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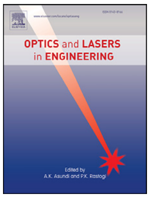

Efficient regional single-pixel imaging for multiple objects based on projective reconstruction theorem

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ABSTRACT

Single-pixel imaging (SPI) is a novel imaging method with a non-spatial detector that is utilized when imaging. SPI exhibits numerous advantages but is time-consuming and ineffective. This paper proposes an efficient regional SPI (ERSI) based on projective reconstruction theorem. The main idea of ERSI is locating object regions first and then adaptively project patterns only on these regions. The ERSI is considerably more efficient than traditional SPI because the former disregards background information. Experiments verified that ERSI shortens the time consumed for SPI to approximately 10% if the scene contains several small objects.

1. Introduction

Single-pixel imaging (SPI), which is also called ghost imaging (GI), is a novel optical imaging technique that differs from those using a pixelated array of detectors. In SPI application, a programmable spatial light modulator (SLM) is used to display patterns, and a single-pixel detector without spatial resolution is used to capture modulated information of a scene [1–3]. A single-pixel detector captures image information from transformation space and is capable to work without facing the scene directly [4–6].

Early GI was performed by using quantum-entangled light sources; this process is alternatively called quantum GI, which correlates the intensity fluctuations of signal and reference light paths. Shih et al. [7] performed the first GI experiment in 1995.

In the early stage, researchers considered ghost images as the result of quantum entanglement, but subsequent studies showed that ghost images can also be captured using classic light sources [8]. In 2002, Bennink et al. [9] realized GI by using a pseudo heat light source. The experiment used rotating mirrors instead of quantum light sources in producing a parallel beam as a light source to complete the GI experiment.

In 2008, Duarte proposed SPI via compressive sampling and improved the efficiency of SPI. In the same year, Shapiro presented computational ghost imaging [10] and proposed a scheme that uses only a single-pixel detector for GI. Bromberg et al. [6] used a 2D phase-based liquid crystal SLM to realize one-arm computational GI.

Recently, the development of SPI technology has been focusing on using patterns generated from complete orthogonal bases. In 2015, Zhang [11] proposed a SPI technique based on acquiring Fourier spectrum, which is based on Fourier transform, and acquired a high-resolution image with SPI. There are some other approaches in single pixel technique based on transforms, such as discrete cosine transform [12] and Hadamard transform [13].

SPI exhibits numerous advantages over traditional optical imaging systems. A single-pixel detector is capable to capture scene indirectly and it performs well with signals of low signal-to-noise ratio. Single-pixel cameras perform well in various applications, including wavelength imaging [14,15], remote sensing [16,17], 3D imaging [18] and encryption [19–21] in which traditional imaging methods meet their choke point. However, SPI is implemented by performing numerous measurements, and the number of measurements increases with the spatial resolution of the image. Therefore, the time consumption becomes unacceptable if an image with high spatial resolution is required, thereby severely limiting the application of SPI.

The reduction of the number of projected patterns is an effective means of reducing the measurement time of SPI. Compressive sampling [22] can be used to reduce the number of patterns, but the signal-to-noise ratio of the reconstructed image will be reduced. In 2016, Bian et al. [23] and Zhang et al. [24] developed efficient SPI techniques to minimize the measurement time of SPI. Only the most informative data in spatial frequency bands was captured and thus numerous patterns were eliminated by adopting this technique.

We have proposed an adaptive regional SPI (ARSI) method [25] to reduce the number of patterns when the reconstructed image contains only one object. This method adopted Fourier slice theorem to locate an object vertically and horizontally and then project patterns on the object area only.

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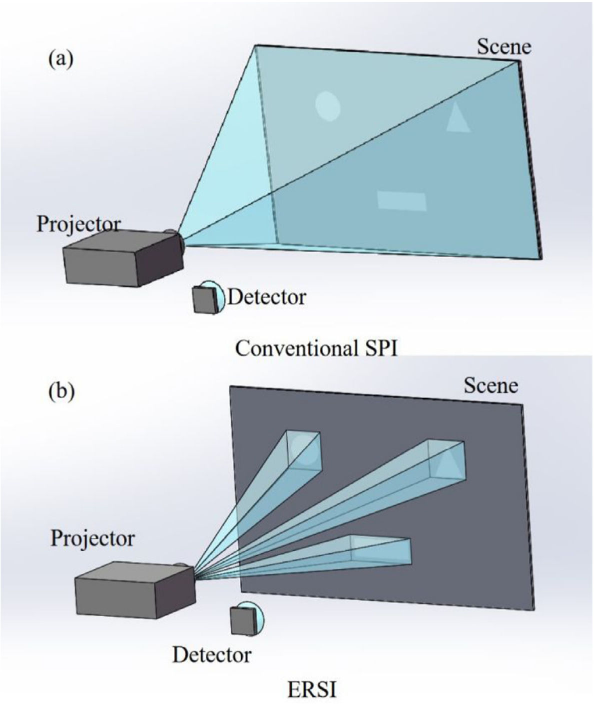

Fig. 1. Schematics of conventional SPI and ERSI. (a) Traditional SPI method, which projects patterns on the entire scene. (b) ERSI with region-locating technique, which projects patterns only on object regions.

