Potential applications of hyperspectral imaging for quality control in dairy foods

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Abstract: *Hyperspectral Imaging (HSI), also known also as Chemical or Spectroscopic Imaging, is an emerging technique that integrates conventional imaging and spectroscopy to attain both spatial and spectral information from an object. Technological advances in spectrograph and detector design leading to decreased cost and improved instrumentation have enabled HSI applications to increase in number and widen in scope over the past twenty years. Reported applications of HSI in food science and technology (while not as numerous as those in established HSI disciplines such as remote sensing) are rapidly emerging[1], with the majority of reported research concerning quality control of vegetable, fruit, grain, meat and poultry products[2]. There have been, to date, very few reported applications of HSI to dairy foods; it's use as a research tool in dairy science has not yet been exploited. However, a wide range of quality and safety testing practices in the dairy industry could be complemented and potentially improved with HSI. In this article, potential applications of HSI to quality monitoring of dairy products are presented, specifically in: process monitoring, compositional analysis, prediction of functional properties, authentication and limitations and safety testing. Current limitations of the technology and potential future developments are also explored.*

1 Introduction

The potential of NIR spectroscopy (NIRS) has recently been investigated for solving a number of problems related to dairy food production. Rapid compositional analysis (e.g. moisture, fat, protein content) of dairy products, including cheese, milk and dairy powders, using near infrared spectroscopy (NIRS) has been presented. More complex concepts such as organoleptic and functional properties of dairy products, most notably cheese, have been correlated with NIR spectral characteristics. Classification of cheese according to maturity and sensory characteristics has also been successfully carried out using NIRS. The potential applications of NIRS in monitoring the formation of cheese from milk have been demonstrated, resulting in the development of low-cost sensors for control of coagulation and syneresis. Fluorescence spectroscopy has also been applied to dairy products; examples include the classification of cheeses according to geographical origin and monitoring oxidation in yoghurts.

Spectrometers integrate spatial information to give an average spectrum for each sample studied; their inability to capture internal component distribution within food products may lead to discrepancies between predicted and measured composition. Furthermore, spectroscopic assessments with relatively small point-source measurements do not contain spatial information, which is important to many food inspection applications. Computer vision systems, which capture spatial information, have been developed for quality control in food processing. Red-green-blue (RGB) colour machine vision systems find widespread use in food quality control for the detection of surface defects and grading operations. Applications of such machine vision systems have been investigated for monitoring quality in dairy foods, for example, in the estimation of functional properties, for characterisation of ingredient distribution and in the prediction of sensory attributes of some yoghurts and cheeses.

However, conventional colour cameras are poor identifiers of surface features sensitive to wavebands other than RGB, such as low but potentially harmful concentrations of contaminants on foods. To overcome this, multispectral imaging systems have been developed to combine images acquired at a number (usually < 10) of narrow wavebands, sensitive to features of interest on the object. Recently, an application of multispectral imaging for dairy products was presented based on a multispectral imaging system based on 8 wavebands in the UV, Vis and NIR wavelength regions for classification of blue cheeses according to their origin.

Hyperspectral imaging can be conceived of as an extension of multispectral imaging; while multi-spectral imagers look at light from up to 10 wavebands, hyperspectral imagers are capable of obtaining spatial information from >100 wavebands; as such, hyperspectral imaging represents a new era in spectroscopy and imaging, combining the potential usefulness of both of these technologies, as further described in the following section.

Hyperspectral imaging (HSI), also known as chemical or spectroscopic imaging, is an emerging technique that integrates conventional imaging and spectroscopy to attain both spatial and spectral information from an object. It was originally developed for remote sensing applications utilizing satellite imaging data of the earth, moon, and planets, but has since found application in such diverse fields as astronomy, agriculture, pharmaceuticals and medical diagnostics.

Hyperspectral images are made up of hundreds of contiguous wavebands for each spatial position of a target studied. Consequently, each pixel in a hyperspectral image contains a spectrum representing the light absorbing and/or scattering properties of the spatial region represented by that pixel (although it should be noted that due to various optical, instrumental and background effects, each pixel spectrum may be influenced by its neighbouring pixels; this becomes a greater problem in high magnification imaging).

