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Hyperspectral Imaging

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Synonyms

Color imaging; Color science; Hyperspectral imaging; Multispectral imaging; Spectral imaging

Definition

The goal of spectral imaging is to recover radiance and reflectance spectra at each pixel in a scene. The stored hyperspectral information for each pixel refers to data from spectra which is sufficiently well scanned so that to be considered as a continuous spectral signal. Typically, such spectral imaging systems consist of a digital camera coupled to a range of spectrally broadband or narrowband filters. Depending on the number of filters used, spectral systems can be classified into multispectral imaging systems, when a small number of 3–10 filters is used, hyperspectral systems, if the number of filters extends up to 10–100, or ultraspectral, when the number is even greater than 100. If the number of filters is sufficiently large and their bandwidths are sufficiently small, as with a hyperspectral and ultraspectral imaging systems [1–3], spectral data can be recovered exactly.

Overview

Multispectral imaging ordinarily uses a digital charge-coupled device (CCD) camera coupled with colored filters of different spectral bands, ranging from just three components, as in a red-green-blue (RGB) conventional camera, up to hundreds of components, as in a hyperspectral system [3]. If the sensor of the CCD camera is monochrome, a high number of narrowband filters is traditionally used, while if the sensor is the RGB color type broadband filters can be used which makes it possible to work with a significantly reduced number of filters. It is the type of sensor which determines the number of channels in a spectral camera thus allowing a first classification of the different typologies of the acquired spectral images, whether with multi- or hyperspectral imaging. The main application of spectral imaging is in areas where a good or high spatial resolution of the spectral measurement is needed. Traditionally, conventional spectroradiometers are the devices used for spectral measurements which are not only expensive but just allow a spectral measurement of a relatively large area (some 2°–10°) of the scene. This significantly limits the spatial details of the scene to be spectrally characterized. On the other hand, the spectral devices used for acquiring images allow, for

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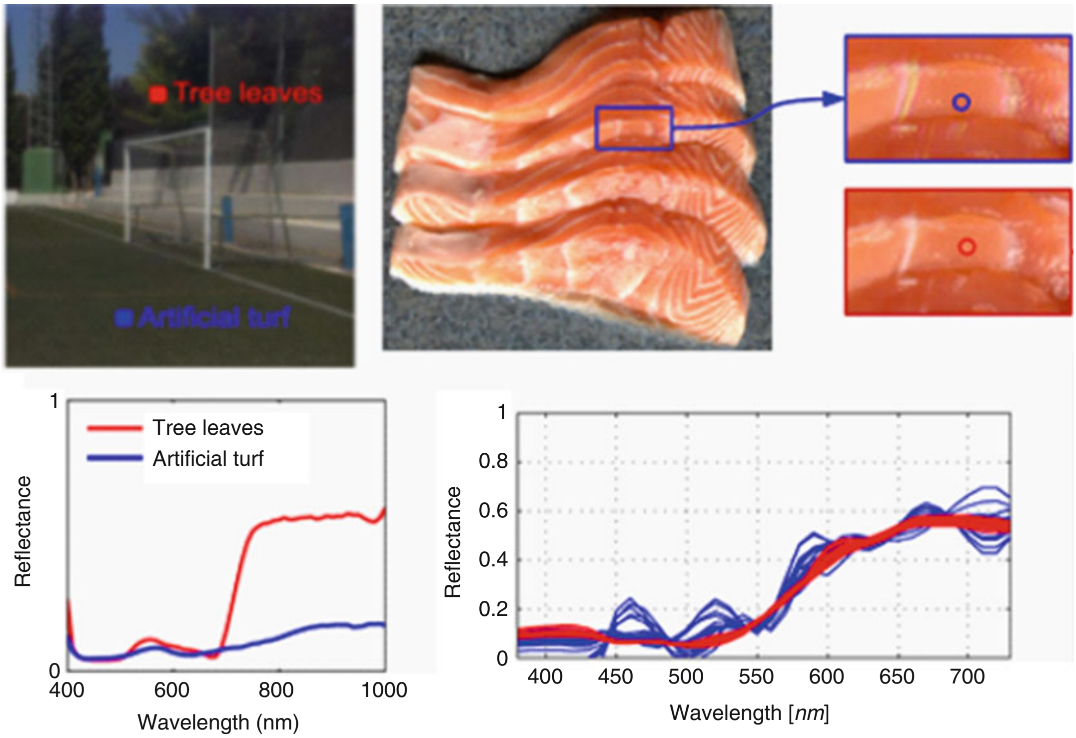


