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Edge detection based on subpixel-speckle-shifting ghost imaging

Le Wang [a,*], Li Zou [a,b], Shengmei Zhao [a]

[a] Institute of Signal Processing and Transmission, Nanjing University of Posts and Telecommunications(NUPT), Nanjing 210003, China
[b] School of Electronics and Information, Nantong University, Nantong 226000, China

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ABSTRACT

In this paper, we propose an edge detection scheme by using a subpixel-speckle-shifting ghost imaging, named SPSGI. In the scheme, a set of subpixel-shifted Walsh–Hadamard speckle pattern pairs with low resolution are used to illuminate an unknown object. The edges information with high-quality and higher resolution of the object could be obtained directly by computing with the detection results from the bucket detector and the subpixel-shifted Walsh-Hadamard speckle patterns. The experimental and numerical simulation results show that the quality of the edge detection results is noticeably improved and the number of measurements is greatly reduced comparing with other edge detection schemes based on ghost imaging. In addition, SPSGI has the advantages of enhancing the resolutions of the edge detection with low resolution speckle patterns, which considerably reduces the requirement of the digital mirror devices' resolutions.

1. Introduction

Ghost imaging (GI) is an intriguing optical imaging technique [1–6] where the imaging information can be obtained by correlating of fluctuating light field. In the conventional GI system [7–9], there are two spatially correlated optical beams. One beam, called signal beam, illuminates an object and is detected by a bucket detector without any spatial resolution. The other beam, named reference beam, is measured by a spatially resolving detector. The image is reconstructed by correlating the signals from the two detectors. Later, computational ghost imaging (CGI) [10,11] was proposed to remove the spatially resolving detector and to obtain the signals from the reference beam by generating through a spatial light modulator (SLM) or a digital mirror device (DMD) and computing offline. The past years have witnessed a rapidly growing interest in applications of GI ranging from lidars [12,13], microscopes [14], object authentication [15,16] to optical encryption schemes [17–21].

Recently, CGI was used to extract the edge information from an unknown object without needing the original image [22,23]. Several effective schemes, such as gradient ghost imaging (GGI) [22] and speckle-shifting ghost imaging (SSGI) [23], were proposed to dramatically improve the performance of the objects' edges comparing with that of performing the edge extraction algorithms on the images reconstructed by GI. It is valuable for the edge detection based on ghost imaging to be used in target recognition and remote sensing. However, the number of measurements of these schemes is large and the quality of edge detection results is still much lower.

On the other hand, the subpixel shifting method was introduced into GI [24,25] to obtain a higher resolution image of the object by illuminating a series of subpixel shifted speckle patterns with a low resolution. Therefore, it overcomes the limits of the spatial resolution of the imaging for cost and technical reasons, and has the potential to realize the super resolution imaging which exceeds the diffraction limit of optics.

In this paper, we propose an edge detection scheme by using a subpixel-speckle-shifting ghost imaging, named SPSGI. In the scheme, a set of subpixel-shifted Walsh–Hadamard speckle pattern pairs with low resolution are used to illuminate an unknown object. With the detection results from the bucket detector and the subpixel-shifted Walsh–Hadamard speckle patterns, the edges information with high-quality and higher resolution of the object could be obtained directly. The advantage of the proposed scheme is that it could dramatically reduce the number of measurements and greatly improve the quality of the edge detection results comparing with other edge detection schemes based on ghost imaging [22,23]. In addition, SPSGI has the advantages of enhancing the resolutions of the edge detection with low resolution speckle patterns, which considerably reduces the requirement of the SLMs' or DMDs' resolutions.

* Corresponding author.
E-mail address: njwanglele@163.com (L. Wang).

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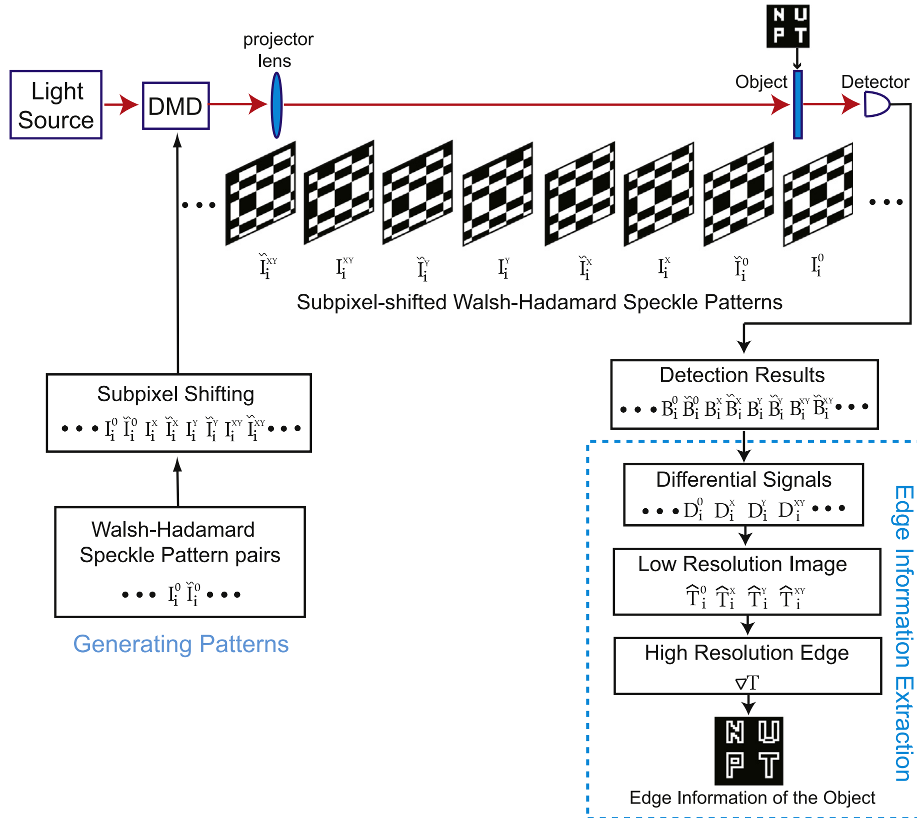