The resulting spectrum acts like a fingerprint, which can be used to estimate chemical compositions of that particular pixel. Hyperspectral images, known as *hypercubes*, can be represented as three-dimensional blocks of data, comprising of two spatial and one wavelength dimension, as illustrated in **Figure 1**. The *hypercube* allows for the visualization of biochemical constituents of a sample, separated into particular areas of the image, since regions of a sample with similar spectral properties tend to have similar chemical composition.

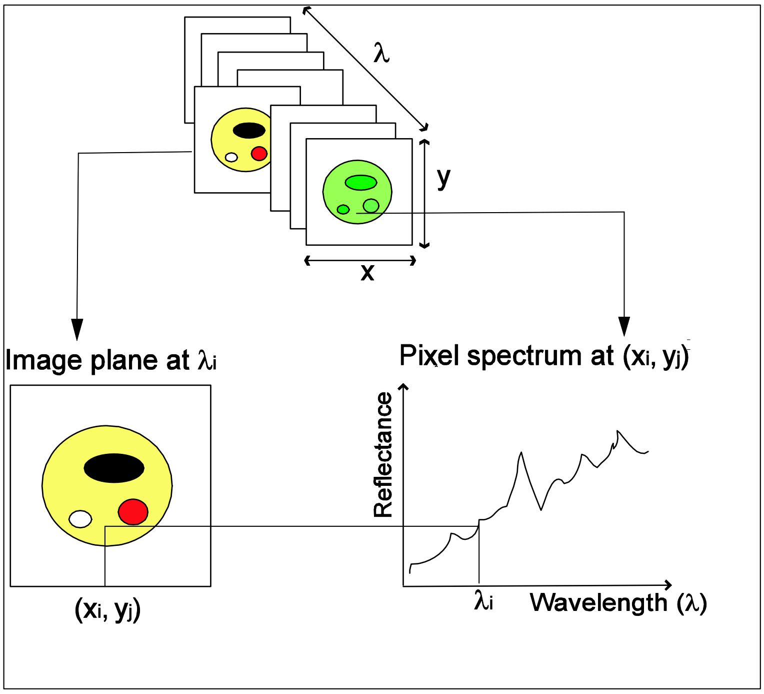

Figure 1: Schematic showing hypercube structure; spatial axes x, y, and wavelength axis (λ)

Some advantages of hyperspectral imaging over conventional NIRS, RGB and multispectral imaging are outlined in **Table 1**. In combining the spectral information provided by spectroscopy and the spatial information provided by imaging, hyperspectral imaging (HSI) offers improved knowledge on the composition and distribution of components in a product. Moreover, HSI is a rapid method (typical scan time < 1 min) compared with traditional quality testing techniques such as HPLC and GC-MS which may take hours including sample preparation steps, and since it is a non-destructive and non-contact technique, samples may be further processed or tested as required without interference with the sample.

The US Food and Drug Administration-led process analytical technology (PAT) initiative aims to understand and control the manufacturing process by monitoring critical performance attributes. The non-destructive, rugged and flexible nature of HSI makes it an attractive PAT tool for identification of critical control parameters that impact on finished product quality. It is anticipated that HSI will be increasingly adopted as a key PAT tool for the food industry, as has already been the case in manufacturing environments such as the pharmaceutical industry.

Table 1: Comparison of RGB imaging (RGB), Near infra red spectroscopy (NIRS), Multispectral imaging (MSI) and hyperspectral imaging (HSI) techniques for dairy product applications.

