Hyperspectral Imaging for the Food Industry

Masoud Taghizadeh

Dept. of Food Science and Technology, Ferdowsi University of Mashhad, Iran

Abstract

Traceability and quality and safety are principal requirements for different foods. Quality and safety control are generally performed with classic methods, such as microbiological and chemical ones. However, today’s food industry demands non-destructive, rapid and accurate on-line procedures to monitor product quality and safety. In recent years, hyperspectral imaging (HSI) has emerged as a useful tool to handle the afore-mentioned goals. It is a rapid analytical method that simultaneously delivers spatial, chemical, structural, and functional information from a target. In this chapter some advantages of HSI, its corresponding apparatus, and recent applications in food quality control are reviewed. In addition, current limitations and likely future applications are discussed.

Keywords: Hyperspectral imaging, Hypercube, Food, Quality control

Introduction

Due to growing concerns over food safety and traceability, and the increasingly stringent legislation that has resulted, today's food industry sector must respect ever stricter standards and more demanding quality control and monitoring procedures. Food quality and safety control are commonly performed with microbiological and chemical methods such as HPLC, GC, ELISA and MS. However, these methods are expensive, time consuming and often require destruction of the sample. Recently, rapid methods including non-destructive and non-contact methods have become available. Surface reflectance and transmittance of various forms of light energy (e.g. ultraviolet, visible, NIR, MIR) provide useful information for food quality control. In particular, NIR spectroscopy contributes some distinct advantages which are valuable in food quality and safety control, e.g. precise data on protein, fat and moisture content. Moreover, little or no sample preparation is required and measurements are largely insensitive to sample geometry. However, spectroscopic assessments with relatively small point source measurements do not contain spatial information, which is important in many food inspection applications. In contrast, imaging techniques characterize spatial variability of sample material, therefore providing potential for the detection of localized defects on a sample material.

Hyperspectral imaging (also known as imaging spectroscopy) is a novel and developing technique that integrates imaging and spectroscopy to acquire both spatial and spectral information from an object. It was first employed as a powerful technique in earth remote sensing, delivering the opportunity to obtain information about objects in a scene that is unavailable to conventional imaging systems. In fact, HSI combines spectroscopy and imaging capabilities of different sensors, i.e., the spectroscopy measures emission, reflectance, transmittance or absorbance when electromagnetic radiation imposes upon an object in time or frequency domains in order to determine important physical and chemical properties of the object being measured. Imaging does not measure fundamental chemical or physical properties, but presents data to human visual systems for perception and understanding. Imaging spectroscopy is a combination of these two tools. However, even though there is a connection between spatial and spectral information, it is complicated to combine and analyze these two properties precisely. In the mid-80s, the combination of imaging and spectroscopy pioneered efforts in airborne remote sensing. Although for much of the past decades, HSI has been available mainly to researchers; recently it has been used widely for many applications such as airborne remote sensing, mining and geology (Allende et al., 2008; Noomen 2007). It has also found limited industrial applications in other fields such as resource management, food and agriculture, pharmaceuticals, mineralogy and environmental monitoring. (Allende et al., 2010; Smith 2006; Gowen et al., 2008). In terms of food monitoring applications, HSI is now being used as an effective technique for automated online inspection of chicken carcasses for the detection of systematically diseased birds on high-speed processing lines. In-plant testing, conducted by a research team from United States Department of Agriculture (USDA), demonstrated an imaging speed of 400 line-scan images per second (Chao et al., 2007). Moreover, HSI is used for early detection of bruise damage on plant materials such as apple and pickling cucumbers (ElMasry et al., 2008; Ariana et al., 2006). Hyperspectral imaging (HSI) for the food industry is generally performed in the wavelength range of 400-2500 nm. The main advantages of HSI are 1) minimal sample preparation, 2) simultaneous determination of several constituents, 3) estimation of both concentration and distribution of sample constituents, 4) robust and easy to use instrumentation.

HSI systems can be specifically designed to meet the needs of pharmaceutical, agriculture and chemical industries in many functions, including research and development, root cause analysis, quality assurance, quality control, process understanding and control. Manufacturing issues for a vast number of products, ranging from pharmaceuticals to vegetables, can be solved using HSI. By simply changing an objective lens, a standard laboratory system can be easily configured for either microscopic or macroscopic imaging. Furthermore, irregularly shaped, coarse and highly colored targets can be analyzed with HSI (Cogdil et al., 2004).

