Feature Article

Spectral Imaging

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Spectral Imaging encompasses a broad range of techniques for scientific image analysis, the end result of which is the production of both the image as well as the spectral composition of a scene of interest. A review of the typical implementations of spectral imaging is discussed in this article. Particular emphasis is placed on the manner of data acquisition, a distinction that frequently determines the suitability of one technique over another for a given application. Our new Simultaneous Hyperspectral Imaging camera is discussed. Its key feature is the ability to collect all spectral and image data in one shot. This feature makes our camera particularly suited to spectral imaging of dynamic scenes in the field as well as in laboratory and industrial environments.

Introduction

As the name suggests, spectral imaging refers to any imaging modality that has as its output a spatial description of a scene of interest as well as its spectral composition at discrete points (pixels) in the image. This output can be visualized as a four dimensional data set (or hypercube), with the first two dimensions (x,y) representing the spatial coordinates, the third dimension the intensity at that spatial point and the fourth dimension (Z) representing the spectral coordinate. Then, the projection of the intensities of any pixel in the (x,y) plane into the z-axis represents the spectrum at that point of the image (Figure 1). With this definition, spectral imaging can be thought of as a generalization of point spectroscopy.

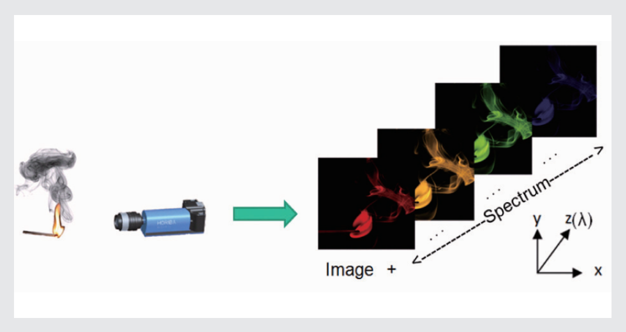


Figure 1 Spectral imaging generates an image of a scene as well as the spectral signatures of the different wavelength components of the scene.

Spectral imaging is recommended when the scene of interest is not homogenous and there is a need to characterize both the spatial as well as the various spectral signatures of the different components of the scene. The need for both spatial and spectral information is a very common requirement in many applications including geological and agricultural studies, color characterization in various media such as fabrics, paints and plasma monitors, as well as in many biological applications.

There are several classification schemes of the different spectral imaging methodologies. Perhaps the broadest of such schemes classifies all spectral imaging methods into one of two groups: *Multispectral* and *Hyperspectral* imaging.[1] In the former case there is a relatively small set of discrete wavelength bands while in the latter case the spectral axis includes a relatively large number of continuous wavelengths. According to this distinction, hyperspectral data sets would frequently contain more spectral detail than multispectral data sets.

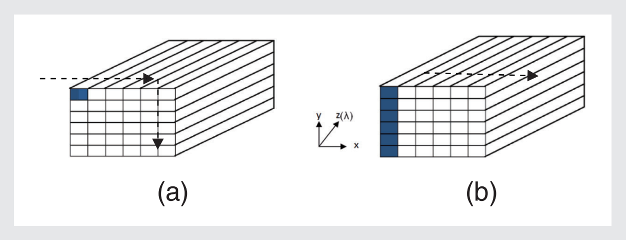
A secondary classification scheme is based on the manner in which the spectral imaging data is collected and processed. This is frequently the basis for choosing one particular method over others for a given application. Spectral imaging data acquisition can be classified as either *sequential* or *simultaneous*.[2] Sequential spectral imaging describes the case where the hypercube data is collected in a series of steps. In simultaneous spectral imaging the hypercube data is collected in one measurement step.

Sequential Spectral Imaging methods

The defining characteristic of the methods in this group is the collection of the hypercube data in a series of measurement steps. These may be further classified as scanning or filter-based methods.

