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Invited Paper

Single-pixel complementary compressive sampling spectrometer

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ABSTRACT

A new type of compressive spectroscopy technique employing a complementary sampling strategy is reported. In a single sequence of spectral compressive sampling, positive and negative measurements are performed, in which sensing matrices with a complementary relationship are used. The restricted isometry property condition necessary for accurate recovery of compressive sampling theory is satisfied mathematically. Compared with the conventional single-pixel spectroscopy technique, the complementary compressive sampling strategy can achieve spectral recovery of considerably higher quality within a shorter sampling time. We also investigate the influence of the sampling ratio and integration time on the recovery quality.

1. Introduction

The spectrometer is one of the most versatile instruments available for the analysis of the attributes of matter, and this device is widely used in a variety of research fields such as chemistry [1], biology [2], and astronomy [3]. The majority of compact spectrometers are based on an optics dispersive component (prism or grating), in which the spectrum is generally measured by a linear detector array. A charge-coupled device (CCD) array is first selected at visible wavelength bands; the CCD is used because of its excellent performance at these bands, along with its low cost. However, at special situations of very weak sources using photomultiplier tube (PMT) detectors or of sources at infra-red (IR) wavelength bands using exotic detector materials, the array mode is less than suitable. This is because these detector arrays are extremely complex, bulky, and expensive.

Recently, Duarte et al. proposed a single-pixel camera setup [4,5] based on "compressive sampling" (CS) theory [6–8]. CS provides a new method of sampling signals, and allows imaging systems to use only a single-pixel detector to image a scene. Thus, the required size, complexity, and cost of the photon detector array can be reduced to that of a single unit, which enables the use of exotic detectors.

Many related CS applications have emerged in the fields of spectrometry [9] and spectral imaging [10–12]. In these applications, in order to realize spectral compressive sampling using linear optical elements, non-negative sensing matrices are adopted. However, these matrices do not satisfy the restricted isometry property (RIP) condition that is essential to ensuring CS robustness; this is not favorable to high-quality spectral recovery. This problem has been termed "the non-negativity problem" by some scholars [13], and Roummel et al. have proposed a method known as "mean subtraction" to overcome this issue [14]. However, in the proposed method, the mean is estimated with relatively poor accuracy. Therefore, the mean subtraction method does not essentially improve the CS reconstruction quality.

Using the previously proposed single-pixel camera structure as a basis, we design a new single-pixel spectrometer. In our design, we use the complementary compressive sampling strategy [15] to solve the non-negativity problem. With this optical structure, the complementary compressive sampling strategy achieves significantly higher-quality spectral recovery than other methods within a shorter sampling time. This paper is structured as follows. In Sections 2 and 3, the CS theory and its application to signal reconstruction are respectively explained. The proposed experimental setup is described in Section 4, and the results of evaluation experiments are presented in Section 5. In Section 6, certain aspects of the findings are discussed, while the conclusions are

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given in Section 7.

2. Compressive sampling theory

CS does not measure signal elements directly, but instead measures the inner products of the signal and a set of test functions named sensing matrices. We take x (a length-n column vector) as an original signal and A as an $m \times n$ ($m < n$) matrix. Then, A can project x on an m-dimensional set of observations y, such that

$$y = Ax + e, \tag{1}$$

where e is noise. As $m < n$, this is generally an ill-posed problem with an infinite number of possible candidate solutions. Nevertheless, CS theory provides a set of conditions restricting A, x and e. If these conditions are satisfied, accurate reconstruction can be achieved by solving a simple convex optimization problem 13. First, x is required to be sparse or compressible under a certain basis. Second, A must satisfy the RIP. For example, if the entries of A are independent and identically distributed according to

$$A_{i,j} = \begin{cases} m^{-1/2} & \text{with probability } 1/2 \\ -m^{-1/2} & \text{with probability } 1/2 \end{cases}, \tag{2}$$

then A has a high possibility of satisfying RIP [6–8]. Third, e must be zero or bounded, so the spectrometer must be designed such that the minimum possible e is obtained (note that increasing the integer time is an effective method of reducing e).

3. Improving reconstruction performance using complementary measurement

Pseudorandom sensing matrices such as those described in Section 2, which satisfy the RIP, provide theoretical guarantees regarding the reconstruction accuracy in the presence of Gaussian or bounded noise. However, approximately half of the elements in these matrices are negative, and it is impossible to construct such a system using linear optical elements. The digital micro-mirror device (DMD) is one such optical element, which is often used to modulate light [10,12]. The DMD consists of a number of micro-mirrors, and each micro-mirror rotates about a hinge and can be independently actuated to two positions oriented at $+12°$ (according to 1 in binary matrix) or $-12°$ (according to 0); thus, light falling on the DMD may be reflected in two directions depending on the mirror orientation. Matrices fed into the DMD must be non-negative, for example, pseudorandom 0/1 binary matrices with 0.5 mean. Although non-negative matrices are physically realizable, such observations cannot be used directly to realize accurate CS recovery.

