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Shadow-free single-pixel imaging

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ABSTRACT

Single-pixel imaging is an innovative imaging scheme and receives increasing attention in recent years, for it is applicable for imaging at non-visible wavelengths and imaging under weak light conditions. However, as in conventional imaging, shadows would likely occur in single-pixel imaging and sometimes bring negative effects in practical uses. In this paper, the principle of shadows occurrence in single-pixel imaging is analyzed, following which a technique for shadows removal is proposed. In the proposed technique, several single-pixel detectors are used to detect the backscattered light at different locations so that the shadows in the reconstructed images corresponding to each detector shadows are complementary. Shadow-free reconstruction can be derived by fusing the shadow-complementary images using maximum selection rule. To deal with the problem of intensity mismatch in image fusion, we put forward a simple calibration. As experimentally demonstrated, the technique is able to reconstruct monochromatic and full-color shadow-free images.

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1. Introduction

Shadows commonly exist in photography and have been extensively studied in digital image processing. On one hand, shadows have some advantages. For example, the shadows of objects allow one to extract the object shape information [1–4]. In virtual reality, adding shadows for the object can improve the realism of the scene. On the other hand, shadows also have some disadvantages. Shadows in the image cause some information loss. Shadows often cause problems to computer vision and graphics applications (such as edge detection [5], objects tracking [6], and visual scene understanding [7]). For instance, in traffic surveillance, shadows can degrade the performance of objects extraction and objects tracking. In digital photography, shadows removal can help to improve the visual quality of photographs. Therefore, detecting and removing shadows are great essentials in computer vision and graphics applications.

In terms of shadows removal, there have been many shadow removal methods proposed for conventional imaging [8–16]. However, single-frame shadows removal methods [8–13] are mainly based on digital image processing. These methods are able to eliminate penumbra, but have difficulty in removing umbra. It is because the image information is completely lost within the area of umbra. The lost image information is hardly retrieved unless any prior knowledge is available. Multi-frame methods [14–16] are potential to remove umbra. To obtain multiple raw images where shadows are complementary by using multi-angle illuminations, the lost image information in one image can be complemented from the others. However, the strategy of multi-angle illuminations requires extra illumination devices and expense. Umbra removal is challenging for conventional imaging.

Single-pixel imaging [4,17–26] is a novel scheme of imaging, which allows one to use a detector without spatial resolution (that is, single-pixel detector) to acquire the spatial information of a scene under view. By illuminating the scene with a sequence of patterns and collecting the resultant light signals from the scene, the image of the scene can be computationally reconstructed. Single-pixel imaging receives increasing attention [4,19–26] in recent years, for it is applicable for imaging at non-visible wavelengths (such as infrared, terahertz, etc.). In addition, single-pixel imaging has advantages in imaging under weak light conditions, because large-sized single-pixel detectors are easier and more cost-effective to produce than pixelated detectors. What is more, single-pixel imaging can also combine encryption technology for optical security applications [19,20].

As is for conventional imaging, shadows likely occur in images acquired by single-pixel imaging. The principle of shadow occurrence in conventional imaging has been well investigated [27]. Due to the reciprocity [28,29] between conventional imaging and single-pixel imaging, the principle of shadow occurrence in single-pixel imaging

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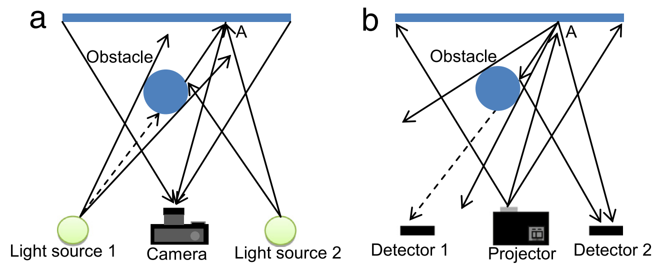

Fig. 1. Illustration of shadows occurrence in (a) conventional imaging and (b) single-pixel imaging.

differs from that in conventional imaging. It is necessary to investigate how shadows occur in single-pixel imaging.

In this paper, the principle of shadow occurrence in single-pixel imaging is investigated. Unlike conventional imaging, the field-of-view of single-pixel imaging is the same by single-pixel detectors with different locations. A simple and efficient computationally technique for shadow-free single-pixel imaging is proposed. Several spatially separated single-pixel detectors are used to obtain images where shadows are complementary to each other. We also use a method termed maximum selection rule [30]. A shadow-free image is obtained by fusing the shadow-complementary images using the maximum selection rule. The proposed technique is able to reconstruct shadow-free monochromatic and full-color images using single-pixel detectors.

2. Shadow occurrence and removal in single-pixel imaging

2.1. Shadow occurrence

Shadows will occur where the light is blocked. Different shadows can be categorized into penumbra and umbra [27]. Penumbra reduces brightness, contrast, and signal-to-noise of images. Umbra is an extreme case of penumbra, zeroing brightness, contrast, and signal-to-noise and making objects invisible. The spatial information in umbra is completely lost.

