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A snapshot light field imaging spectrometer

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ABSTRACT

A light field camera can capture 2D spatial and 2D angular information of light rays from a scene and re-distributes the 4D information on a 2D detector array. The spectrum information can be coupled with angular dimension by placing a spectral filter at the aperture of a light field camera. This construction is a snapshot imaging spectrometer based on light field imaging technology. In this paper, a snapshot light field imaging spectrometer based on a microlens-array is proposed. The principles of system design and discussions of system-tradeoffs are presented. The analysis of diffraction-limited resolution and optical efficiency shows that a mirolens-array based camera is preferred over a pinhole-array based camera for designing a snapshot imaging spectrometer. A prototype and preliminary experimental results are demonstrated.

1. Introduction

Imaging spectrometers collect 2D spatial (x, y) and 1D spectral (λ) information of a scene, and form a spatial-spectral datacube in (x, y, λ) dimensions. Most conventional imaging spectrometers can only obtain 2D information of the 3D datacube in a single frame [1–5]. A form of temporal scanning process in either a spatial dimension or the spectral dimension is required to fill the datacube. The scanning artifacts increase the complexity of the systems and limit the applications of the instruments. Researchers are now focusing on eliminating the scanning parts and developing "snapshot" imaging spectrometers which capture the datacube in a single shot. Several snapshot imaging spectrometers have been developed, such as the coded aperture snapshot spectral imaging (CASSI) presented by Gehm et al. [6], and the computed tomography imaging spectrometer (CTIS) proposed by Descour [7].

Recently, light field imaging has emerged as a new technology [8], which can capture 2D spatial and 2D angular information of light rays from a scene and re-distributes the 4D information on a 2D detector array in a single frame. The research and developments of light field cameras were first associated with digital reconstruction of the captured light field, such as digital refocusing, depth estimation, 3D reconstruction and non-chromatic correction [8–10].

Later on, Horstmeyer et al. placed an array of filters to divide the objective aperture of a light field structure for modulating the spectrum, polarization state, or intensity of the light rays in a single shot [11]. Then, Horstmeyer et al. implemented a continuously variable spectral filter to form a multispectral imager [12]. This design eliminated the scanning parts for spectral imaging and achieved the "snapshot" of the spatial-spectral datacube for a scene. However, Horstmeyer et al.'s design employed a pinhole-lens array which offers much less optical efficiency and worse resolution comparing to a lenslet array. Later, Zhou et al. proposed another conceptual design of a light field imaging spectrometer using a microlens array [13]. In this paper, we present a snapshot spectrometer based on Zhou et al.'s concept by using a linear variable filter (LVF) as the filter. The principle of a light field imaging spectrometer is briefly introduced, followed by analysis of the system design and spectral-spatial tradeoff for the presented spectrometer. The diffraction-limited resolution and optical efficiency of a microlens and a pinhole are discussed and compared. A prototype snapshot light field imaging spectrometer is built and preliminary experimental results are presented to demonstrate the snapshot of spatial-spectral datacube.

2. Principle of a light field imaging spectrometer

The schematic of a light field imaging spectrometer based on a light field imaging camera is shown in Fig. 1. The camera field lens is

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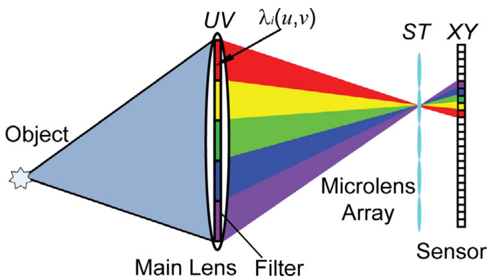

Fig. 1. Schematic of the proposed imaging spectrometer.

simplified as an ideal main lens at (u, v) plane, and a microlens array is placed at (s, t) plane as the diffusing element. A 2D filter array, consisting of a number of spectral filters at different wavelengths, is placed at the pupil aperture of the main lens and imaged onto the sensor by each microlens to form a sub-image.

In a 1D system, as shown in Fig. 2(a), a pixel image $I(u, s)$ of a sub-image corresponds to a sub-aperture (u) on the main lens aperture, while a sub-aperture (u) corresponds to a narrow-band wavelength filter $\lambda(u)$. Therefore, a pixel image becomes $I(\lambda(u), s)$, and the spectral image at given wavelength can be abstracted as shown in Fig. 2(b). Expanding the system to 2D, a pixel image corresponds to $I(\lambda(u, v), s, t)$ and a three-dimension spatial-spectral datacube can be formed with a set of $I(\lambda(u, v), s, t)$. In other words, corresponding pixels under each microlens form a spectral image $\Sigma_t \Sigma_s I(\lambda_i(u, v), s, t)$ of the object through the corresponding sub-aperture of the main lens. The entire raw image on the sensor is then considered as a redistribution of $N \times N$ sub-aperture images at different wavelength, where N is the number of pixels covered by each microlens in one direction. If each sub-aperture corresponds to a narrow-band filter at a specific wavelength, $N \times N$ different spectral images can be extracted.