Attribute	**RGB**	**NIRS**	**MSI**	**HSI**
Spatial information	✓		✓	✓
Spectral information		✓	**Limited**	✓
Multiconstituent information	**Limited**	✓	**Limited**	✓
Sensitivity to minor components			**Limited**	✓

1.1 Hyperspectral image acquisition and instrumentation

It is currently unfeasible to obtain information in all three dimensions of a *hypercube* simultaneously; one is limited to obtaining two dimensions at a time, then creating a three dimensional image by stacking the 2 dimensional 'slices' in sequence. There are two conventional ways to construct a *hypercube*. One method, known as the "staring imager" configuration involves keeping the spatial image field of view fixed, while restricting or filtering light throughput, thereby obtaining images one wavelength after another (the use of traditional waveband filters is another option, but becomes difficult when greater than 100 wavebands are required). *Hypercube*s obtained using this configuration thus consist of a three dimensional stack of images (one image for each wavelength examined), which may be stored in what is known as the Band Sequential (BSQ) format. "Staring imager" instruments incorporating tuneable filters have found a number of applications in pharmaceutical quality control, their lack of moving parts representing an advantage in many situations.

Another configuration involves acquisition of two dimensional camera frames representing complete spectral measurements acquired simultaneously from a series of adjacent linearly spaced spatial positions. Acquisition of the full hypercube thus requires relative movement between the object and the detector along the second spatial axis. Such line mapping instruments which record the spectrum of each pixel across a line of a sample simultaneously recorded by an array detector, known as "pushbroom" acquisition results in a *hypercube* stored in the Band Interleaved by Line (BIL) format. This method is particularly well suited to conveyor belt systems, and may therefore be more practicable than the staring imager configuration for some food industry applications.

Some instruments produce hyperspectral images based on a single complete spectrum - point step and acquire mode: complete spectra are obtained at single points on the sample, while the sample is rastered or moved in the X, Y spatial dimensions. *Hypercubes* obtained using this configuration are stored in what is known as the Band Interleaved by Pixel (BIP) format. This is a very time consuming process, but may result in extremely high resolution spectra with hundreds of wavelength channels. Recent advances in detector technology have reduced the time required to acquire these *hypercubes*.

Typical hyperspectral imaging systems contain the following components: focusing lens, wavelength modulator, detector, illumination and acquisition system as shown in **Figure 2a**. In the case of pushbroom line-scanning HSI systems, a spectrograph is used for wavelength modulation; a line of light reflected from or transmitted through the sample under investigation enters the objective lens and is separated into its component wavelengths by diffraction optics contained in the spectrograph; a two-dimensional image (spatial dimension x wavelength dimension) is then formed on the detector; two-dimensional line images acquired sequentially at adjacent positions from the sample target are stacked to form a three-dimensional *hypercube* which may be processed immediately in real time or stored for further analysis. For such pushbroom systems relative movement between the object and detector is necessary and this may be achieved either by moving the sample (e.g. via use of a translation stage, see **Figure 2b**, or a conveyor belt) and keeping the hyperspectral camera in a fixed position or by moving the camera and keeping the sample fixed.

Wavelength of incoming light in the “staring imager” configuration is typically modulated using a tuneable filter; Acousto-optic Tuneable Filters (AOTFs) and Liquid Crystal Tuneable Filters (LCTFs) are the two most common types employed. AOTFs have been used in the construction of commercially available HSI systems; the main advantages of AOTFs are good transmission efficiency, fast scan times and large spectral range. On the other hand, LCTFs show greater promise for filtering of Raman images. More recently, staring-imager systems have been developed that incorporate a tuneable laser as the light source, thus removing the need for a wavelength modulator. Such systems can produce hyperspectral images in a fraction of the time required by conventional systems based on tuneable wavelength filters, representing a significant advance in the field.

Hyperspectral images can be obtained for reflected, transmitted or emitted light coming from the UV, through the Vis-NIR and up to the short wave infrared (SWIR) regions of the electromagnetic spectrum. The camera, wavelength modulator and illumination conditions determine the wavelength range of the system. Commercially available Vis-NIR HSI systems typically range between 400-1000 nm, and utilize cameras with Charge Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) sensors; longer wavelength systems require more expensive IR focal-plane array detectors. The sample/target is usually diffusely illuminated by a tungsten-halogen light source. Data acquisition and storage is a major issue in hyperspectral imaging; a typical image of 320 x 240 pixels in size will contain over 75,000 spectra, each with > 100 spectral data points, resulting in a file containing > 7,500,000 numbers; if each number is stored in floating point double precision (16-bytes), the resultant image will be > 100 MB in size!