In this paper, we adopt a complementary measurement method to address the non-negativity problem. In this method, two complementary measurements are performed in a single CS reconstruction. We suppose that A_+ and A_- are two pseudorandom 0/1 binary matrices with 0.5 mean, and their elements satisfy the relationship

$$A_+(i,j) = 1 - A_-(i,j), \tag{3}$$

i.e., A_+ and A_- are complementary matrices. Then, we obtain two measurement results y_+ and y_- for A_+ and A_- respectively, where

$$y_+ = A_+x + e_+, \tag{4}$$

$$y_- = A_-x + e_-, \tag{5}$$

by subtracting Eq. (5) from Eq. (4), we obtain the complementary differential measurement result y_d:

$$y_d = y_+ - y_- = (A_+ - A_-)x + (e_+ - e_-) = A_dx + e_d. \tag{6}$$

Here, A_d is a pseudorandom $-1/1$ binary matrix with zero mean, i.e., A_d completely satisfies the RIP condition and has the same distribution as A_+, except -1 takes the place of 0. Thus, by solving Eq. (6) using an appropriate CS algorithm, we can, in theory, realize accurate signal reconstruction. It is possible to reconstruct x by solving the optimization problem

$$\min_x \frac{1}{2}\|y_d - A_dx\|_2^2 + \tau\|x\|_1 \tag{7}$$

where τ is a constant scalar and $\|\ldots\|_p$ represents the l_p norm, defined as $(\|x\|_p)^p = \sum_{i=1}^n |x_i|^p$.

4. Experimental setup

A schematic diagram of the experimental setup is given in Fig. 1. Here, Optical source is focused and passes through a slit entrance, which is then collimated by the L1 lens. The collimated light is dispersed by a fixed diffraction gating along different angles in space according to its wavelength. Under the influence of the L2 lens, the spectrum is imaged onto the DMD. We employ a Texas Instruments (TI) DMD which consists of 1024 × 768 micromirrors, each of which is 13.68 × 13.68 μm in size. As the spectral image is a one-dimensional signal, we treat each DMD column as one unit. This means that the spectral signal x is separated into 1024 spectrum bands (n=1024). When the DMD columns are rotated according to the pseudorandom 0/1 sensing matrix that is fed into the device, randomly selected parts of x are deflected by $+12°$ and collected by L3 lens. The total intensity of the selected light is measured by a single PMT detector after it passes through L3.

In Fig. 1, the slit width is 100 μm, and the focal lengths of L0, L1, L2, and L3 are 30, 30, 100, and 50.8 mm, respectively. The gating is produced by the Thorlabs Company, and has a 500 nm blazing wavelength, with 1800 lines per mm. The angle of incidence of the light on the grating is 60°. Theoretically, the average optical spectral resolution is approximately 0.92 nm. The PMT is of photon-counting type, and is produced by the Hamamatsu Company.

Note that we employ a one-arm-detector structure in our experiment, i.e., only the light deflected by the $+12°$ direction of the DMD is measured by the PMT. Thus the light deflected by $-12°$ is discarded. If we perform a positive measurement, the light deflected by $-12°$ corresponds to a negative measurement.

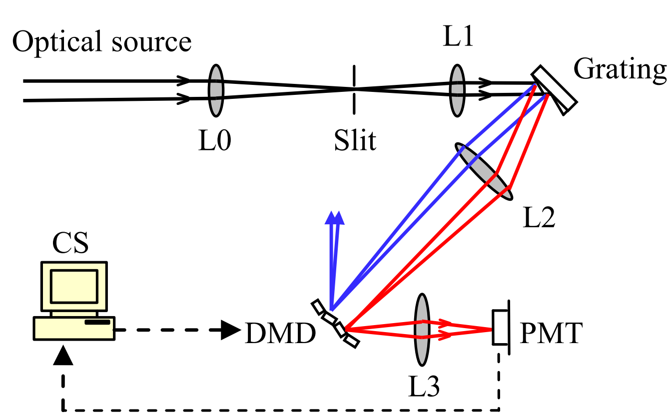

Fig. 1. Experimental setup for spectral complementary compressive sampling (CS). The distance from L1 to the slit is 30 mm (the L1 focal length). The distance from L2 to the DMD is 100 mm (the L2 focal length).