Hyperspectral Imaging, Fig. 1 Rendered scenes (top row) and (bottom row) captured spectra from a commercial Bragg-grating-based hyperspectral imager and a commercial multispectral camera truePIXA (https://www.chromasens.de/en)

example, the measurement of the spectral reflectance of each pixel in the scene (Fig. 1). The hyperspectral techniques used for acquiring images are very important in color imaging because they allow a full spectral reflectance or spectral radiance measurement for each pixel image, thus "preserving" almost the exact colorimetric components of the scene, by just converting this spectral radiance or reflectance to the CIE XYZ tristimulus values [4, 5].

Some Basics on Image Acquisition and Spectral Imaging

Image capture devices are used in general to obtain digitized images of real-world scenes by forming a real image of the scene into its sensor plane area. Thus, their purpose is to transform the continuous, wide range, and very detailed real world into a set of flat quantized values, each corresponding to a pixel. For a conventional RGB color image, this process is equivalent to building a stack of three planes (or sets of organized pixels), each one corresponding to the red, green, and blue dimensions. The camera sensor can either be a CCD (charged-coupled device, known as the technology of moving and storing the electron charge) or a CMOS (complementary metal oxide semiconductor, known as the technology used to build a transistor into a semiconductor wafer). Typically, an organized array of small square color filters called a Bayer filter is placed in front of the sensor to allow color image capture. The raw data from the sensor are fed into the image processor which performs the transformation of the raw data to the quantized three-plane color image. For most color digital cameras, the color is read by placing a mask of colored filters in front of the sensor, and then interpolating the readings of adjacent pixels to get the three RGB values. The fact is that standard color digital cameras never have full-color resolution, as each pixel is obtained by interpolating from adjacent pixels, and this is the cause of some artifacts such as color fringing in the image in some cases. The interpolation procedure also makes the capture process slower. Moreover, the usual practice in color imaging is to modify the natural spectral response of the sensor by placing an infrared-blocking filter to cut-off the higher wavelength response, and also of course the three RGB filters (either in a Bayer arrangement or covering the whole area of the sensor). In the end, the color cameras have three spectral response curves, each corresponding to a red, green, or blue color channel.

A hyperspectral image of *n* bands (or *n* channels) with spatial resolution of *(r x c)* can be represented as a three-dimensional data cube $\mathbf{C} = [C(x; y; \lambda)]_{(rxcxn)}$, where x and y represent the spatial dimensions of the images, and λ represents the spectral dimension; in most cases, the image intensity corresponds to either the spectral radiance or spectral reflectance factor [3, 5, 6]. As can be seen in the next sections, there are many ways of capturing that spectral cube. Some spectral imaging systems need dispersive optics elements (a prism or a single slit) to spectrally decompose the incoming light. Alternatively, other system architectures use a set of a number of optical filters mounted in a filter wheel placed sequentially in front of a monochrome camera. For the purpose of a proper calibration, raw image sequences have to be corrected for noise (e.g., camera dark-current noise and non-uniformity in the sensor array response), stray light, off-axis vignetting, and potential chromatic differences of magnification or translation. The spectral reflectance at each pixel can be estimated by normalizing the aforementioned corrected signals against that obtained from a neutral reference flat-field placed in the captured scene [3, 5]. As illustrated in Fig. 2, the spectral data collected are stored as a "hypercube" **C**, which contains spatial data in two dimensions and spectral data along a third dimension for each pixel in the image.