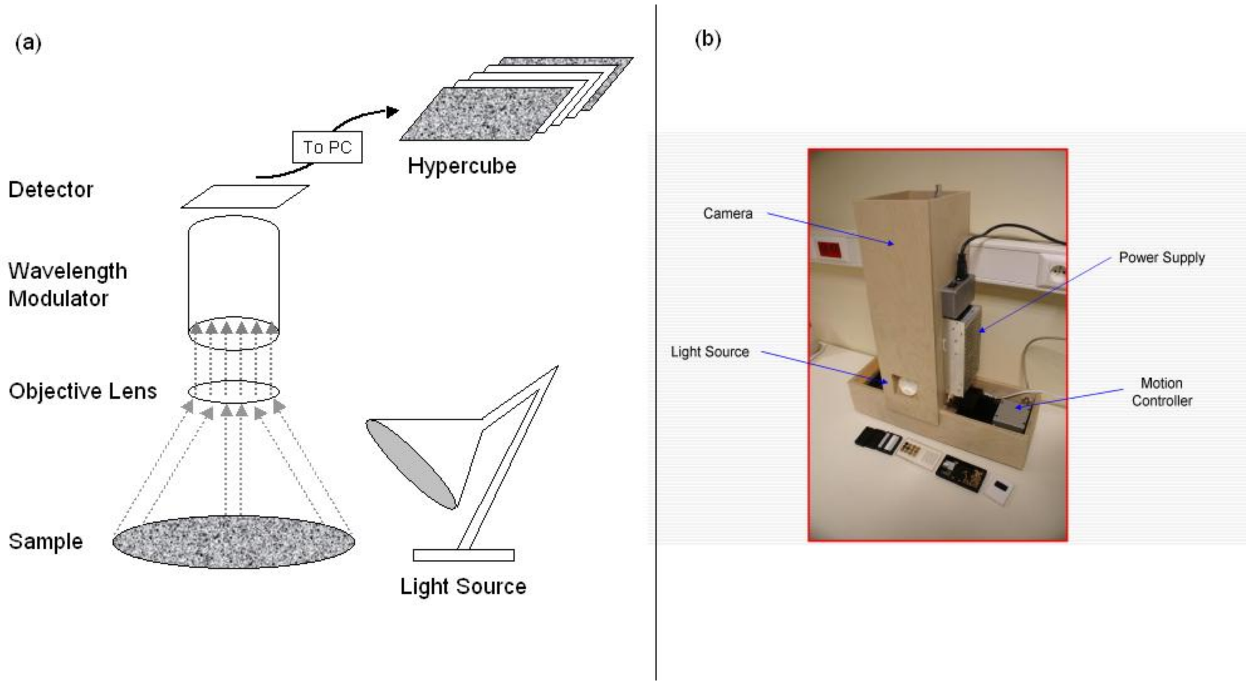

Figure 2a: Schematic showing typical components of a hyperspectral imaging system, (b) example of prototype turnkey pushbroom hyperspectral imaging system.

1.2 Hyperspectral image analysis

Numerous techniques exist to analyse hyperspectral imaging data, all of which aim to optimally reduce the immensity of the data while retaining important spatial and spectral information with the power to classify important chemical or physical areas of a scene. Typical steps followed in analysing hyperspectral images are briefly described below.

