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Single-pixel imaging with high spectral and spatial resolution

MINGYUE SONG,[1] ZHAOHUA YANG,[1] PING LI,[1] ZIDONG ZHAO,[1] YING LIU,[1] YUANJIN YU,[2,*] AND LING-AN WU[3]

[1]School of Instrumentation and Optoelectronics Engineering, Beihang University, Beijing 100191, China
[2]School of Automation, Beijing Institute of Technology, Beijing 100081, China
[3]Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
*yuanjin.yu@bit.edu.cn

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It has long been a challenge to obtain high spectral and spatial resolution simultaneously for the field of measurement and detection. Here we present a measurement system based on single-pixel imaging with compressive sensing that can realize excellent spectral and spatial resolution at the same time, as well as data compression. Our method can achieve high spectral and spatial resolution, which is different from the mutually restrictive relationship between the two in traditional imaging. In our experiments, 301 spectral channels are obtained in the band of 420–780 nm with a spectral resolution of 1.2 nm and a spatial resolution of 1.11 mrad. A sampling rate of 12.5% for a 64 × 64 pixel image is obtained by using compressive sensing, which also reduces the measurement time; thus, high spectral and spatial resolution are realized simultaneously, even at a low sampling rate.

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1. INTRODUCTION

It is well known that, as a new computational imaging method, single-pixel imaging (SPI) has the important advantage of high sensitivity compared with traditional imaging methods [1–3]. It applies a series of two-dimensional (2-D) random speckle patterns or Hadamard matrices to illuminate the sample and, from multiple measurements of the reflected/transmitted light received by a bucket detector, obtains a corresponding series of light intensity values [4–7]. Through convolution of the bucket intensities with the 2-D illumination matrices, an image of the object can be reconstructed. Compared with traditional array detectors, the bucket detector has no spatial resolution, but can detect light under extremely low flux conditions [8].

However, SPI needs multiple measurements for image reconstruction, which leads to low time resolution and increases the imaging time [9–12]. Compressive sensing can realize sub-Nyquist sampling and has already been widely used in SPI to solve this problem [11,13–15] so that only a small amount of random measurement data is necessary to reconstruct high quality images, which greatly reduces the amount of computation and data storage required. Furthermore, the order of the Hadamard patterns can be optimized to reduce the redundancy of random measurements, further decreasing the sampling rate [16–18].

Spectral imaging can obtain 2-D spatial and one-dimensional (1-D) spectral information of an object simultaneously, and thus generate a three-dimensional (3-D) cube [19–22]. High spectral resolution is of great significance for precise object detection. To date, conventional hyperspectral imaging can achieve resolutions of <10 nm, but it is difficult to obtain both high spectral and spatial resolution at the same time [23,24]. Single-h (SPSI) provides a new way to solve this problem and systems based on spectral filtering, Fourier transform and grating splitting have emerged which can realize multispectral or hyperspectral imaging [19,25–30]. However, most of these only focus on spectral resolution and do not discuss the spatial resolution parameters.

In this paper, we designed a SPSI measurement system that can realize data compression and obtain good spectral and spatial resolution at the same time. The spectral bandwidth can be narrowed using data optimization, and the corresponding change in the spatial resolution is examined. The experimental results showed that, with a spectrometer of 1.2 nm spectral resolution, hyperspectral imaging could be realized with a spatial resolution of 1.11 mrad at a greatly reduced sampling rate of 12.5% for a 64 × 64 pixel image. Moreover, by using compressive sensing, this method greatly reduces the amount of data that has to be stored and transmitted.

2. PRINCIPLE

In our SPSI measurement system, the light reflected from an object is modulated by a digital micromirror device (DMD), which passes through the entrance slit of a spectrometer and,

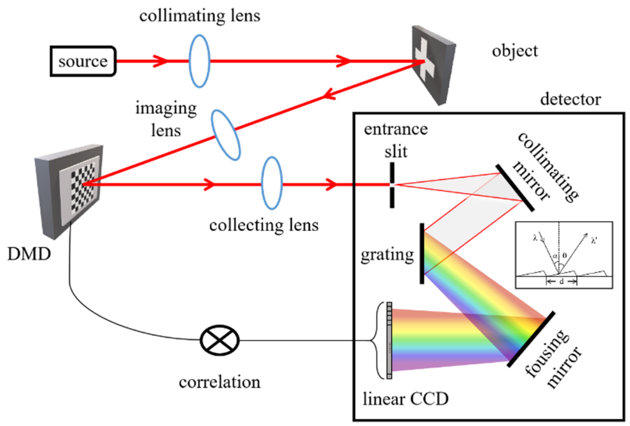

Fig. 1. Schematic diagram of the SPSI measurement system.

after multiple reflections, arrives at a grating where the different wavelengths are dispersed at different diffraction angles to be detected by a linear array detector CCD, as shown in Fig. 1. The SPSI measurement can be described by

$$Y = \Phi X, \tag{1}$$

where $Y \in \mathbb{R}^{M*L}$ represents the measurements; (M is the sampling number, and L is the number of spectral channels); $X \in \mathbb{R}^{N*L}$ represents the 3-D cube (N is the total number of pixels of a 2-D image); and $\Phi \in \mathbb{R}^{M*N}$ represents the measurement matrix projected by the DMD. To obtain Y, we require the light intensity values of the spectrum measured by the spectrometer, which is based on the following principle [31]:

$$\theta(\lambda) = \arcsin\left[\frac{m\lambda}{d} - \sin\alpha\right], \tag{2}$$

