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Digital micro-mirror device based multispectral imaging using compressed Fourier spectrum

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ABSTRACT

In this paper, a multispectral imaging method using compressed Fourier spectrum is introduced. It has similar optical architecture with the Hadamard Transform Spectral Imaging (HTSI) method, but needs less number of measurements for multispectral image reconstruction. The key is encoding the spectra by sinusoid coding patterns generated by Digital Micro-mirror Device (DMD). Sinusoid patterns transform the spectra into Fourier domain. The multispectral images can be reconstructed using finite Fourier coefficients by Inverse Fourier Transform (IFT). A testbed is built and two sets of experiments are conducted. The experiment results show that, about 10% of Fourier coefficients would be able to reconstruct the multispectral images well, and the number of measurements is about 80% less than that of the HTSI. Additionally, the presented method provides an alternative way to realize Fourier Transform Spectral Imaging (FTSI) by use of grating and DMD, distinguished from the interferometer-based FTSI and the sinusoid filter-based FTSI.

1. Introduction

Multispectral imaging gives both 2D spatial and 1D spectral information of an object or a scene and is useful for many applications such as color pattern identification and biomarker detection. There have been a variety of methods to compute multispectral images from 2D image. Scanning methods based on multi-shots are often used, such as the spatial scanning method [1], the spectral scanning method [2], the time-scanning Fourier interferometer [3,4], and the pattern-scanning Hadamard Transform Spectral Imaging (HTSI) [5–7], and so on. These methods are essentially taken different tradeoffs among the light collection, the spatial resolution, the spectral resolution and the measurement time. The HTSI, for example, is a multiplexing method that has the advantage of high throughput and high signal to noise ratio (SNR). However, to get spectral images with K wavebands, it needs K measurements under K Hadamard coding patterns, respectively, which is time-consuming. Recent years, the Digital Micro-mirror Device (DMD) [5–7] is used for building the Hadamard coding patterns instead of the mechanical patterns. Due to the programmable characteristic of DMD, the pattern switching speed of HTSI is significantly increased, but it is still critical to reduce the number of measurements for rapid multispectral imaging.

In this paper, we present a DMD-based multispectral imaging method using compressed Fourier spectrum. It combines the multiplexing feature of HTSI and the compressive feature of Fourier transform, thus providing an efficient way for multispectral imaging. On one hand, the proposed method has the similar architecture with HTSI [5–7], where DMD is used for spectra encoding and dual gratings are used for spectral dispersion and recombination. On the other hand, sinusoid patterns are generated by DMD instead of the Hadamard patterns. The spectra are encoded by sinusoid functions with different harmonic orders and transformed to the Fourier domain. As the spectral information is usually sparse in Fourier domain, only a small number of Fourier coefficients can ensure a faithful reconstruction of multispectral images by Inverse Fourier Transform (IFT). That means, the number of measurements based on sinusoid patterns can be reduced compared with conventional HTSI.

The proposed method also provides a new and alternative way for Fourier Transform Spectral Imaging (FTSI). In the classical FTSI [3], a Michelson interferometer is used to transform the spectrum (denoted by wavenumber) into the Fourier domain, i.e., the interferogram. A series of optical path differences generated by the moving mirror represent the harmonic orders for Fourier transform. The interferometer-based FTSI

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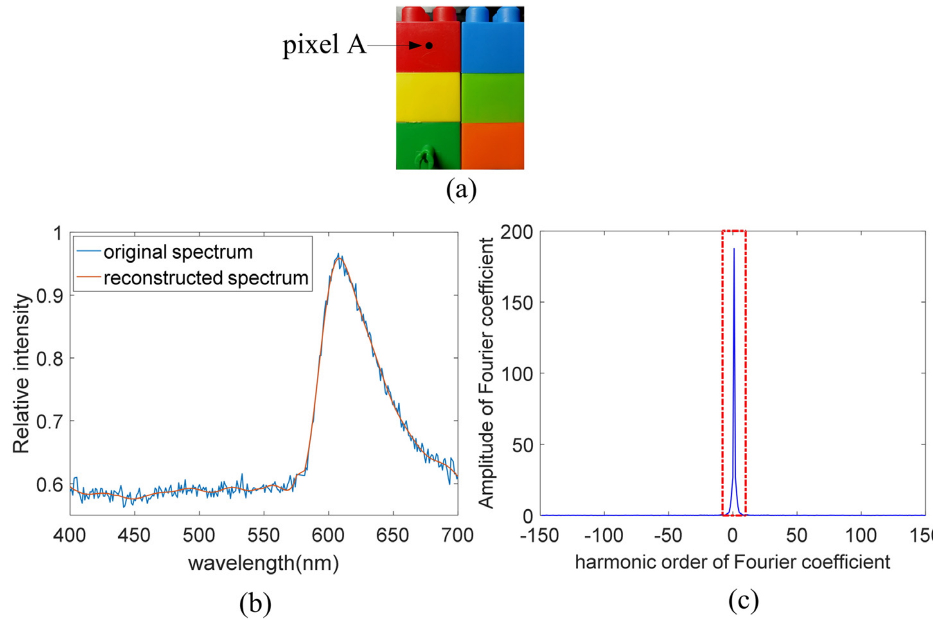

