuming, which makes the system complex in experiment. In the field of image encryption, an indexed-image-based color image encryption was proposed by Zhang and Karim [1]. In Ref. [1], color images with three channels are transformed into one-channel images. With such a transformation, techniques designed for gray-scale image processing can be used for color images.

In single-pixel imaging, few work has been done for color image reconstruction. Ref. [2] proposed a method for color image reconstruction by using computational ghost imaging technique. However, the work in Ref. [2] still treats a color image as three channels and respectively recovers them, and quality of final reconstruction is not high. Single-pixel ghost imaging (GI) has been developed for many years [3-13]. In general, an object is illuminated with random patterns which are typically generated by a spatial light modulator (SLM), and a single-pixel (or bucket) detector is used to collect the total light intensities for each illumination pattern. Correlating the illumination pattern with data captured by single-pixel detector can reconstruct the desired image. Since quality of recovered image in single-pixel GI relies on measurement number, a great number of illumination patterns are usually required, which are commonly larger than pixel counts of images. However, a high-quality reconstruction cannot be obtained by just increasing

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measurement number. In Ref. [14], 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 signal-to-noise ratio (SNR) value with respect to the number of measurements.

In this paper, a color image reconstruction method based on single-pixel GI is proposed. Color images with RGB format are firstly transformed into indexed images. After measuring the indexed image, correlation algorithm of conventional GI is used to reconstruct an image. Since the quality of reconstructed indexed image is low, it is difficult to recover original color image. The algorithm proposed in Ref. [14] is used to improve the quality dramatically. The reconstructed indexed image with improved quality can be used to recover original color image with high quality.

2. THEORETICAL ANALYSES

The setup for single-pixel color ghost imaging is shown in Fig. 1. A monochromatic laser going through a pinhole is collimated by a lens and modulated by a spatial light modulator (SLM). The SLM can generate a sequence of illuminating patterns $\{I_i(x,y)\}_{i=1}^{M}$. For each illumination pattern, after transmitting through the object $O(x,y)$, a single-pixel (or bucket) detector is used to collect the total light intensities $\{B_i\}_{i=1}^{M}$. Then, the measurement process can be expressed as [11]

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

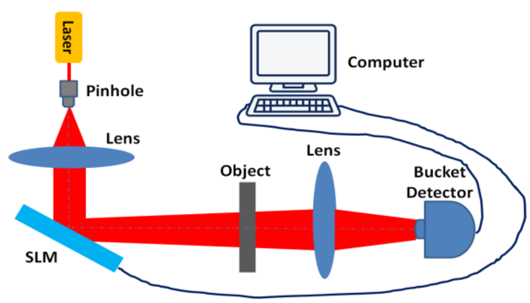

Figure 1. The schematic setup for a single-pixel ghost imaging.

It should be noted that the object in the setup represents an indexed image instead of a color image with RGB format. Hence, an indexed image is recovered firstly by the setup, and then the color image is extracted from the recovered indexed image using colormap. Correlating the illumination patterns with the detected signals can reconstruct the desired image. The correlation algorithm can be expressed as [11]

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

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

Since quality of initial guess obtained by Eq. (2) is low, a Gerchberg-Saxton-like algorithm introduced in Ref. [14] is used to further improve its quality. In comparison with conventional GI, the Gerchberg-Saxton-like algorithm can lead to a nonlinear growth in SNR with respect to measurement number, while conventional method has a linear growth in SNR. The definition of SNR used in this paper is [15]

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

where $\bar{O}$ denotes the mean of O and T represents the recovered image.

3. RESULTS AND DISCUSSION

Figure 2 shows some simulation results for three different color images (RGB format) with 64×64 pixels. The first column represents three original color images. Using the proposed method, the three color images should be transformed into indexed images (Figs. 2(b), 2(h) and 2(n), respectively) at first. By using GI technique, three recovered indexed images (Figs. 2(c), 2(i) and 2(o), respectively) can be obtained. Their SNR values are 0.3, 0.23 and 0.34, respectively. Since the quality of these results is low, it is difficult to extract useful information from them, as shown in Figs. 2(d), 2(j) and 2(p), respectively. However, the quality of Figs. 2(c), 2(i) and 2(o) can have a dramatic improvement after using Gerchberg-Saxton-like algorithm, and Figs. 2(e), 2(k) and 2(q) are the improved results based on Figs. 2(c), 2(i) and 2(o), respectively. The SNR values of Figs. 2(e), 2(k) and 2(q) are 7.6×10^4, 2.2×10^4 and 7.2×10^4, respectively. Then, the information recovered from Figs. 2(e), 2(k) and 2(q) is shown in Figs. 2(f), 2(l) and 2(r), respectively.