where θ is the grating diffraction angle, λ is the wavelength, d is the width of the grating grooves, α is the incident angle, and $m = 0, \pm 1, \pm 2, \cdots$ is the diffraction order. Therefore, for the same d and α, the dispersion angle $\theta(\lambda)$ varies nonlinearly with λ. The intensity detected by the CCD for a given wavelength can be expressed as [31]

$$I(\lambda) = S(\lambda) \cdot \varepsilon(\lambda) \cdot \tau_1 \cdot \tau_2 \cdot r(\lambda) \cdot \Phi_0(\lambda), \tag{3}$$

where $S(\lambda)$ is the detector sensitivity; $\varepsilon(\lambda)$ the absolute diffraction efficiency of the grating; τ_1 and τ_2 are the transmittance of the incident and exit slits, respectively; $r(\lambda)$ is the reflectivity of the collimating mirror of the spectrometer; and $\Phi_0(\lambda)$ is the incident light flux at wavelength λ. As can be seen from the above equation, $I(\lambda)$ is a nonlinear function of λ. In practice, the measured intensity $I(\lambda_i)$ actually covers a region of $\lambda_i \pm \Delta\lambda_i/2$ and, correspondingly, a spatial region of $\Delta\theta_i = \theta(\lambda_i + \Delta\lambda_i/2) - \theta(\lambda_i - \Delta\lambda_i/2)$. The limiting factor of the spectral resolution of modern spectrometers is the size of a CCD pixel, that is, the $\Delta\lambda$ corresponding to the $\Delta\theta$ covered by a single pixel. Since $\theta(\lambda)$ is nonlinear, but the pixel array is regularly spaced, correction must be made for the actual resolution at different wavelengths.

We perform piecewise linearization within each segment of the spectrum, as shown schematically in Fig. 2, where the colored curve is the effective response of the spectrometer. The solid black curves represent the actual intensities measured at λ_i and λ_{i+1} by two neighboring pixels. The bandwidths of each spectral section are not the same; that is, $\Delta\lambda_i \neq \Delta\lambda_{i+1}$, but $\Delta\lambda_i$ is very small, so we assume that the change within each spectral segment is linear, and the dashed lines are the linearized spectral response at wavelengths $\tilde{\lambda}_i$ and $\tilde{\lambda}_{i+1}$ separated by a width of $\Delta\tilde{\lambda}$, which is the linearized spectral resolution.

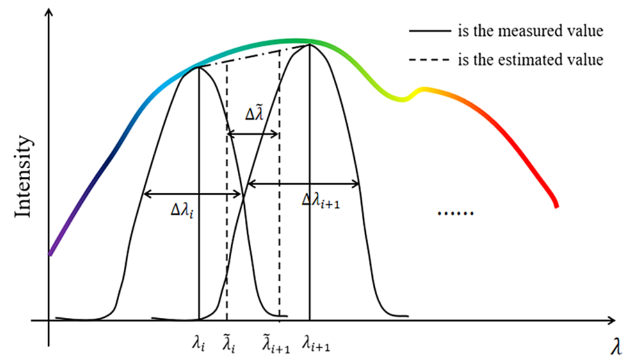

Fig. 2. Schematic diagram of piecewise linearization of the spectral response.

During the calculation, we take the sum of the values from $\tilde{\lambda}_i - \Delta\tilde{\lambda}/2$ to $\tilde{\lambda}_i + \Delta\tilde{\lambda}/2$ as the total light intensity at $\tilde{\lambda}_i$ as follows:

$$I(\tilde{\lambda}_i) = \int_{\tilde{\lambda}_i - \Delta\tilde{\lambda}/2}^{\tilde{\lambda}_i + \Delta\tilde{\lambda}/2} I(\lambda)\mathrm{d}\lambda. \tag{4}$$

Thus, the measurement matrix Y can be expressed as

$$Y = \begin{bmatrix} I_1(\tilde{\lambda}_1),\ I_2(\tilde{\lambda}_1),\ \cdots,\ I_M(\tilde{\lambda}_1) \\ I_1(\tilde{\lambda}_2),\ I_2(\tilde{\lambda}_2),\ \cdots,\ I_M(\tilde{\lambda}_2) \\ \vdots \\ I_1(\tilde{\lambda}_L),\ I_2(\tilde{\lambda}_L),\ \cdots,\ I_M(\tilde{\lambda}_L) \end{bmatrix}. \tag{5}$$

Even if we take a value of $\Delta\tilde{\lambda}$ smaller than the specified resolution of the spectrometer, our method can still reconstruct object images, demonstrating that our system can achieve higher spectral resolution digitally. In the subsequent experiments, we explore the value of $\Delta\tilde{\lambda}$ which can restore the image without distortion.

For a quantitative comparison of the quality of the images, we use the contrast-to-noise ratio (CNR), defined as [32]

$$R_{CN} = 10\log_{10}(\sigma_o/\sigma_b), \tag{6}$$

where $\sigma_o = \sum_{x_o} (T_o(x_o) - \overline{T_o})^2/P_o$ is the variance of the object, $T_o(x_o)$ is the gray value, $\overline{T_o}$ is the average gray value, and P_o is the number of pixels; $\sigma_b = \sum_{x_b} (T_b(x_b) - \overline{T_b})^2/P_b$ is the variance of the background, $T_b(x_b)$ is the gray value, $\overline{T_b}$ is the average gray value, and P_b is the number of pixels; x_o and x_b represent the pixel positions of the object and background, respectively.

3. EXPERIMENTAL SETUP

The experimental setup of SPSI is shown in Fig. 3. The beam from a supercontinuum laser source (LEUKOS ROCK 400,