Background

HSI involves the acquisition of images across a large, usually contiguous series of narrow spectral bands comparable to single-point spectroscopic techniques, thus integrating the complete spatial and chemical information of the sample. The acquired data can be considered as an image cube (*hypercube*) where the third dimension is represented by hundreds of contiguous spectral bands (Neil et al., 2004). The *hypercube* (which is shown in Fig. 1) can be treated as a series of spatially resolved spectra (pixels) or as a series of spectrally resolved images. An imaging pixel is actually a column vector with dimensions equal to the number of spectral bands. Hence, *hypercubes* contain immense amounts of information from the sample. For instance, a hyperspectral imaging system with a 1024 × 1024 pixel detector array that samples 75 wavelengths will collect 1,048,576 spectra during each analysis, in a 1024 × 1024 × 75 array. Accordingly, the major challenge in HSI is to extract useful data from the information-dense *hypercube*; multivariate chemometric analysis combined with image processing techniques are usually employed to achieve this.

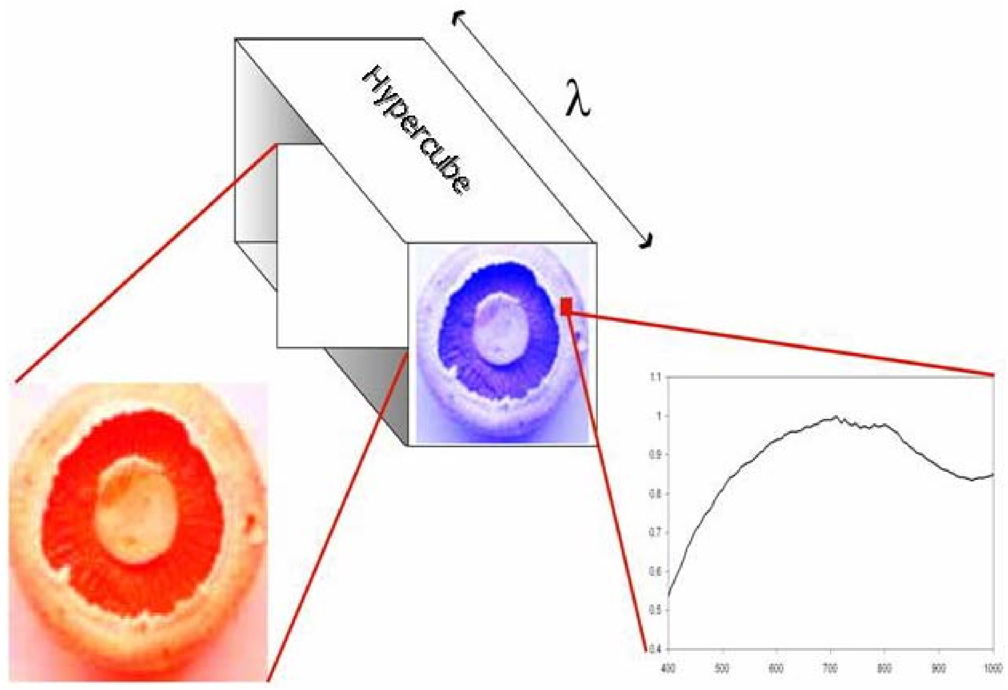

Fig.1. A *hypercube* which contains 2 spatial and 1 spectral dimension

Instrumentation

HSI systems are typically composed of a light source, lens, spectrograph, detector, and acquisition system as demonstrated in Fig.2. The lighting unit usually contains a tungsten halogen light source which may be delivered through dual fibre optic light lines (Ariana et al., 2006). The detector is typically an InGaAs or CCD camera. The imaging spectrograph, which typically contains a tuneable filter or a holographic prism (depending on the system configuration, as described below), scans one plane of the hypercube at a time.