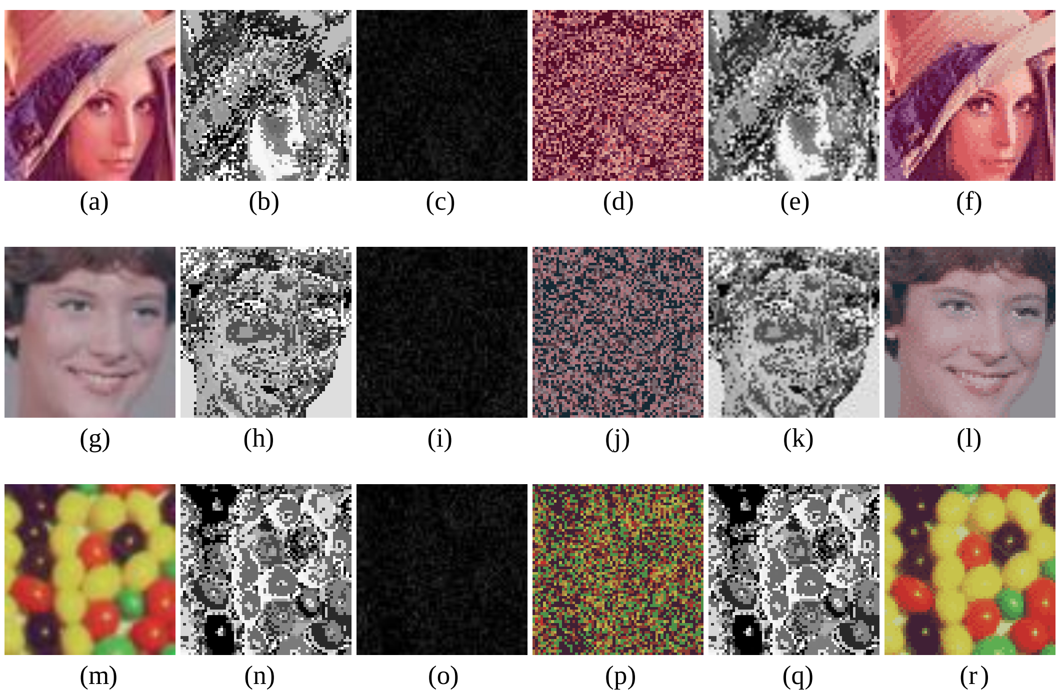

Figure 2. Results with 5000 measurements for color images (RGB) format of 64×64 pixels. (a), (g) and (m) the three original color images; (b), (h) and (n) the corresponding indexed images; (c), (i) and (o) the recovered indexed images by using correlation algorithm (Eq. (2)); (d), (j) and (p) the recovered color images by using (c), (i) and (o), respectively; (e), (k) and (q) the improved results based on (c), (i) and (o) using the Gerchberg-Saxton-like algorithm, respectively; (f), (l) and (r) the information recovered from (e), (k) and (q), respectively.

The aforementioned results and discussions show that a high-quality indexed image is necessary for obtaining a clear color image. To further show the effectiveness of the proposed method, it is meaningful to compare the error between original indexed images and recovered indexed images with Gerchberg-Saxton-like algorithm, i.e., the second column and fifth column of Fig. 2. The error calculated here is defined as $\varepsilon = \sum (T-O)^2$, and the results are shown in Fig. 3. It can be seen that the error decreases dramatically by using Gerchberg-Saxton-like algorithm.