Scanning Methods

Scanning methods include cases in which the hypercube is generated as a series of point spectra - each point being a discrete unit of space or pixel as shown in Figure 2a.[3] Another scanning technique is where the hypercube data is collected from a series of spatial bands or lines with each spatial band representing a discrete unit of space or a column of pixels. The technique is sometimes referred to as push-broom or line scan.[4] The spatial unit from which spectra are collected during each measurement is usually larger than the interrogated area in point methods (illustrated in Figure 2b) and contains multiple spectra, so that the hypercube is generated much faster than is typical with point methods.



(a) (b)

Figure 2 (a) The blue rectangle represents the spatial unit (pixel) from which a spectrum (z-axis) is collected during each measurement. The measurement is repeated over all pixel positions in order to generate the hypercube. The process is usually slow with the achievable spatial resolution limited by the collection optics. (b) Represents a push-broom technique with data collected over a spatial column and typically imaged on an array detector via a spectrometer. Push-broom techniques are typically faster than point methods.

The point scanning methods are frequently used when one is limited to using commonly available point spectroscopy methods — usually microscope-based (Raman, Fluorescence, etc) when it is necessary to generate an image of an inhomogeneous field of view. In these cases a raster-scan (x,y) of the field is performed and a composite spectral image generated from a series of point spectra (see Figure 2a). The line scanning method is usually employed when a segment or column of the field of view can be imaged via a spectrograph onto a 2-dimensional array detector thereby collecting all the spectral data for that column in the field of view. In this instance, one need only scan in one direction to obtain the complete hypercube as shown in Figure 2b.

In both cases (point and line), there is a need to physically move either the object of interest or the imaging spectrometer assembly in a sequential fashion in order to obtain the complete hypercube. The relative motion between the object of interest and detector assembly makes the scanning methods unsuitable for cases in which the phenomenon being monitored is changing on a time scale much shorter than the scan time of the detector assembly (except when the relative motion between object and detector is synchronized with the phenomenon being measured). Furthermore, the motion requirement makes scanning measurements particularly susceptible to errors from mechanical aberrations. Perhaps the most significant advantage of scanning methods is the flexibility to choose from a range of spectrographs offering low to very high spectral resolution and also the possibility of using well established point-spectroscopic techniques. Thus, these are the methods of choice when one is more concerned with more spectral information at a small number of spatial points.

Filter-based Methods

Filter-based methods include all spectral imaging techniques in which all the spatial information at a given wavelength (or narrow band of wavelengths) is captured in one measurement and the hypercube is generated by repeated acquisition of a set of narrow band images at sequential wavelengths as shown in Figure 3.

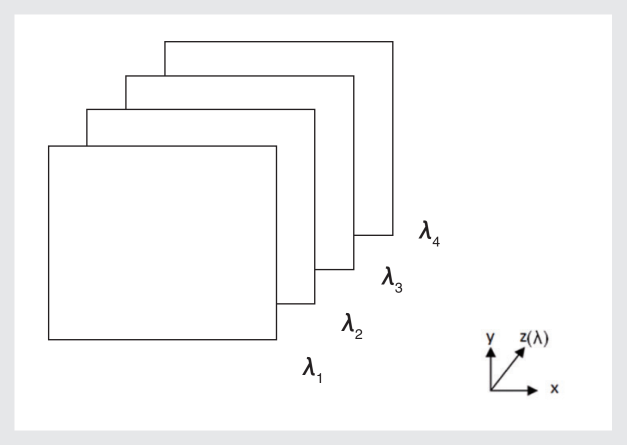


Figure 3 Filter based hypercube generation.

The filters used in filter-based spectral imaging can be passive filters selected apriori or dynamic (tunable) filters allowing selection of specific wavelengths of interest.[2] Common tunable filters used are based on acousto-optic (AO) or liquid crystal (LC) technology. In both cases voltages are used to change the refractive indices of the filter material resulting in a voltage-dependent transmission bandpass. The ability to easily change the filter properties offers the added advantage of dynamically selecting the spectral bands of interest.

