Multi-Dimensional Hyperspectral Imaging System

David Mendlovic and Ariel Raz
Department of Physical Electronics, Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel
mend@eng.tau.ac.il , arielraz@post.tau.ac.il

***Abstract*—Common Silicon-based imaging systems allow acquisition of spectral and/or depth information by paying a significant penalty in resolution. Computational cameras, however, reduce this penalty by applying compressed sensing techniques but require modified optical hardware and rely on preliminary knowledge. This article presents a new concept for imaging system that enables color imaging and hyperspectral imaging by both multiplexing and compressed sensing approaches.**

I. INTRODUCTION

The industry standard for color imaging utilizes a color filter array (CFA), placed in front of a monochrome image sensor [1]. Introduced by Bayer, this technique allows trading off color information with spatial resolution, as each pixel acquires a single color component (red, green or blue) followed by color interpolation [2]. Multiple variants for the standard Bayer CFA have been developed over the years but the basic pattern prevailed in many commercial grade cameras. In the past few years, the image quality of such cameras has been improved by reducing the pixel pitch and improving the image processing capabilities. Today, however, the pixel pitch has reached the diffraction limit and the CFA bottlenecks the resolution. Moreover, small pixel pitch results in poor noise performance which worsens in low light conditions.

Recently, the sequential filtering scheme [3] has been proposed as a possible direction for improving image quality. This scheme requires a fast and tunable color filter for acquire consecutive frames, each of which at a different color. This approach offers ×4 resolution over conventional Bayer CFA sensors. Moreover, in case the tunable filter is capable of transmitting white spectrum, these panchromatic frames could be used for improving the noise characteristics of color frames [4].

Such a color filter could be realized via a Fabry-Perot interferometer (FPI), which is an interference based spectral filter. FPIs have been used for spectral filtering [5], optimized per application in terms of spectral tuning range and spectral band-pass (FWHM). This approach of fine filtering is not suitable for imaging as many exposures would be needed to accurately reconstruct colors, each of which with low light efficiency. Our approach, however, utilizes a counter intuitive approach of coarse spectral filtering (low finesse FPI) and very few exposures.

In this project we combine the FPI based camera with multi-dimensional detection capabilities. This achievement allows both color imaging and hyperspectral (HS) imaging by enabling both spatial-spectral multiplexing and compressed sensing approaches in one apparatus.

II. PROPOSED APPROACH

A scene could be completely described by the Plenoptic function, including 3D position, light rays directions, spectral content and time dependence [6]. Standard cameras incorporate image sensor that on top of using Bayer-based CFAs, utilize a rolling shutter sampling scheme that permits sampling only within a spatio-temporal parallelogram. Moreover, as common cameras include lens modules that tend to maximize the amount of incident light and MTF and minimize optical aberrations, the angular information is disregarded. In sum, most of the information is lost.

Other imaging systems allow multiplexing of either spectral, depth or temporal information with spatio-temporal resolution. Pushbroom and whiskbroom HS imagers require multiple exposures and the overall spectral resolution equals the number of exposures. Improved frame rate, for example, could be achieved by adjusting the shutter address generator and reading out interlaced rows [7]. The frame rate improvement ratio equals the vertical resolution degradation ratio. Similarly, depth and spectral information could be obtained by incorporating suitable multiplexers, such as lenslet array [8] and dispersive lenslet array [9], respectively. Overall, the multiplexer shifts degrees of freedom between the dimensions of the Plenoptic function.

Another kind of imaging systems rely on compressed sensing techniques for reducing the spatial/temporal resolution degradation ratio. For example, HS snapshot imagers may include some variant of coded apertures [10]-[11]. Another realization may include coded shutter techniques for obtaining a blur-free image [7].

The latter two types of imaging systems lack flexibility as both multiplexers and coded apertures are fixed optical hardware that cannot be tuned per application. These imaging systems would be optimized per specific application (e.g., spectral snapshot acquisition) but would provide sub optimal performance for different use cases (i.e., low light efficiency) when a scene is very different from the image set.