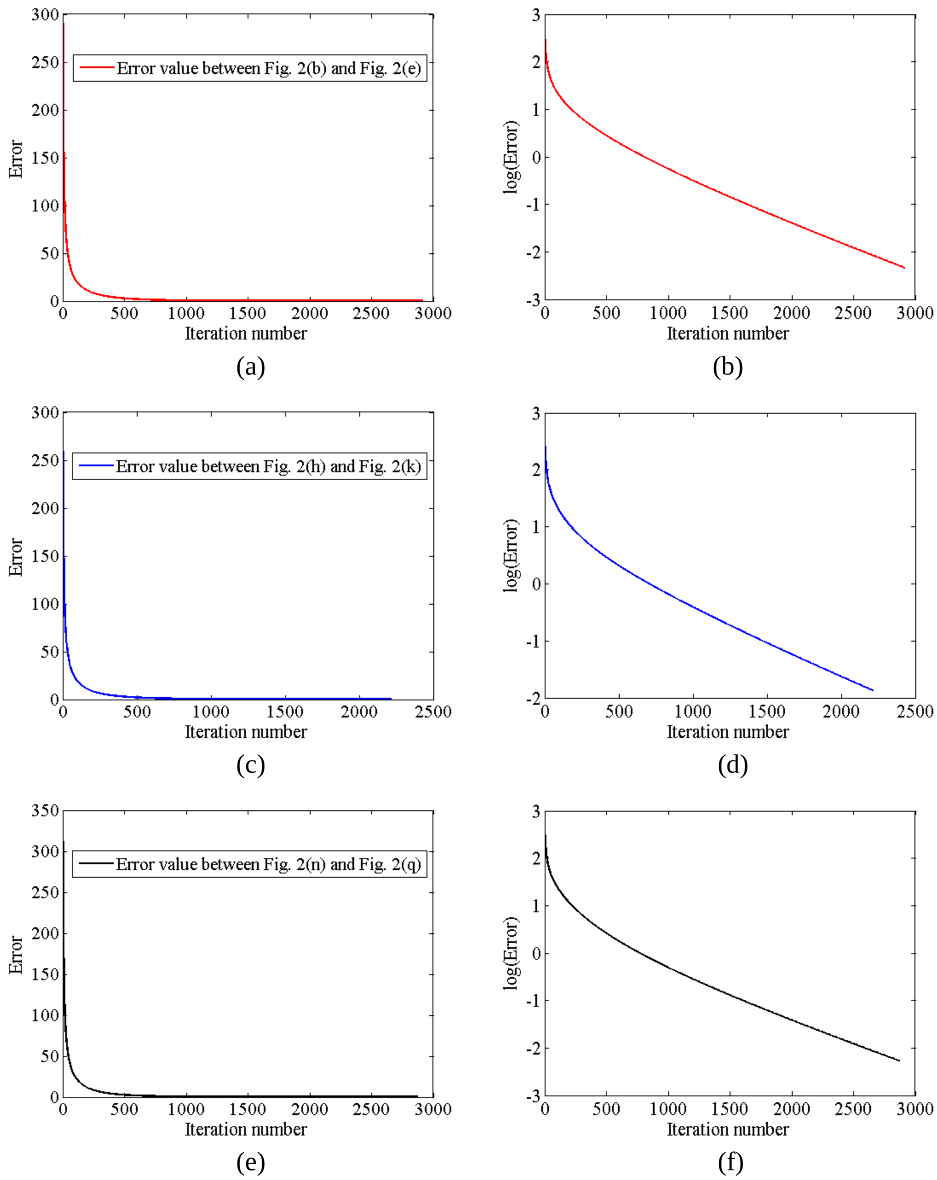

Figure 3. Errors calculated between original indexed images (Figs. 2(b), 2(h) and 2(n)) and the recovered indexed images (Figs. 2(e), 2(k) and 2(q)) using Gerchberg-Saxton-like algorithm. (a), (c) and (e) the error values versus iteration number ; (b), (d) and (f) the corresponding logarithmically scaled value based on (a), (c) and (e), respectively.

4. CONCLUSIONS

A single-pixel color ghost imaging method has been proposed. Effectiveness of the proposed method is validated by using three different color images. Taking advantage of the property of Gerchberg-Saxton-like algorithm, a high-quality indexed image can be recovered, and useful information (color images) can be recovered from the extracted high-quality indexed image.

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