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Edge detection based on computational ghost imaging with structured illuminations

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ABSTRACT

Edge detection is one of the most important tools to recognize the features of an object. In this paper, we propose an optical edge detection method based on computational ghost imaging (CGI) with structured illuminations which are generated by an interference system. The structured intensity patterns are designed to make the edge of an object be directly imaged from detected data in CGI. This edge detection method can extract the boundaries for both binary and grayscale objects in any direction at one time. We also numerically test the influence of distance deviations in the interference system on edge extraction, i.e., the tolerance of the optical edge detection system to distance deviation. Hopefully, it may provide a guideline for scholars to build an experimental system.

1. Introduction

Correlated imaging (or ghost imaging, GI), as a newly emerging optical imaging technique, has received great attention and achieved considerable development in recent years. This technique obtains the imaging information of objects via the quantum (or classic) fluctuation and their correlation of light fields [1–4]. In the intensity correlated imaging [5,6], a collimated coherent light is modulated by a rotating diffuser and split into two beams: one is the reference beam, which is usually detected by a charge-coupled device (CCD) after propagating in free space; the other is the object beam, whose intensity is collected by a single-pixel (or bucket) detector without spatial resolution after the wavefront of this light beam interacts with the target. The object can be imaged by performing correlation operation on the multiple measurements of the two light beams. Recently, Shapiro et al. proposed a GI system with a single arm, i.e., computational ghost imaging (CGI) [7], in which the speckle intensity patterns are generated by the computer-controlled spacial light modulator (SLM) and used to modulate the object information. Then, the reference arm can be replaced by a virtually computational part. This technique simplifies the GI system and also avoids the error caused by the distance deviation of the reference arm in measurement [8]. Given the great potential of GI, the research concerned is gradually focused on its practical applications, such as remote sensing [9] and biomedical imaging [10].

In GI, a major obstacle to target recognition and feature extraction is that noise inevitably exists in the retrieved image due to the mechanism of GI. At present, many techniques have been proposed to improve the image quality of GI [11–19], such as differential GI [11], compressive GI [12], normalized GI [13], iterative GI [14–16], sinusoidal GI [17] and so on. As an essential natural feature of an image, the boundaries contain abundant information about the object. Edge detection is the basis of high-level image processing techniques [20], such as image segmentation, feature extraction, pattern recognition and so on. Recently, Liu et al. have successively proposed a gradient GI (GGI) technique to extract the edge of an object based on multiple pairs of structured illumination [21]. When a series of gradient intensity patterns with a direction are projected on the object, its edge in this direction will be present by correlation operation. Subsequently, Mao et al. have improved the GGI and extracted the edge of an unknown object with no-direction [22]. Meanwhile, Wang et al. have proposed a high speed CGI technique which can increase the speed of edge detection [23]. In these methods, the structured intensity patterns used to modulate the object are generated by the digital micro-mirror device (DMD). These methods may be successively applied in the field of target recognition and localization.

In this paper, we find that the edge of an object can also be extracted by a series of structured illuminations, which are generated by the edge modes of several speckle intensity patterns. However, the structured intensity patterns are generally grayscale while DMD is a binary device. This requires the DMD to display several binary patterns to form a grayscale one [24]. Thus, error in the quantization of the grayscale

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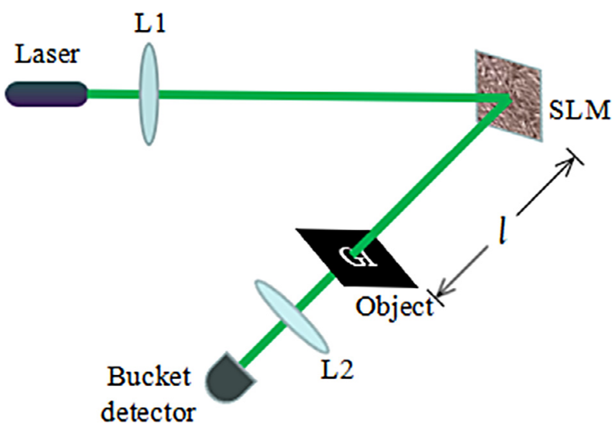

Fig. 1. Schematic diagram of CGI. L_1, collimated lens; L_2, convergent lens; SLM, spatial light modulator used to generate a series of random phase masks.

patterns is inevitable and further affects the quality of the detected edge if the quantization levels are not enough. We then propose a method for generating the structured illuminations at the object plane based on the interference principle [25]. In this method, two coherent light beams interfere with each other after being modulated by two phase-only spatial light modulators (SLMs), then a series of structured intensity patterns are generated at the object plane, and finally the light transmitted from the object is converged into a single-pixel detector. The two phase functions generated by SLMs are obtained by computer according to the interference principle. This paper is organized as follows. After the introductory Section 1, Section 2 illustrates the edge detection principle based on CGI. The generation method of the structured illumination at the object plane is analyzed in Section 3. In Section 4, we discuss the feasibility of the proposed method with the numerical simulation results, and the conclusion is given in Section 5.

