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Metasurface-based Single-pixel Hyperspectral Imaging

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Abstract: We present a lightweight, filter-based single-pixel hyperspectral imaging system enabled by metasurface and deep learning, achieving high spectral reconstruction fidelity even at low sampling ratios.

1. Introduction

Hyperspectral imaging (HSI) provides rich spatial and spectral information, enabling detailed material identification across a wide range of applications, from biomedical sensing to environmental monitoring. However, traditional HSI systems are typically bulky and expensive, and their performance often degrades significantly under low-light conditions [1]. To address these issues, single-pixel HSI has gained attention by reconstructing hyperspectral datacubes from compressed measurements using a single broadband detector [2].

Nevertheless, conventional single-pixel hyperspectral systems still depend on dispersive optics or narrowband filter wheels, which remain limited by low acquisition speed and poor scalability [3]. In fact, the spectral dimension of natural scenes often exhibits strong redundancy, making it amenable to compressive sensing. This opens the door to using a small number of broadband spectral filters to encode the scene, followed by computational reconstruction. Metasurfaces, with their ability to manipulate light across multiple dimensions via engineered nanostructures, provide a powerful platform for implementing such filters [4]. In this work, we design a metasurface-based filter wheel and integrate it with a deep learning framework to recover high-fidelity hyperspectral information from compressed measurements, enabling a compact and efficient single-pixel HSI system.

2. Method

The single-pixel HSI system can be mathematically modeled as a linear measurement process:

$$\mathbf{Y} = \mathbf{AXB} + \mathbf{n}, \tag{1}$$

where $\mathbf{X} \in \mathbb{R}^{p \times q}$ represents the reshaped hyperspectral datacube, with p denoting the spectral dimension and q the flattened spatial dimension. $\mathbf{A} \in \mathbb{R}^{m \times p}$ is the spectral modulation matrix, constructed from the spectral responses of m distinct metasurface-based broadband filters. $\mathbf{B} \in \mathbb{R}^{q \times n}$ is the spatial modulation matrix composed of n predefined spatial patterns. $\mathbf{Y} \in \mathbb{R}^{m \times n}$ is the compressed measurement matrix, and $\mathbf{n}$ denotes additive measurement noise.

We employ a 220 nm-thick monocrystalline silicon layer as the functional material on a quartz substrate. Each unit cell, with a period of 700 nm, is discretized into a 7×7 grid of squares, where the binary etching state (etched

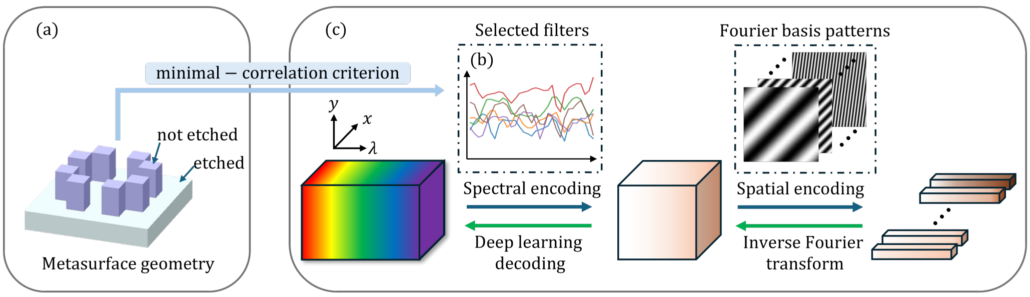

Fig. 1. This diagram illustrates (a) the approach for generating metasurface geometries, (b) the selected 6 filters via minimal-correlation criterion, and (c) the sensing and reconstruction scheme of the proposed single-pixel HSI system.

or unetched) of each square defines the metasurface geometry, as illustrated in Fig. 1(a). Using finite-difference time-domain simulations, we compute the spectral response functions of all candidate structures and select 6 filters based on a minimal-correlation criterion, as illustrated in Fig. 1(b). These spectral response functions are then used to compose the spectral modulation matrix, while Fourier basis patterns serve as the spatial modulation matrix.

A Divide-and-Conquer strategy is implemented to reconstruct the hyperspectral datacube from compressed single-pixel measurements. Initially, the four-step phase-shifting method recovers the Fourier coefficients for each spectrally encoded channel, and an inverse 2D Fourier transform is then applied to generate a set of grayscale images, each corresponding to a distinct spectral filter's encoding.

To reconstruct the full spectral content, we employ a deep convolutional neural network (CNN) as a spectral decoder. The network is trained in a supervised manner to map the grayscale-filtered images back to the corresponding hyperspectral datacube. Once trained, the CNN effectively learns to invert the spectral encoding imposed by the metasurface responses and recover the high-dimensional spectral profiles from a limited number of grayscale measurements, enabling accurate and robust hyperspectral reconstruction. The complete encoding and decoding process of the system is illustrated in Fig. 1(c).

We use the ICVL hyperspectral dataset and extract image patches of size $64 \times 64 \times 31$ (height $\times$ width $\times$ spectral bands). The spectral compression ratio (CR) is $6/31 \approx 19.4\%$. For spatial modulation, a CR of 50% is adopted to construct the spatial modulation matrix. Thus, the overall CR is the product of the spectral and spatial CRs, yielding a total CR of approximately 9.7%. To better simulate real-world conditions, additive white Gaussian noise is introduced to the measurement process.

3. Result

Under a challenging CR of only 9.7%, our proposed single-pixel HSI system achieves remarkable reconstruction performance on the ICVL test set, with a peak signal-to-noise ratio (PSNR) of 25.54 dB and a structural similarity index measure (SSIM) of 0.7967. Two randomly selected samples are shown in Fig. 2. To display all spectral bands simultaneously, we convert the hyperspectral images to an RGB representation via the CIE color-matching function. The RGB images of the ground truth and the reconstruction match excellently, as further evidenced by the spatial MSE map and the comparison at a selected spatial location. These results confirm that our method effectively recovers high-fidelity hyperspectral datacubes from extremely limited measurements.

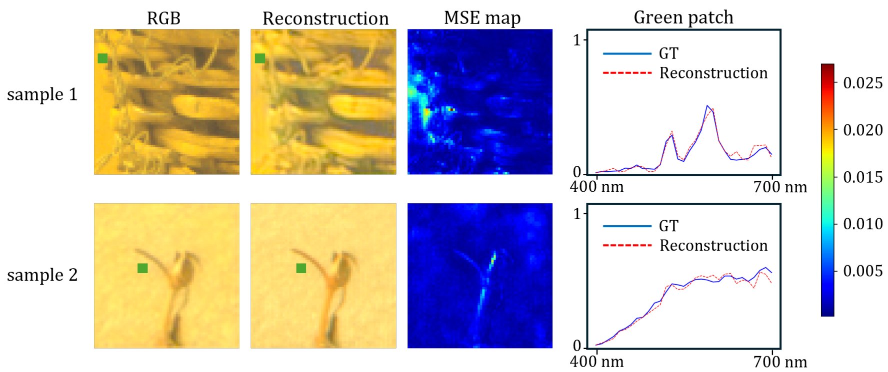

Fig. 2. Two samples using the proposed single-pixel HSI system showing the reconstruction in RGB format, MSE map, and selected patch reconstructions.

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