Direct Spectral Measuring Systems

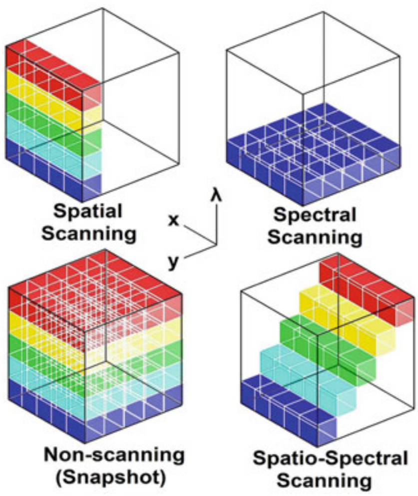
These systems are conventionally known as hyperspectral imaging systems. If the number of channels *n* is sufficiently large and their bandwidths are sufficiently small, spectral data can be recovered exactly from the data cube **C**. Thus, these systems require both a huge amount of processing time and a large storage capacity [7]. Such hyperspectral systems in turn can be classified in three main categories, depending on the scanning step introduced along the spectral and spatial dimension: spectral domain scanning systems, spatial domain scanning systems, and snapshot-based systems.

Spectral Domain Systems

These spectral systems scan an image in the spectral domain by separating the light into its spectral components. To this end, they use a monochrome sensor coupled to a set of narrowband filters. To record a complete hyperspectral cube C, several image captures of the scene are needed (one per spectral band), which means that the objects within the scene should be remain static. One of the most used narrowband filters used in these types of systems is the liquid crystal tunable filter (LCTF). The LCTF is a tunable interference filter based on the electro-optic effect present in liquid crystals (or crystals). In short, it consists of two polarizers and a variable retarder placed between them, which changes its refraction index when an electrical field (voltage difference) is applied which provokes an electro-optic effect. The LCTF illustrated in Fig. 3 was manufactured by the Varispec series of CRI with a usable wavelength range from 400 to 720 nm, and the optical resolution or bandwidth of the spectral transmittance peaks was from 7 to 20 nm. This device allowed a tuning resolution of 1 nm and thus is equivalent to the use of a large set of narrowband filters. In the case of outdoor hyperspectral imaging, varying daylight illumination has to be taken into account [8, 9].

Spatial Domain Systems

These systems are based on a local scan of the areas of the scene in order to obtain the complete spectral information of each of these areas. The most common configuration to achieve this scan is the use of line-scan CCD sensors which allow a line by line sweep of the scene, resulting in a high spatial resolution. A line-scan camera scans moving objects by repeatedly capturing a single line of pixels at a high frequency. Therefore, these spectral systems act like line scanners which disperse the polychromatic light emerging from each pixel and separately register each wave length component of each point in the scanned line. One of the most commonly used setups is Specim's Imspector (see Fig. 4) where either the sample or the camera has to be moved to achieve the special scan required. This device is commonly used in the quality inspection industry to monitor the quality of fruit and foodstuffs and for the accurate color classification of the products.



Hyperspectral Imaging, Fig. 2 Illustration about how to store the spatial and spectral information in different hyperspectral imaging systems

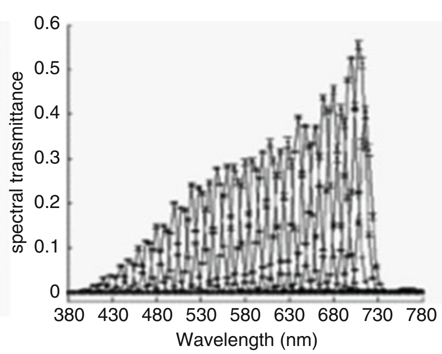
Snapshot-Based Systems

These systems are able to spectrally decompose the incoming light from very small areas of the scene. Thus, in the sensor array, they receive both bidimensional spatial and spectral information. This is a clear advantage in comparison with other spectral systems but due to the complex pupil and lens arrays used to reimage the dispersed areas of the scene in the sensor, the sensor resolution is poor (around 300×300 pixels) and needs a powerful controlled illumination. These systems are thus mainly used in microscopy [10].