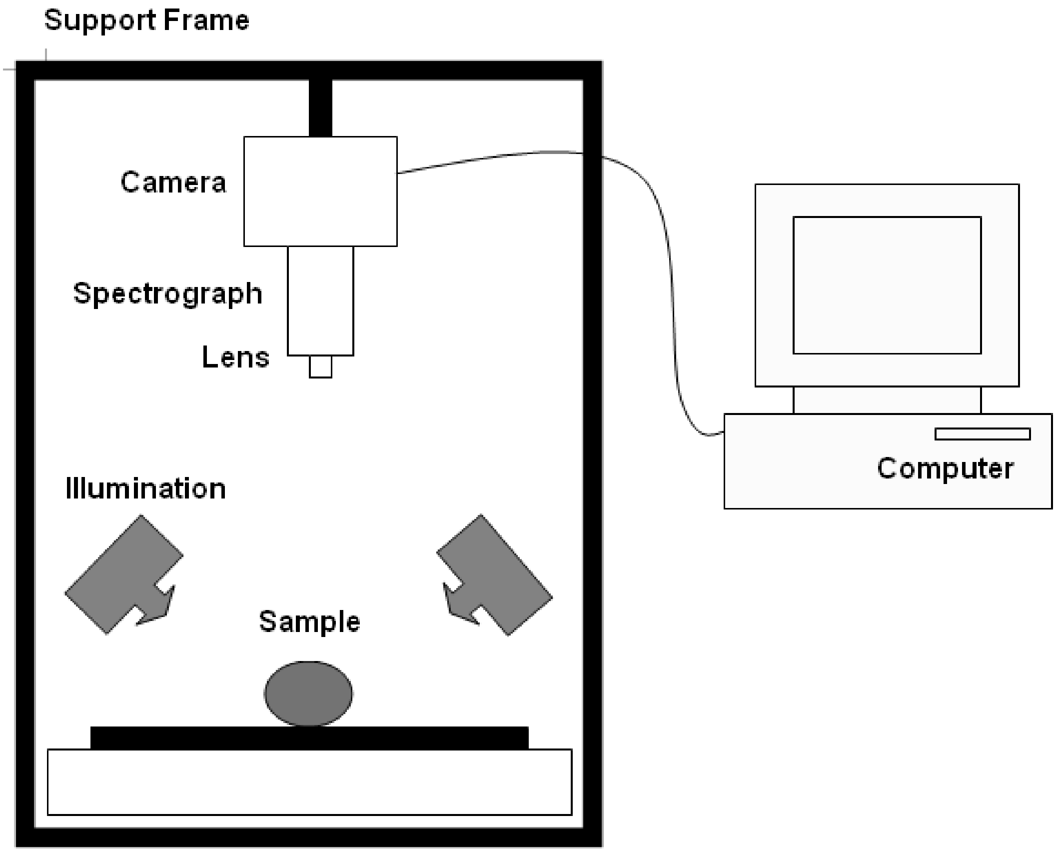

Fig.2. Typical components of an HSI system

Generally, there are two different configurations for hypercube acquisition. The first method is known as the “staring imager” configuration, in which sample and camera are kept stationary and single images are recorded for each wavelength. Tuneable filters are usually applied for this configuration, which is typically used for pharmaceutical analysis. Images recorded at different wavelengths are combined by software and the spectra are then calculated. The second approach, which is applicable to conveyor belt survey, is known as the “push-broom” scanning configuration (Reich 2005). This method requires a relative movement between camera and sample to scan over the surface. In this arrangement, holographic prisms are applied. The imaging system records the spatial information line wise and provides spectral information for each pixel along the line by projection along the second axis of the two-dimensional camera chip. Computer software then reconstructs the full *hypercube*. An example of a “push-broom” hyperspectral imaging system is demonstrated in Fig.3.

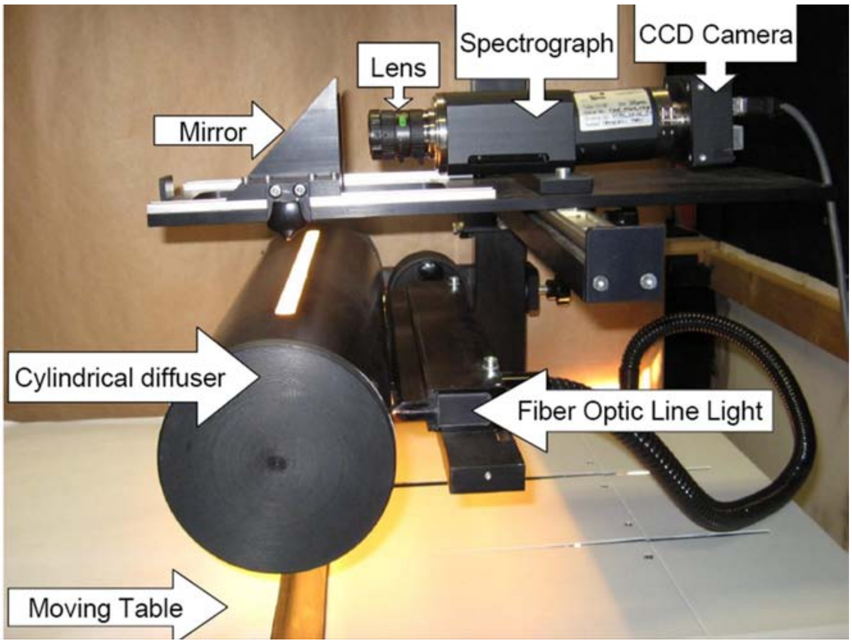

Fig. 3. The push-broom HSI system used in the study (DV Optics, Italy).