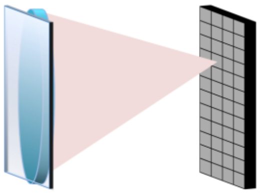

Fig. 1. Tunable etalon in front of the imaging system

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The apparatus, as seen in Fig. 1, includes a monochrome image sensor, an imaging lens (or lens module), an image processing unit and a tunable low finesse FPI. Its tuning is obtained by varying between the mirrors. As the FPI is dispersive, its spectral transmission curve depends on the angle of incidence. Per this apparatus, (FPI in front of the lens), the actual spectral transmission curve is a weighted average of ray angles within the field of view. This effect results in color inconstancy across the sensor and could be compensated for by using telecentric lens or by applying color correction (within the image processor).

This effect, however, provides much more spectral information compared to standard CFAs. Specifically, each pixel acquires a slightly different spectral projection of the imaged scene. The magnitude of these differences is determined by the filter and lens properties, as well as the physical configuration.

III. IMAGING MODES

A. *Color Imaging*

Sequential color filtering is described in [3]. In case the imaging lens module in non-telecentric, color correction must be applied as a part of the image post processing. Such scheme improves both resolution and noise performance.

B. *Spatial-spectral multiplexing*

Rolling shutter image sensors allow sampling only within a spatial-temporal parallelogram that is defined by the sensor properties and exposure duration. Several recent works have shown some advantages of using coded-shutter schemes. However, utilizing standard interlaced readout mode, together with a fast enough tunable color filter is sufficient for spatial-spectral multiplexing. For an image sensor of M rows and a K-mode spectral filter, a HS cube of K spectral bands and M/K rows could be acquired (the number of columns is unchanged). This is achieved by switching the spectral filter K times during the exposure time (synced with the first row of each sub-image). Furthermore, per sub-image, the frame rate is also accelerated.

C. *Compressed Imaging*

The configuration in Fig. 1 further allows HS snapshot acquisition by utilizing the spectral-angular coupling [12]. The underlying assumption is that adjacent points within imaged objects share the spectral content (up to a gain coefficient due to lighting variations).

Standard spatial-spectral multiplexing techniques are pre-configured to for a constant number of spectral bands which is the spatial resolution degradation factor. For example, a HS imager of 16 spectral bands and 5 MP sensor results in approx. VGA resolution per spectral band. The suggested scheme, on the other hands, offers flexibility in the number of spectral bands per application. Consequently, this type of imager could be used for HS cube acquisition with several different spectral resolutions.

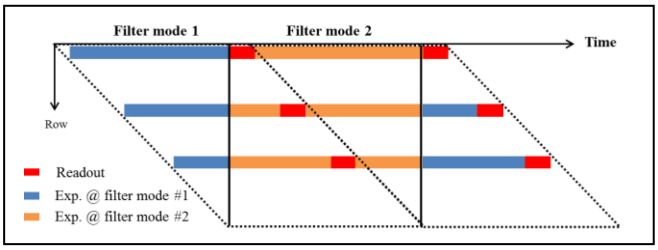

Fig. 2. Tuning the filter during the exposure

Computer simulations [12] prove reasonable reconstruction for several 10's of spectral bands.

Another method of capturing the HS content of objects is to utilize a two (or more) mode color filter. In this scheme, the filter is switched during the exposure so that each row integrates over a weighted average of transmission curves, resulting in transmission profile that varies per row. Similarly to the case of angular-multiplexing, the object is assumed to be large and with uniform spectrum. Fig. 2 illustrates the concept.

IV. CONCLUSIONS

This paper presents a hybrid imaging system that enables color imaging, HS multiplexing and compressed HS imaging. As other imaging systems are optimized for a single application, the presented imaging system offers sufficient flexibility and supports all imaging modes.

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