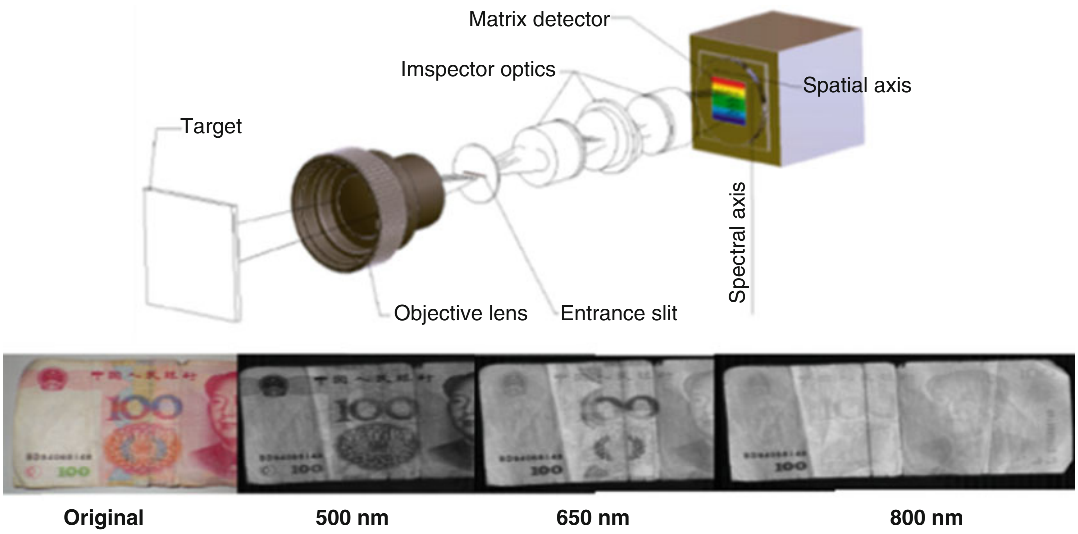
Indirect Spectral Imaging Systems

When a CCD digital color camera is pointed at a surface with a spectral reflectance function r(x,y; λ), the response of the *nth* sensor for pixel (x,y) can be modeled linearly by,

$$C_n(x, y) = \sum_{\lambda=400}^{700} E(x, y; \lambda) r(x, y; \lambda) Q_n(\lambda) \Delta\lambda \tag{1}$$



Hyperspectral Imaging, Fig. 3 (Left) CCD monochrome camera coupled with an LCTF placed in front of the lens of the camera; (right) spectral sensitivities of the channels selected in the LCTF [9]