2. Edge detection method based on CGI

The setup of CGI is shown in Fig. 1. A collimated laser beam illuminates on the SLM which is controlled by computer to generate a series of random phase patterns $\{\varphi_r(x,y)\}$, then the modulated wavefront is diffracted at distance l from the SLM to the object plane. This process can be computed by the Fresnel–Huygens propagator [8]

$$E_r(x,y;l) = \frac{\exp(i\lambda l)}{i\lambda l}\int \exp\left[i\varphi_r(x-\xi,y-\eta)\right]\exp\left[\frac{i\pi}{\lambda l}\left(\xi^2+\eta^2\right)\right]d\xi d\eta \tag{1}$$

where λ is the wavelength of the incident light. For each phase realization of $\varphi_r(x,y)$, the bucket detector measures the total transmitted light after the intensity pattern $I_r = |E(x,y;l)|^2$ interacts with the object $T(x,y)$, i.e.,

$$B_r = \sum_x\sum_y I_r(x,y)T(x,y) \tag{2}$$

where $r = 1,2,\ldots,M$, and M is the number of measurements. The object is ghostly imaged by correlating the intensity patterns $\{I_r(x,y)\}$ with the data $\{B_r\}$ measured by the bucket detector,

$$T(x,y) = \frac{1}{M}\sum_{r=1}^{M}\left(B_r - \langle B\rangle\right)I_r(x,y) \tag{3}$$

where $\langle B\rangle$ is the average value for the measured intensity sequence $\{B_r\}$.

We assume that the horizontal and vertical gradient patterns of $I_r(x,y)$, respectively noted by $I_r^H(x,y)$ and $I_r^V(x,y)$, are extracted by Prewitt operator, which is a famous edge detection operation [20], i.e.,

$$\begin{aligned} I_r^H(x,y) &= I_r(x+1,y-1) + I_r(x+1,y) + I_r(x+1,y+1) \\ &-I_r(x-1,y-1) - I_r(x-1,y) - I_r(x-1,y+1) \end{aligned} \tag{4}$$

and

$$\begin{aligned} I_r^V(x,y) &= I_r(x-1,y+1) + I_r(x,y+1) + I_r(x+1,y+1) \\ &- I_r(x-1,y-1) - I_r(x,y-1) - I_r(x+1,y-1) \end{aligned} \tag{5}$$

If the structured intensity patterns $I_r^H(x,y)$ and $I_r^V(x,y)$ are projected on the object plane, the transmitted or reflected light will be detected by the bucket detector to obtain a pair of measurement data

$$B_r^H = \sum_x\sum_y I_r^H(x,y)T(x,y) \tag{6}$$

and

$$B_r^V = \sum_x\sum_y I_r^V(x,y)T(x,y) \tag{7}$$

Then, the horizontal and vertical edge of the object will be imaged by correlation operation after M measurements, i.e.,

$$T_{edge}^H(x,y) = \frac{1}{M}\sum_{r=1}^{M}\left[B_r^H - \left\langle B^H\right\rangle\right]I_r(x,y) \tag{8}$$

and

$$T_{edge}^V(x,y) = \frac{1}{M}\sum_{r=1}^{M}\left[B_r^V - \left\langle B^V\right\rangle\right]I_r(x,y) \tag{9}$$

where $\langle\cdot\rangle$ denotes the average operation for the measurements $\{B_r\}$, $r = 1,2,\ldots,M$. The edge of the object will be obtained by

$$T_{edge} = \left|T_{edge}^H\right| + \left|T_{edge}^V\right| \tag{10}$$

$|\cdot|$ is the absolution of the element.

3. Generation of the structured illuminations at the object plane

From Eqs. (4) and (5) we know that the structured intensity patterns $I_r^H(x,y)$ and $I_r^V(x,y)$ are generally grayscale, but the state-of-art DMD is a binary device. Thus, several binary patterns must be generated by DMD to form a grayscale one [24]. Error generated in the quantization of the grayscale patterns should be considered in edge detection. Moreover, the SLM is usually distanced from the object and the diffraction should not be ignored. How to produce the structured grayscale intensity patterns at the object plane? This problem can be solved by the interference of two coherent light beams and the system is schematically shown in Fig. 2. Here, the phase-only masks in the two arms generated by the SLMs are obtained according to the interference principle [25] rather than arbitrarily selected speckle functions, so that the two coherent light beams modulated by them are able to interfere with each other and generate the structured intensity pattern ($I_r^H(x,y)$ or $I_r^V(x,y)$) on the object plane. The method is described as follows and only the structured intensity $I_r^H(x,y)$ is taken as an example here.

We assume that two phase-only masks φ_1 and φ_2 are unknown but the interference between them can get a definite complex wavefront [25]

$$\exp\left(i\varphi_1\right) * h(\xi,\eta;l) + \exp\left(i\varphi_2\right) * h(\xi,\eta;l) = I_r^H\exp(iR) \tag{11}$$

For simplicity, we omit the coordinates in equation. R is an arbitrarily selected random phase function, $h(\xi,\eta;l)$ is the point pulse function of Fresnel diffraction, and $*$ denotes the convolution operation. After simply deducing Eq. (11), we can have

$$\exp\left(i\varphi_1\right) + \exp\left(i\varphi_2\right) = \mathfrak{I}^{-1}\left\{\frac{\mathfrak{I}\left\{I_r^H\exp(iR)\right\}}{\mathfrak{I}\{h(\xi,\eta;l)\}}\right\} \tag{12}$$

where $\mathfrak{I}$ and $\mathfrak{I}^{-1}$ denote the Fourier and the inverse Fourier transform respectively. For simplicity, we let

$$D = \mathfrak{I}^{-1}\left\{\frac{\mathfrak{I}\left\{I_r^H\exp(iR)\right\}}{\mathfrak{I}\{h(\xi,\eta;l)\}}\right\} \tag{13}$$