Fig. 1. A schematic diagram of the SPSGI scheme.

The organization of the paper is as follows. In Section 2, SPSGI is presented. In Section 3, the performance of SPSGI is discussed. Finally, Section 4 concludes the paper.

2. Scheme description

Fig. 1 shows the schematic diagram of the proposed SPSGI scheme. The light is modulated by a DMD to produce pairs of Walsh–Hadamard speckle patterns [26]. Each speckle pattern pair includes a speckle pattern $I_i^0(x,y)$ and its inverse pattern $\tilde{I}_i^0(x,y)$, where the value of $I_i^0(x,y)$ is either black (−1) or white (+1) for each coordinate (x,y), $\tilde{I}_i^0(x,y) = -I_i^0(x,y)$, and the resolution of the speckle pattern is $N_x \times N_y$. The ith Walsh–Hadamard speckle pattern $I_i^0(x,y)$ is obtained by reshaping the ith row of the natural order Walsh–Hadamard transform matrix [26]. Then DMD modulates the incident light to generate a subpixel shifted speckle pattern $I_i^j(x,y)$ and its inverse pattern $\tilde{I}_i^j(x,y)$. Here, three shifted patterns are considered in the paper, including a half-pixel shifted pattern along x-axis direction $I_i^X(x,y) = I_i^0(x-1/2,y)$, a half-pixel shifted pattern along y-axis direction $I_i^Y(x,y) = I_i^0(x,y-1/2)$, and a half-pixel shifted pattern along x- and y-axis direction $I_i^{XY}(x,y) = I_i^0(x-1/2,y-1/2)$. After beam expansion with a projector lens, the speckle pattern interacts with an object and then is measured by a bucket detector. The pairs of detection results, B_i^j and $\tilde{B}_i^j$, are obtained for each pair of speckle patterns, $I_i^j(x,y)$ and $\tilde{I}_i^j(x,y)$ $(j = 0, X, Y, XY)$, and the differential signal $D_i^j = B_i^j - \tilde{B}_i^j$ is recorded. Then the edge image of the object with the resolution $2N_x \times 2N_y$ can be reconstructed by using the differential signal D_i^j and the shifted speckle patterns $I_i^j(x,y)$.

The system displays each pair of speckle pattern $I_i^0(x,y)$ and its inverse pattern $\tilde{I}_i^0(x,y)$, and obtains two corresponding detection results from the bucket detector,

$$B_i^0 = \eta \sum_{x=1}^{N_x}\sum_{y=1}^{N_y} I_i^0(x,y)T(x,y) + n, \tag{1}$$

and

$$\tilde{B}_i^0 = \eta \sum_{x=1}^{N_x}\sum_{y=1}^{N_y} \tilde{I}_i^0(x,y)T(x,y) + n, \tag{2}$$

where η is the bucket detector responsivity, $T(x,y)$ is the distribution function of the object, and n represents the environmental illuminations. Therefore, a differential signal D_i^0 between the two corresponding detection results B_i^0 and $\tilde{B}_i^0$ is,

$$D_i^0 = B_i^0 - \tilde{B}_i^0 = \eta \sum_{x=1}^{N_x}\sum_{y=1}^{N_y} \Delta I_i^0(x,y)T(x,y), \tag{3}$$

where $\Delta I_i^0(x,y) = I_i^0(x,y) - \tilde{I}_i^0(x,y)$. The interferences of the environmental illuminations n could be removed efficiently.

When the speckle patterns $I_i^0(x,y)$ are coregistered on a higher resolution grid, Eq. (3) can be rewritten as

$$D_i^0 = \eta \sum_{x'}\sum_{y'} \Delta I_i^0(x',y')T(x',y') \tag{4}$$

when $x' = 1/2, 1, 3/2, \dots, N_x$ and $y' = 1/2, 1, 3/2, \dots, N_y$. Thus the image of the object corresponding to $I_i^0(x,y)$ can be reconstructed by intensity correlation algorithm [3], which could be expressed as

$$\hat{T}^0 = \frac{1}{N_x N_y} \sum_{i=1}^{N_x N_y} D_i^0 \Delta I_i^0(x',y') \propto T(x',y'). \tag{5}$$

Similarly, when the system displays the subpixel shifted speckle pattern pairs, a set of differential signals D_i^j, $j = X, Y, XY$, are obtained,

$$D_i^j = \eta \sum_{x'}\sum_{y'} \Delta I_i^j(x',y')T(x',y'), \tag{6}$$