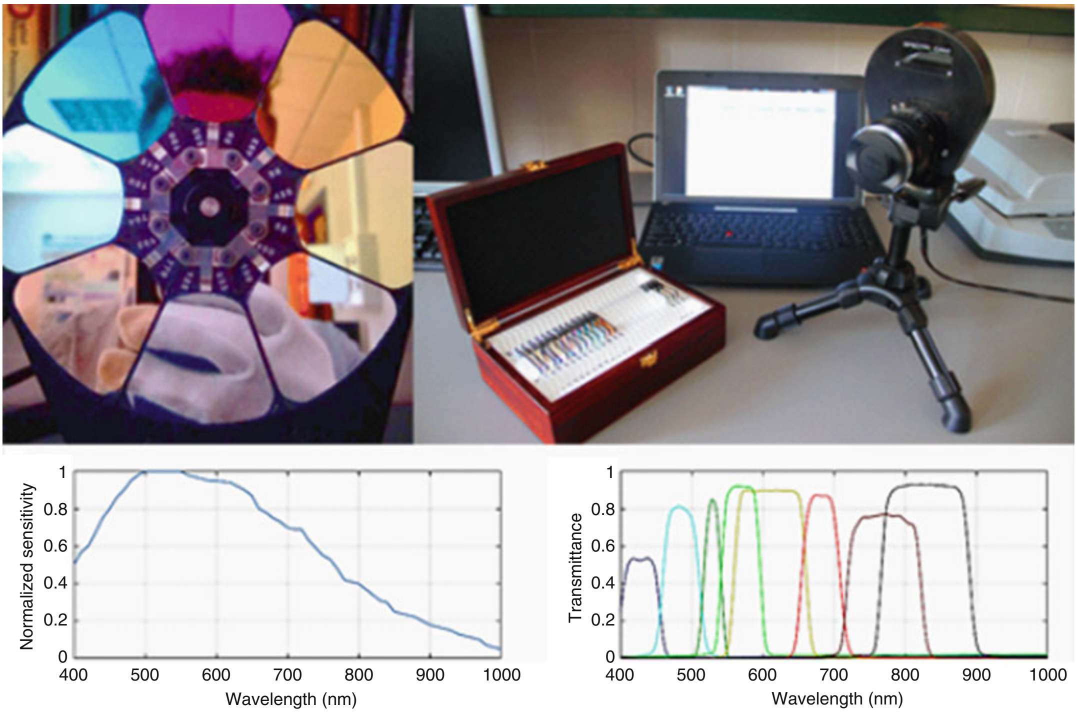


Hyperspectral Imaging, Fig. 4 Working principle of the Specim's Imspector (top row) and (bottom row) example of a scene captured in three spectral bands (from https://www.specim.fi/)

where $Q_n(\lambda)$ is the spectral sensitivity of the *nth* sensor and $E(x,y;\lambda)$ is the spectral power distribution of the illumination impinging on the surface. Equation (1) means that if the number of channels *n* is small, with just a few broadband filters, the spectral recovery, either $r(x,y;\lambda)$ or $E(x,y;\lambda)$, represent an ill-posed problem. Many multispectral-imaging methods exploit the underlying smoothness of signal spectra, with illuminants and spectral reflectances represented by low-dimensional models based on principal component analysis (PCA) or independent component analysis (ICA) [2, 11, 12]. Thus, given a linear model, if the number of PCA (or ICA) coefficients of a particular set of spectra is the same as the number of camera responses (three in the simple trichromatic case), then the spectra can be derived by an inverse transformation of the set of camera responses, with the forward transformation being estimated from a representative ("training") data set. If the number of coefficients is more than the number of response values, then the latter may need to be increased by imaging the scene under different illuminants or by introducing colored filters one at a time in front of the camera to modify the sensor spectra. An alternative to the two previously mentioned configurations is the use of a monochrome camera coupled to a monochrome sensor and a set of band-pass filters (Fig. 5).

Applications

Hyperspectral imaging is used in many fields where applications demand high spatial and spectral resolution and need accurately color coding between similar colors or materials. For instance, in agriculture, hyperspectral imaging enables monitoring of plant health, pest control, and evaluation of ripeness. Classical applications can be also found in astronomy where ultraspectral imaging systems allow to inspect planets at distance or to determine a spatially resolved spectral image of stars. In food processing and research, hyperspectral imaging systems are used to identify defects, apply intelligent food classification, and characterize product quality. In remote sensing, spectral systems (when mounted in a drone) are now able to track forest health, water quality, or potential sources of fires. In general, spectral imaging is also becoming more and more popular in museums, geology, chemical imaging, skin care, cosmetics, etc.