Image calibration

Hyperspectral image calibration is required to account for spectral and spatial variations in light source intensity, detector response, and system optics. Calibration of spectral response can be achieved using narrow-band light sources (e.g. laser ‘pen lights’) or calibrated standard reference materials such as NIST (National Institute of Standards and Technology) glasses, and this calibration should be verified periodically. Spatial calibration over the field of view of the HSI instrument should be carried out using a spatially and spectrally homogeneous sample (e.g. flat ceramic tile). Intensity calibration is required to compensate for changes in the detector response and should be carried out using certified reference standards (e.g. Spectralon grayscale standards). Development of suitable reflectance standards and use of correct calibration transformations remains a challenge in hyperspectral imaging. Spatial and intensity calibration should, at the very minimum, be carried out on a daily basis as small changes in electrical power sources, illumination, detector response and system alignment may result in significant changes in the detected response. Inclusion of *internal reference* standards in each hyperspectral image acquired is recommended; this is also a good way to monitor the performance of the system over time.

Spectral and spatial pre-processing

Pre-processing is usually performed to remove non-chemical biases from the spectral and spatial information contained in a hyperspectral image (e.g. scattering effects due to surface inhomogeneities) and to prepare the data for further processing. A number of spectral pre-processing techniques exist, including polynomial baseline correction, Savitzky-Golay derivative conversion, mean centering and unit variance normalisation. Spatial operations usually carried out at the pre-processing stage include (but are by no means limited to): thresholding and masking to remove redundant background information from the *hypercube;* image filtering (e.g. Gaussian filtering) to decrease noise and interpolation (e.g. bilinear interpolation) to decrease image size.

Classification and regression

Classification of hyperspectral images aims to identify regions or objects of similar characteristics using the spectral and spatial information contained in the hypercube. Various unsupervised methods, including Principal Components Analysis (PCA), k-nearest neighbours clustering and hierarchical clustering, can be applied in either the spectral or spatial domains to achieve classification. These methods are particularly useful in the analysis of samples of unknown composition, enabling the identification of spectral and spatial similarities within or between images that can further be used for their characterisation. PCA is commonly used as an exploratory tool in hyperspectral imaging, as it represents a computationally fast method for concentrating the spectral variance contained in the > 100 image planes of a HSI image into a smaller number (usually < 10) of principal component score images. Supervised classification methods, including partial least squares discriminant analysis (PLS-DA), neural networks, linear discriminant analysis and spectral angle mapping require the selection of well-defined and representative calibration and training sets for classification optimisation. One of the major advantages of HSI in this respect is the sheer volume of data available in each hypercube with which to create calibration and training sets.

Hyperspectral image regression enables the prediction of constituent concentration in a sample at the pixel level, thus enabling the spatial distribution or mapping of a particular component in a sample to be visualised. Many different approaches are available for the development of regression models (e.g. partial least squares regression (PLSR), principal components regression (PCR), stepwise linear regression), all of which require representative calibration sets containing spectra with corresponding accurate reference values (e.g. fat content, protein content). This poses a problem in hyperspectral imaging: it is practically impossible to measure the precise concentration of components in a sample at the pixel scale and therefore impossible to provide reference values for each pixel spectrum. To overcome this, regression models may be built using mean spectra obtained over the same region of sample (or a representative region) on which the reference value was obtained. After model optimisation through training and testing, the regression models developed using the mean spectra can be applied to the pixel spectra of the hypercube, resulting in model predictions at the pixel level. This results in a prediction map in which the spatial distribution of the predicted component(s) is easily interpretable. An example of this approach is presented in the following section.

Image processing

Images from different planes in a hypercube may be combined using algorithms based on straightforward mathematical operators, e.g. addition, subtraction, multiplication and division. Image processing is also carried out to convert the contrast developed by the classification/regression analysis into a picture depicting component distribution. Greyscale or colour mapping with intensity scaling is commonly used to display compositional contrast between pixels in an image. Image fusion or false colour mapping, in which two or more images at different wavebands are represented as red, green, or blue channels and combined to form a new RGB image may be employed to enhance apparent contrast between distinct regions of a sample.