Similar to filter-based techniques but implemented differently are techniques that achieve the filtering function by the use of dispersive media such as prisms, so that the spectral images are dispersed in space and can be recorded by using different sensors or using one sensor that moves to different locations in space to record the spectral signature at those points.

Like the scanning methods, the filter-based spectral imaging modalities are limited by the tuning speed from one wavelength band to another, which can vary from several seconds in the case of passive filters on a wheel to a few microseconds in the case of the acousto-optic and liquid crystal technologies. In the case where the tuning function is achieved by the use of passive media such as prisms, the acquisition speed is limited by the time it takes to move the detector from one point to another, or to move the desired image in front of a static detector by rotating the prism. Also, the tuning efficiency of acousto-optic elements and liquid crystals is usually temperature dependent, adversely affecting performance when the ambient temperature is not well controlled. In general the filter based methods are usually faster than the scanning methods and offer very high spatial resolution since the entire sensor is used to register only one spectral slice of the hypercube during each measurement. Thus, these are the methods of choice when one is more concerned with more spatial information at a few wavelengths.

Simultaneous Spectral Imaging Methods

Simultaneous spectral imaging methods are superior to the sequential spectral imaging methods discussed above, at least with respect to acquisition speed. In such cases, the necessary data for generating the hypercube is captured in one measurement step on a time scale that is usually much shorter than any changes in the scene of interest.

Pseudo-Simultaneous Spectral Imaging Methods

For relatively static scenes, several techniques based on multiple filters, multiple sensors, or both, have been used to collect hypercube data. These methods attempt to maximize the number of color planes while minimizing the total acquisition time of the hypercube. In the multi-filter scenario, practical limitations generally dictate eight to sixteen colors using optical filters mounted on a spinning disc placed before the image sensor. The filter positions on the spinning disc are synchronized with the sensor's exposure circuitry, capturing one image of each color in a rapid sequential fashion. While relatively fast, these methods are limited to situations where temporal requirements are not extremely demanding.

HORIBA Scientific Simultaneous Hyperspectral Imaging Camera

While there are methods intended for rapid capture of hypercube data (as described in section 2.1 above), as of this writing there are no truly simultaneous hypercube acquisition instruments on the market. HORIBA Jobin Yvon Inc., in partnership with Snapshot Spectra Inc. of Pasadena, California has developed a new, patented Simultaneous Hyperspectral Imaging (SHI) camera system. This camera is capable of capturing all the data needed to generate a hypercube in one shot, in as little as 3 milliseconds. The acquisition speed is determined mainly by the type of sensor being used.

The technology relies on a two-dimensional transmission grating sandwiched between a pair of imaging lenses (see Figure 4b).[5] The first lens from the left serves to collimate the light coming from the scene of interest and the second lens re-images the diffracted light from the grating onto the sensor. The uniqueness of the system derives from the grating design which creates a two dimensional diffraction pattern at the sensor. The image projected on the sensor consists of an accurate representation of the field of view in the center of the image (undiffracted zeroth order) and higher diffracted orders around the center. Since the angle of diffraction is a function of the wavelength, with the angle increasing from short (blue) to long (red) wavelengths, the higher order diffracted images consist of a smearing of the wavelengths across the sensor containing all the spectral information in the scene (see Figure 5a). The hypercube