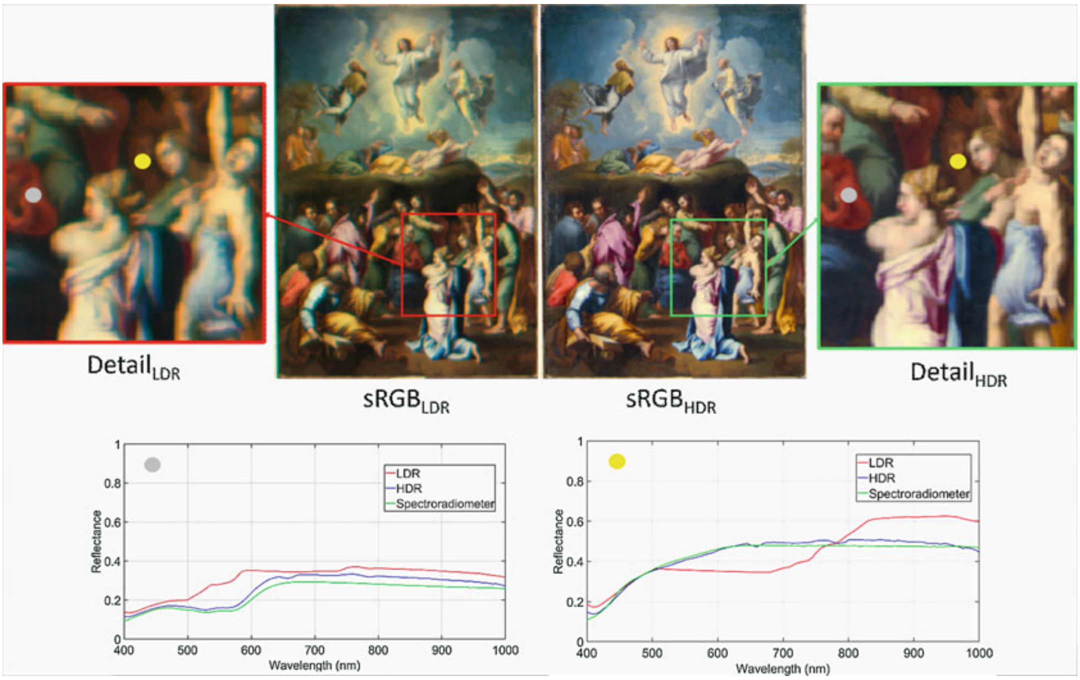
Hyperspectral Imaging, Fig. 5 Pixelteq Spectrocam VIS-NIR with the 8-slot filter wheel facility and the available set of 16 band-pass filters in the visible and near-infrared spectrum (from https://pixelteq.com/)

Hyperspectral Imaging of Pictorial Artworks

Spectral imaging is a very powerful technique which, when properly applied, can retrieve useful information from art objects in a noninvasive manner. This is especially important when the objects are very old and delicate, such as paintings, ancient documents, old maps, etc. [1, 6, 13]. All these items are subject to the action of degradation agents as well as the intervention of conservation and restoration professionals. The main problem in these spectral applications is that the illumination is no longer so well controlled. Even if standard light sources are used to illuminate the painting, it will not be homogeneously illuminated, presenting highlights and shadowy areas due to the common presence of high reflectivity binders, varnishes, or materials. Moreover, different spatial locations and spectral bands might register huge variations in intensity of the reflected light from the painting. This might exceed the dynamic range of the device, making it necessary to use HDR techniques to be able to recover useful information for each pixel and every spectral band [6, 13].

Unfortunately, hyperspectral scanners only allow one exposure time to be set for each complete capture, which means that in a single scan, all the wavelengths and areas of the scene are captured using the same single exposure time. In these uncontrolled conditions, the high dynamic range and the focusing problem due to chromatic aberrations can be overcome by using multiple captures with different focus positions and exposure times. Figure 6 shows how the use of a low dynamic range hyperspectral cube can affect the color fidelity of the rendered painting in comparison with the use of an HDR cube.

In addition, recent studies have shown how spectral imaging also allows surface geometry recovery of the whole scene. A six-band scanner can be used as a multispectral imaging system in such a way that the surface properties of a painting, spectral reflectance of each pixel and the shape information of normal surface and height can be estimated [14]. This is of particular interest



Hyperspectral Imaging, Fig. 6 Comparison between a color image rendered from a hyperspectral image capture using (left) a low dynamic range LDR cube and (right) a high dynamic HDR cube. Two spectra from different areas of the image are shown below by comparing the spectra obtained from the hyperspectral imager and conventional spectroradiometer measurements