For conventional imaging, shadows are set by light sources and the field-of-view is determined by the camera. For single-pixel imaging, shadows are set by detection units (such as, photodiode) and the field-of-view is determined by illumination units (such as, spatial light modulators), which is subject to Helmholtz reciprocity [31]. According to the reciprocity, detectors in single-pixel imaging are equivalent to light sources in conventional imaging, and a projector for illumination in single-pixel imaging is equivalent to a camera in conventional imaging. The two setups shown in Fig. 1 are reciprocal to each other. The conventional imaging setup shown in Fig. 1(a), there are two light sources. Considering point A in the scene, the obstacle blocks the light from light source 1 and only the light from light source 2 can reach there. As a result, the reflective intensity from point A is weaker than elsewhere. Penumbra occurs at point A in the image captured by the camera. If light source 2 is removed from the scene, light cannot reach point A and therefore umbra will be caused. The single-pixel imaging setup shown in Fig. 1(b), there are two detectors and point A is under illumination by the projector. The backscattered light from point A can be detected by detector 2 while the obstacle blocks the light from point A to detector 1. Therefore, the reconstructed image by detector 1 in Fig. 1(b) is the same as the image captured by the camera in Fig. 1(a) when only light source 1 is presented. Umbra occurs at point A in the image. Similarly, the reconstructed image by detector 2 in Fig. 1(b) is the same as the image captured by the camera in Fig. 1(a) when only light source 2 is presented. Neither umbra nor penumbra occurs at point A.

Shadows in the reconstructed image by single-pixel imaging are set by the detectors. Such a feature of single-pixel imaging allows one to capture a scene and simultaneously derive multiple images each of which corresponds to a unique illumination.

2.2. Shadow removal

In conventional imaging, shadow-free images can be obtained by illuminating the object from different angles. Thus, according to Helmholtz reciprocity, a shadow-free image can be obtained by using multiple detectors in single-pixel imaging. The shadow profile in the reconstructed image is different from that in other images. As long as the shadows in all reconstructed images are complementary, the shadow-free image can be computationally derived by fusing the images.

Fig. 2 shows a setup with which we derive shadow-complementary images. As shown in the figure, the scene to be imaged is under structured illumination by the projector. Four spatially separated photodiodes (PD1, PD2, PD3, PD4) are set to collect the backscattered light from the scene. As the shading profile is determined by the position of the detectors, the reconstructed images share the same field-of-view and are shadow-complementary. Data acquisition board (DAQ) converts the PD signals to digits and feeds to a computer for reconstruction.

In our experiment, we conduct Fourier single-pixel imaging for object images acquisition [21]. Fourier single-pixel imaging allows one to reconstruct an image by projecting a sequence of Fourier basis patterns (also known as fringe patterns or sinusoidal patterns). The single-pixel detector collects the resultant back-scattered light intensities. The desired image is computationally reconstructed via an inverse Fourier transform. Each Fourier basis pattern is characterized by its spatial frequency $\left(f_x, f_y\right)$ and initial phase ϕ. The intensity of a sinusoidal fringe pattern is expressed as

$$P_\phi\left(x, y; f_x, f_y\right) = a + b \cdot \cos\left(2\pi f_x x + 2\pi f_y y + \phi\right), \tag{1}$$

where a is the mean intensity, b is the amplitude of sinusoidal, and (x, y) represents the 2D Cartesian coordinates in the scene. When a Fourier pattern P_ϕ is projected onto the object surface, the single-pixel detector collects the resultant back-scattered light intensity and results in the electrical signal D_ϕ:

$$D_\phi\left(f_x, f_y\right) = D_n + \beta \iint_\Omega R(x, y)\, P_\phi\left(x, y; f_x, f_y\right) dx\,dy, \tag{2}$$

where Ω denotes the illumination areas, $R(x, y)$ is the surface reflectance distribution function of the object in the scene, D_n is the response of environmental illumination, β is a scale factor whose value depends on the size and the location of the detector.

Fourier single-pixel imaging performs spiral scanning in the Fourier space. In other words, Fourier single-pixel imaging samples the coefficients in the Fourier spectrum along a spiral path. Each coefficient is acquired by projecting four Fourier basis patterns with the same spatial frequency $\left(f_x, f_y\right)$ and different initial phases ($\phi = 0, \pi/2, \pi, 3\pi/2$). The four patterns are denoted by P_0, $P_{\pi/2}$, P_π, $P_{3\pi/2}$ and the resultant electrical signals by D_0, $D_{\pi/2}$, D_π, $D_{3\pi/2}$. The Fourier coefficient, $\widetilde{I}\left(f_x, f_y\right)$, corresponding to spatial frequency $\left(f_x, f_y\right)$ is assembled by

$$\begin{aligned}\widetilde{I}\left(f_x, f_y\right) = &\left[D_0\left(f_x, f_y\right) - D_\pi\left(f_x, f_y\right)\right] \\ &+ \mathrm{j} \cdot \left[D_{\pi/2}\left(f_x, f_y\right) - D_{3\pi/2}\left(f_x, f_y\right)\right],\end{aligned} \tag{3}$$

where j denotes the imaginary unit. With the complete Fourier spectrum acquired, the object image is reconstructed by applying a 2-D inverse Fourier transform:

$$I(x, y) = F^{-1}\left\{\widetilde{I}\left(f_x, f_y\right)\right\}, \tag{4}$$

where F^{-1} denotes the inverse Fourier transform operator. The final reconstructed image $I(x, y)$ is acquired.

2.2.1. Integrated detector method

To simulate a shadow-free operation lamp, we can sum up the responses of all photodiodes. The summed response D_s is termed integrated response. The integrated response is obtained by

$$D_s = D_1 + D_2 + D_3 + D_4, \tag{5}$$

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