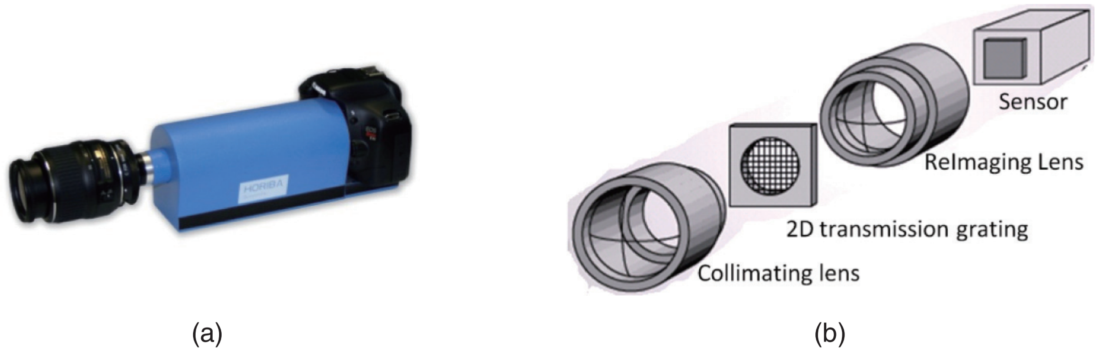
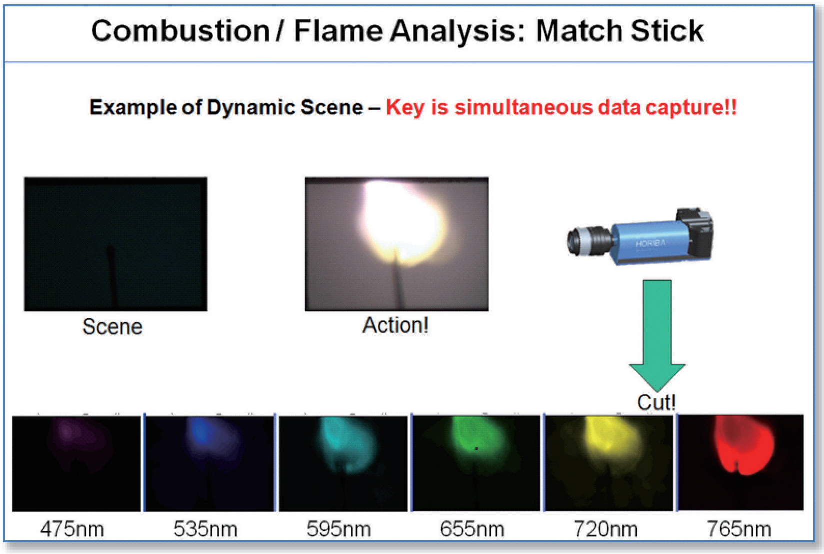


Figure 4 (a) Prototype of Hyperspectral Imaging Camera. (b) Functional components (within the blue casing in the prototype in Figure 4a).

Figure 5 (a) Raw image from Hyperspectral camera. The image consists of a zeroth order image that replicates the original scene surrounded by several higher diffraction orders in both directions. The diffracted orders contain all the spatial and spectral information in the scene. The bottom right insert is an image of the scene taken by a regular camera. (b) Illustration of hypercube generated by software reconstruction using the image in (a) as input.



Combustion / Flame Analysis: Match Stick

Example of Dynamic Scene – Key is simultaneous data capture!!

Figure 6 Example of a dynamic scene (flaring of a match stick). The bottom row shows a few slices of the hypercube in pseudo-color with the colors downshifted so that the highest wavelength is shown in red.

(illustrated in Figure 5b) is generated from a software reconstruction algorithm using the raw image data as input.

Figure 6 shows an example of a typical application for this technology. In this simple example of combustion analysis, the SHI camera captures both the image and the spectra from a flaring matchstick. A critical requirement for the spectral imaging system in this case is the ability to capture all the spatial and spectral data simultaneously as the scene is rapidly changing with time.

Conclusion

Spectral imaging is becoming increasing important as users seek to multiplex data collection in order to save time (as is the case in multiple fluorophore excitation in bio-imaging applications),[6] or in applications where neither spatial or spectral information alone is sufficient, such as multispectral mixing analysis. HORIBA Jobin Yvon Inc. will soon release a new simultaneous hyperspectral imaging camera which will offer both the rich data sets afforded by spectral imaging as well as the ability to collect all the necessary data in a truly simultaneous fashion. The design is very portable and does not have any moving parts, making the architecture fairly rugged. This combination of features makes the hyperspectral imaging camera described here an ideal system for applications involving spectral imaging of transient phenomena that cannot be measured using more conventional techniques such as in engine combustion diagnostics.

References

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