Hence, a light field imaging camera with a spectral filter array captures and redistributes the set of $I(\lambda(u, v), s, t)$ data in a single shot without scanning. Therefore, the proposed system is called a snapshot light field imaging spectrometer. It is very clear

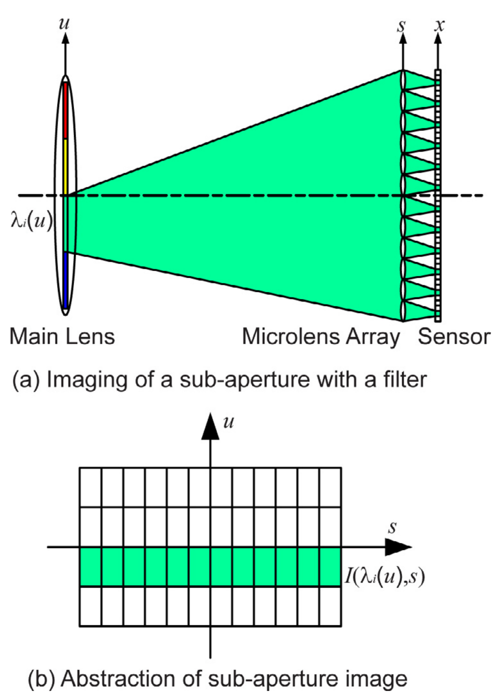

Fig. 2. 1D illustration of coupling the spectral information with the sub-aperture of a light field imaging camera.

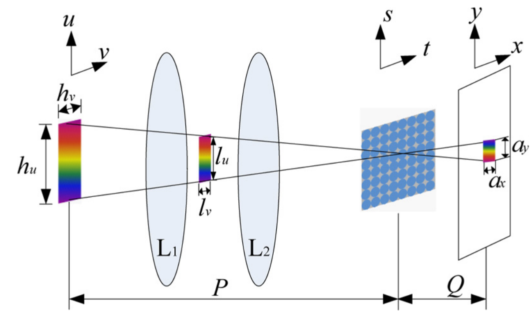

Fig. 3. Setup diagram of the imaging spectrometer.

that designing a snapshot spectrometer based light field imaging includes two important parts: 1. designing a light field imaging camera, 2. selecting a spectral filter array.

3. System design and tradeoff

3.1. System design

In this section, the system design and tradeoffs associated with the proposed light field image spectrometer are addressed. A light field imaging camera using a microlens array was built for this research and will be given in Section 5. Detailed description of designing this type of camera can be found in the work Ng et al. [8]. Our design also followed several principles established by Ng et al. including: 1. matching the f-number of the main lens and that of microlens, 2. placing the sensor at the back focal plane of the microlens. The first principle allows maximum utilization of the senor pixels, while the second principle maximizes the directional resolution of the system.

For a light field imaging camera, the diffusing element, such as a microlens array, is a critical component which determines the spatial and angular resolution of the system. In this research, the microlenses were designed as a circle and arranged into a square array. Assuming the sensor size is (W_x, W_y) and the microlenses have a diameter d, the spatial resolution of the camera is given by $(W_x/d, W_y/d)$ based on the analysis of Ng et al. [8]. If the pixel size of the sensor was Δx_p, the maximum angular resolution is given by $d/\Delta x_p$.

An ideal imaging spectrometer with maximum spectral resolution can be achieved by designing a filter array with each narrow-band filter corresponding to one pixel covered by a microlens. However, the mechanical misalignment and the effects of physical optics will cause the imaging overlap and spectral mixture between adjacent pixels. In this research, we only use one linear variable filter (LVF) as a filter for proof-of-concept demonstration and spatial-spectral tradeoff analysis.

Fig. 3 shows the simplified diagram of the snapshot spectrometer. Similar to Horstmeyer's design [11,12], a size (l_v, l_u) LVF is placed at the aperture stop which is located within the compound lens system of a conventional camera lens. The lens system is simplified to lenses L_1 and L_2 as shown in Fig. 3. A image of the LVF at the u-v plane is re-imaged onto the sensor by each microlens. The size (h_v, h_u) of the LVF image and distance P can be measured by experiments or determined by using system parameters. For a microlens array based light field imaging system, Q is equal to the focal length f of the microlens. Then, the microlens image sizes of the LVF along x and y directions are given by:

$$(a_x, a_y) = \frac{f}{P}(h_v, h_u) = \frac{f}{P}\frac{1}{M_2}(l_v, l_u) \quad (1)$$

where, M_2 is the magnification between the virtual image and actual size of the filter. As shown in Fig. 3, the length h_v is