In this paper, we propose an improved method for multiple objects based on Fourier slice and projective reconstruction theorems to enhance the efficiency of SPI. The background region typically occupies a large portion of an image, but the background is unnecessary in most cases. Consequently, the background pixels cost high measurement time when capturing a full-scene image if the scene consists of several small objects. The ERSI is used to select the object regions out from the background and then only project patterns to the selected regions. Small project regions result in few patterns; therefore, the measurement time can be substantially reduced by ERSI because the image acquired in reality is considerably smaller than a full-scene image.

2. Principle

The main idea of ERSI is performing SPI only on the objects and disregarding the background. The object regions are in the projector coordinate system. Patterns are adaptively generated and then projected once the object regions are located. The image of objects is reconstructed based on the measurement intensity of each pattern from the single-pixel detector and then placed back to the region in the projector coordinate system.

The difference between ERSI and the traditional SPI method is illustrated in Fig. 1. In Fig. 1 (a), a traditional method must apply patterns on a full-scene area to reconstruct the object image, which is time-consuming. In Fig. 1(b), ERSI applies patterns only on the object regions, which prevents the waste of measurement time on the background.

2.1. Locating the regions of objects based on projective reconstruction theorem

Region location is the most critical technique in ERSI. The main idea of this technique is performing 2D projection of the target image from different directions based on Fourier slice theorem, and the results are used to calculate the line integrations of the image. Several line integrations of different directions can be combined to analyze the position of the target object based on projective reconstruction theorem. The quality and accuracy of region location are closely related to the image quality and measurement time of ERSI.

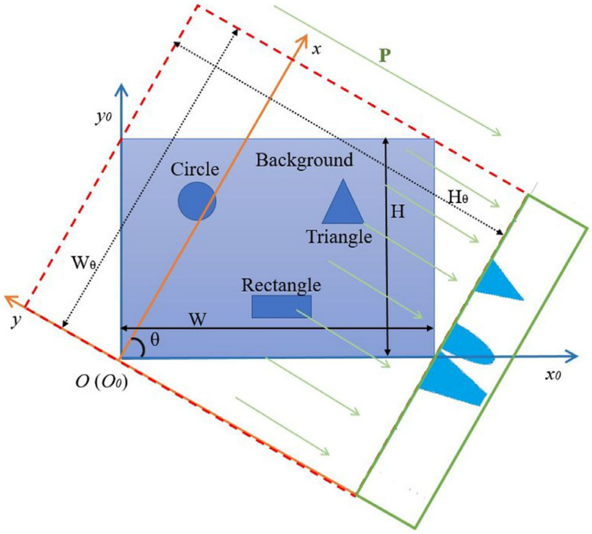

Fig. 2. Two-dimensional projection of an image along Direction P to realize line integration. The scene contains a circle, a triangle, and a rectangle. The original image is under the coordinate system (O_0; x_0, y_0), and (O; x, y) is established with x-axis vertical to Direction P. The image can be projected along Direction P into a 1D line integration, which is shown in the green (rightmost) rectangle, by performing Fourier slice. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to demonstrate ERSI simply, we use a circle, a triangle, and a rectangle in Fig. 2 to represent the target objects to be imaged. The original image is under the coordinate system (O_0; x_0, y_0). An additional 2D Cartesian coordinate (O; x, y) is established with x-axis vertical to Direction P. We apply Radon transform to perform the 2D projection of the image along Direction P. Point (x, y) under (O; x, y) can be calculated from its counterpart (x_0, y_0):

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_0 \\ y_0 \end{pmatrix}. \tag{1}$$

The relationship between the original image under (O; x, y) and the minimum bounding rectangle (MBR) of the image under (O_0; x_0, y_0) is described as Eq. (2).

$$\begin{cases} H_\theta = H\cos\theta + W\sin\theta \\ W_\theta = H\sin\theta + W\cos\theta \end{cases}, \tag{2}$$

where θ is the angle between the x-axis and image coordinate x_0-axis; H and W denote the height and width of the original image respectively; and H_θ and W_θ correspond to the height and width of the MBR of the transformed image (red (leftmost) rectangle in Fig. 2).

The Radon transformation from image $g(x_0, y_0)$ to image $f(x, y)$ is

$$\begin{aligned} T(x,\theta) &= \int_{H_\theta} g(x_0, y_0)dy \\ &= \int_{H_\theta} g(x\cos\theta - y\sin\theta, x\sin\theta + y\cos\theta)dy \\ &= \int_{H_\theta} f(x, y)dy, \end{aligned} \tag{3}$$

where $T(x, \theta)$ denotes the line integration of the image along Direction P. $g(x_0, y_0)$ indicates the image under (O_0; x_0, y_0). $f(x, y)$ indicates the image under (O; x, y). We can draw further conclusions by applying