In an HSI system, image contrast is based on chemical differences between the various components of the sample. After the desired chemical contrast is derived, images can be further processed and converted to values that may be used to reliably qualify the samples, thus comparative analysis will be available. For data collection and analysis, numerous methods exist. Chemometric tools, including principal component analysis (PCA) and partial least square (PLS) are regularly employed to process the data and transform qualitative information contained within an image into quantitative metrics. The true value of HSI is exploited with the use of appropriate statistical and image analysis techniques. HSI enables images at a large number of wavebands (typically >100) with greater resolution to be examined. With the aim of decreasing spectral variability introduced by sample morphology, which is one of the most important challenges in HSI data analysis, it is desirable to apply spectral or spatial pre-processing to the HSI data. Pixel spectra obtained from each region is subjected to chemometric pre-treatments such as multiplicative scatter correction (MSC) and standard normal variation (SNV) pre-processing (Burger and Geladi, 2007).

HSI applications in food quality control

Application of HSI in food quality and safety control has been reported by several researchers. Table 1. lists a summary of selected key published works in which use of hyperspectral imaging in food quality control have been reported. Polder et al. (2000) showed that an HSI system in the spectral region of 396 to 736 nm was more effective than RGB imaging for discriminating ripeness level in tomatoes, regardless of illumination condition tested. Ariana et al. (2006) studied the application of HSI in the same spectral region for the detection of bruise on pickling cucumbers. They found that reflectance for bruised tissues was generally lower than that for normal tissues and detection accuracy was dependent on the time after bruising.

Table 1.
Selected key papers published on hyperspectral imaging of food products

duct	ameter	asurement	velength	sification	erence
oratory scale					
ato	ness	lectance	- 736 nm	ar discriminant analysis A)	der et al., 2000
eat	gal disease	lectance	- 750 nm		hammad and Larsolle 2003
le	face defects	lectance	- 900 nm	d difference (BD)	hl et al., 2004
le	er pit	lectance	- 1350 nm		olai et al., 2006
le	al contamination	lectance	- 900 nm	d ratio (BR)	et al., 2007
le	tharvest quality	rescence	- 1040 nm	Artificial neural network N)	and Lu 2007
lnut	lnut shell and pulp	rescence	- 775 nm	tor machine	g et al., 2007
lfish	natodes	nsmittance	- 950 nm		a et al., 2007
f	derness	lectance	- 1000 nm		anathan et al., 2008
le	ling injury	lectance	- 1000 nm	N	lasry et al., 2009
eat kernels	ct damage	lectance	0 - 1600 nm		h et al., 2009
us	en fruit	lectance	- 1042 nm		moto and Lee 2009
les	rnal defects and colour surface	lectance and nsmittance	- 1000 nm		na and Lu 2010
t scale					
ltry	anic residues	lectance	- 951 nm		et al., 2007
ltry	ased chicken	lectance	- 735 nm	zy logic	o et al., 2007

A similar system was used to evaluate pork quality and marbling level (Qiao et al., 2007a) with up to 85% classification accuracy. More recently, Diwan and Lu (2010) employed an HSI system operated in visible spectral range (400 – 675 nm) for sensing of surface colour and bloater damage in whole pickles. PCA was used for bloater damage detection and an accuracy of 86% was achieved, compared with an accuracy of 70% by the human inspectors. With the development of new HSI equipments, application of systems in the spectral regions up to 2500 nm will be increasingly exploited.

HSI future in food industry

To facilitate industrial adoption of HSI technology for on-line food monitoring, validation at pilot or commercial-scale is required. Although, HSI is a powerful platform technology for food quality control, currently there are two major barriers to its widespread adoption in the food industry. The first is the high capital cost of HSI systems (camera, spectrograph etc.). The second limiting factor arises from the relatively lengthy time necessary for Hypercube image acquisition, processing and classification. In order to facilitate online imaging based food grading on an industrial scale, a multi-spectral approach which is cost effective and rapid would address the main challenges encountered for routine use of HSI in industry. Multispectral usually operates on 10 wavebands or less. However, further work is required to identify the key spectral bands necessary for any certain food product quality assessment to facilitate the development of a low-cost high speed imaging system for identification of sub-standard batches foodstuffs. In addition, it can be expected that future developments in optical system components, such as improved cameras and faster hardware will shorten processing and classification time, facilitating increased adoption of HSI monitoring system in the food industry.

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