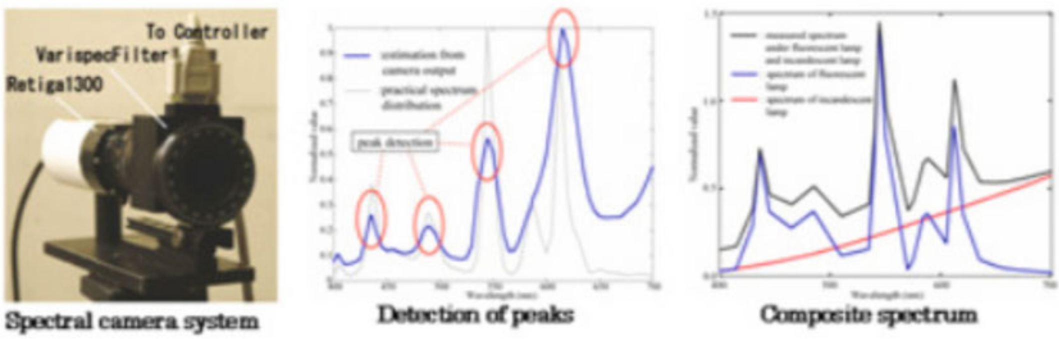
in painting analysis because experts can have access to the usually complicated shape of surfaces of paintings (i.e., irregular canvas, not uniform painter strokes on the canvas, etc.).

Multispectral Imaging of Natural Scenes

Acquiring outdoor spectral image data is an extra challenge because the radiometric conditions of the image scene are generally not static and the illumination does not have a smooth spectrum. Therefore, additional measures for dealing with these issues are required. Due to the great deal of time needed for hyperspectral imaging techniques, multispectral imaging based on indirect measurements can be an easy alternative. Using a conventional RGB color camera with a limited set of one to three broadband color filters (i.e., number n of bands of 4–6) in combination with a direct-mapping method [11], the spectral reflectances of natural scenes can be recovered with good spectral and color quality. Given a set of training spectra **S** (i.e., spectral radiances or spectral reflectances at a pixel) and the corresponding set of camera responses **C** (as defined by Eq. 1), a recovery transformation matrix **D** can be defined by $\mathbf{D} = \mathbf{S}\mathbf{C}^{+}$, where $\mathbf{C}^{+}$ is the pseudo-inverse of **C**. If **C** has full rank, then $\mathbf{C}^{+} = (\mathbf{C}^{t}\,\mathbf{C})^{-1}\,\mathbf{C}^{t}$, where $\mathbf{C}^{t}$ is the transpose of **C**. An estimate **S**e of a set of test spectra **S**p may then be obtained from the corresponding set of camera responses **C**p by applying the transformation **D**, that is, **S**e = **DC**p. Direct-mapping is an easy and a fast procedure to get spectra recovery of a pixel without consuming much time; however, the training step should be carefully taken into account to get accurate results [8, 11, 12].

Multispectral Image Capture of Natural and Artificial Illumination

Although intense research has focused on the analysis of multispectral data to recover spectral reflectance functions of objects, spectral recovery in the context of the spectral power distribution of artificial illumination has received little attention.



Hyperspectral Imaging, Fig. 7 Examples of recovery of the spectral power distribution of fluorescent illuminants using a multispectral imaging system (RGB color camera with a broad-band color filter) [15]

Natural and artificial scene illuminant recovery can also be addressed by estimating the spectrum distribution of an unknown illuminant using a spectral camera system. Spectral characterization of both daylight and artificial illumination is important in fundamental research and applications, in particular for the analysis and synthesis of scenes. Nevertheless, artificial illuminants, such as fluorescent light, are characterized by complicated spectral power distributions (i.e., containing several pronounced peaks) which so far are difficult to spectrally estimate [15]. An accurate spectral estimation of fluorescent lights can be obtained by using a direct-based spectral imaging setup with a monochrome CCD camera attached to a liquid crystal tunable filter (Fig. 7).

Cross-References

- ▶ CIE Chromaticity Coordinates (xyY)
- ▶ Color Appearance
- ▶ Image Quality
- ▶ Spectral and Color Rendering

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