Fig. 1. Illustration of the method, (a) pixel A of an object; (b) The original spectrum and the reconstructed spectrum using the center part of the Fourier coefficients marked in red in Fig. 1(c) (i.e., the compressed Fourier spectrum); (c) The Fourier coefficients of the original spectrum of pixel A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Nomenclature

- $\left[I_{mn}\left(\lambda_r\right)\right]_{r=0}^{K-1}$: the spectrum for pixel (*m, n*), a sequence; λ_r indicates waveband, $r = 0, 1, \ldots, K-1$; each element $I_{mn}\left(\lambda_r\right)$ represents the spectral intensity at λ_r for pixel (*m, n*);
- $\left\{I_{mn}\left(\lambda_r\right)\right\}$: the datacube, a three dimensional matrix; $m = 1, 2, \ldots, M$; $n = 1, 2, \ldots, M$; $r = 0, 1, \ldots, K-1$;
- $T_{mn}(k, \varphi, r)$: the sinusoid coding pattern generated by DMD for the spectrum of pixel (*m, n*); $k = 0, 1, \ldots, K-1$ is the harmonic order to index the Fourier coefficients; $\varphi = 0, \pi/2$ is the initial phase;
- $D_{mn}(k, \varphi)$: the detected intensity of pixel (*m, n*) using the coding pattern$T_{mn}(k, \varphi)$;
- $P_{mn}(k)$: the Fourier coefficient of the *k*-order harmonic for pixel (*m, n*), including rear part and imaginary part;
- F^{-1}: the inverse Fourier transform (IFT);
- K: the number of wavebands for spectral imaging, and also the number of Fourier coefficients in the Fourier domain;
- $\boldsymbol{R}$: the number of Fourier coefficients used for reconstruction.

has high spatial resolution and high throughput, but the requirement of precise moving components typically increases the complexity and decreases the reliability of the system. The sinusoid transmission filter arrays [8–10] are developed to realize FTSI instead of the interferometer. A group of filters with sinusoid transmittance at wavenumber range are designed and fabricated, and then the Fourier coefficients of different harmonic orders can be obtained by filter switching. The structure of the sinusoid filter-based FTSI system is simple and not sensitive to vibration, which gives inspiration to us. In this paper, the proposed method replaces the sinusoid filters with DMD and gratings. The presented system is more complicated, but it is more flexible to get varying Fourier coefficients through programming the DMD coding patterns.

The rest of the paper is organized as follows. Section 2 presents the principle, including the encoding and reconstruction process. Section 3 shows a simulation example. Section 4 presents the experimental setup and the experiment results. Section 5 gives some discussions. Finally, Section 6 contains conclusions.

2. The principle

2.1. Pixel spectrum, compressed Fourier spectrum

Usually, much natural information is sparse in Fourier domain and mainly concentrates at the low frequency. Prior work [8–10] has proved that only a few sampling can preserve the spectrum feature, like the emission, transmission or absorption peaks, in Fourier domain. Let us consider a simple example. Fig. 1 shows the spectrum and the Fourier Transform of it for a given pixel, “A”, on a Lego block. Fig. 1(a) shows the pixel position on the Lego block. In Fig. 1(b), the blue color curve represents its spectrum, denoted by wavelength. Fig. 1(c) shows the Fourier coefficients computed using Fast Fourier Transform (FFT) with a shift to the center. It is seen that the red box in the center contains most of the information and thus, can be used as the compressed Fourier spectrum to rebuild the spectral curve of “A”. Fig. 1(b) compares the original pixel spectrum and the reconstructed spectrum. It is seen that the reconstructed spectrum is almost the same as the original spectrum. This demonstrates that we can use selected Fourier coefficients to rebuild the spectrum, which reduce the number of measurements without losing effective information.

2.2. Reconstruct multispectral images using compressed Fourier spectrum

Fig. 2 gives the schematics of our multispectral imaging system. It is the same as the dual-disperser HTSI system [5–7]. First, Grating 1 disperses the object light to a serial of wavebands. The dispersed spectral images are focused on DMD. Then, the DMD generates a coding sinusoid pattern and encodes the spectra. Next, Grating 2 recombines the wavebands, forming a spectrally encoded image. Finally, the image is captured by a CCD camera for processing. The dual-gratings system is firstly proposed in the windowing spectral imager [11] which has a slit. In our system, DMD is used instead of the slit. On the DMD plane, the

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