2 Potential applications of hyperspectral imaging in dairy foods

Technological advances in spectrograph and detector design leading to decreased cost and improved instrumentation have enabled hyperspectral imaging (HSI) applications to increase in number and widen in scope over the past twenty years (**Figure 3a**). Reported applications of HSI in food science and technology (while not as numerous as those in established HSI disciplines such as remote sensing) are rapidly emerging (**Figure 3b**), with the majority of reported research concerning quality control of vegetable, fruit, grain, meat and poultry products. There have been, to date, very few reported applications of HSI to dairy foods; its use as a research tool in dairy science has not yet been exploited. However, a wide range of quality and safety testing practices in the dairy industry could be complemented and potentially improved with HSI. Therefore, it is expected that research on its application in dairy science will expand in the future. In the following sections, the few reported applications of HSI to dairy products are discussed, and potential applications are explored.

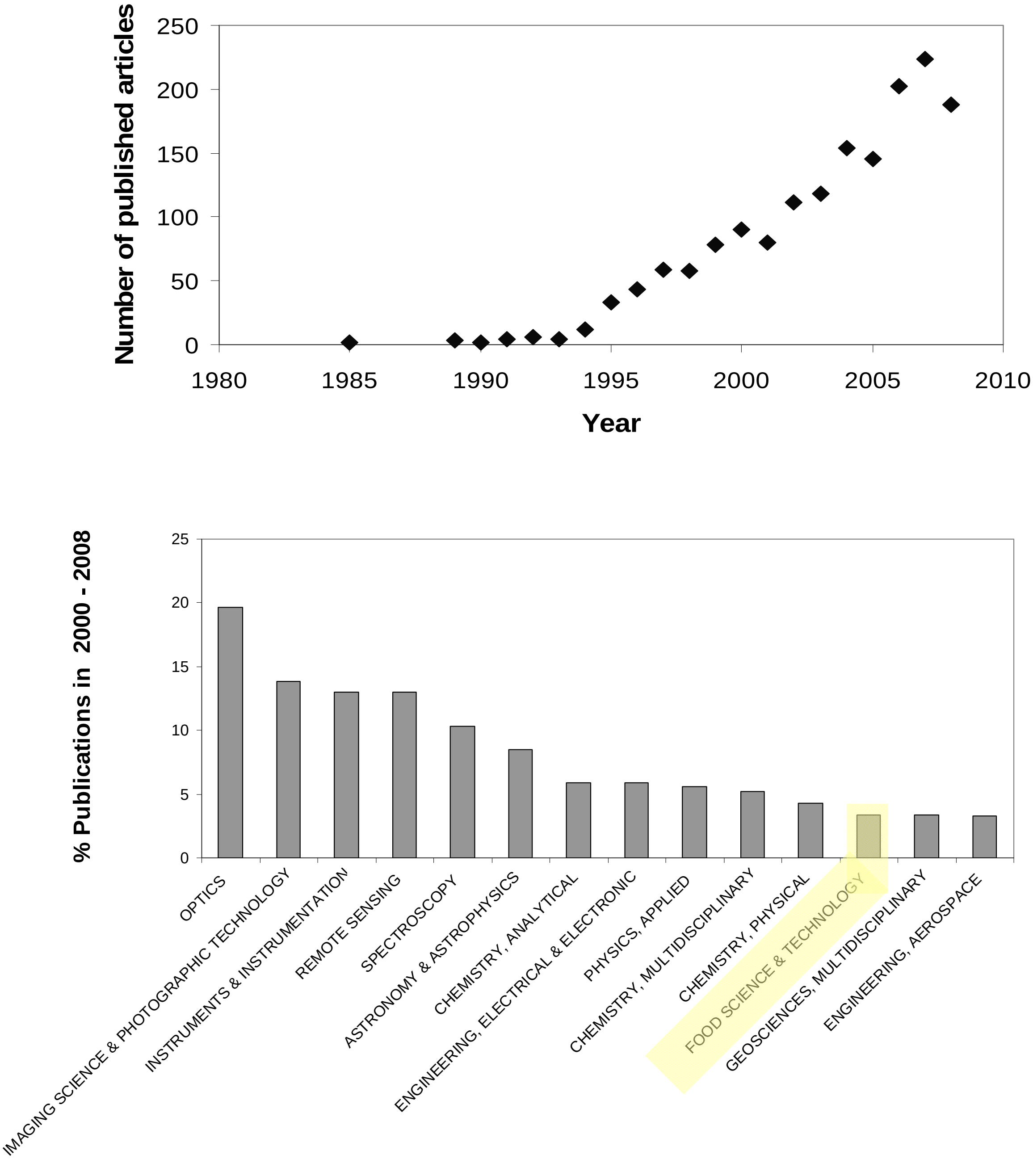

Figure 3a: Number of published scientific articles with “Hyperspectral Imaging” or “Chemical Imaging” or “Imaging Spectroscopy” in the title (Source: Web of Science Citation Reports, January 2009).

2.1 Process monitoring

Dairy products are subjected to numerous heat, pressure, mixing and fermentation stages during processing to produce from milk the wide range of dairy products currently available, such as cream, butter, cheese and yoghurt. Driven by international economic, social and legislative trends, dairy production has increasingly shifted from small-scale farm production to high volume industrial-scale processing. Advances in computer processing technology have enabled an increased level of integration in the automation and control of dairy processes. Automated dairy processing and manufacturing units are required to consistently meet the stringent safety and quality standards set out by food regulatory agencies. Monitoring these unit process operations and characterizing their influence of final product quality is a major challenge for dairy producers. Potential applications of HSI in the control of some typical dairy processes are described below.

Milk homogenization

The yield and functional properties of subsequent dairy products is influenced by the homogeneity of the milk used in their production. Milk is an emulsion in which globules of fat are dispersed among a matrix of water, sugars and proteins; the fat and aqueous phases of this emulsion do not mix, and large fat globules rise quickly,, causing the formation of a layer of cream on top of the milk. During the homogenization process, high pressure and temperature treatments are applied to reduce the size of fat globules (to approximately 1 - 2μm) in order to produce a stable emulsion. Hyperspectral imaging may be used to measure size distribution of fat globules in milk during the homogenization process, since concentration of fat in milk varies spatially. If HSI could be applied in this context, it could lead to improved characterization of the effects of process parameters (temperature and pressure) on particle size distribution and thus more accurate prediction of the end-point of the homogenization process. However, due to the dynamic spatial nature of liquid samples such as milk, the pushbroom hyperspectral imaging set up would probably not be viable in this particular application. The staring face imager set up may be more appropriate, but the relatively long acquisition times (1-2 min) required for the tunable filter set-up would also pose problems. One compromise to overcome the problems posed in hyperspectral imaging of liquid foods is to scan just one line of a sample; thus obtaining spectra resolved in just one spatial dimension. This would allow for the distribution of different sizes of fat globules to be estimated along one spatial axis, which would be useful in determining the uniformity of homogenization achieved.

Milk coagulation and curd formation

Scattering of light is intrinsically related to the size and distribution of particles in a sample; for example, smaller particles of glass tend to scatter more light and appear whiter in colour than larger ones. Changes in the light-scattering properties of milk due to modifications in the size and distribution of fat globules can be used for automatic non-destructive quality control of the cheese-making process. Monitoring changes in the optical properties of milk arising during coagulation and curd formation using Vis-NIR spectroscopy and RGB imaging is well documented. These light scattering properties have been successfully exploited in the development of on-line sensors based on Vis-NIR spectroscopy for optimization of the gel cutting step in cheese making. Hyperspectral imaging may offer improved characterization of the coagulation and curd formation processes, through spatial characterization of the spectral response. The time required (typically 1-2 min for current instrumentation) for hyperspectral image acquisition may limit its use, since milk is a spatially dynamic product; hyperspectral line scanning as mentioned in the previous section may also be useful here.

Dehydration

Spray drying is commonly employed for the preservation of dairy products and in the production of milk powders. The resulting chemical, microbial, physical, functional and organoleptic properties of the dairy product are highly dependent on the drying conditions applied. The potential of HSI in monitoring the drying process lies in its ability to provide spatial information on the distribution of water in a sample. Water molecules have known absorbance features in the Near Infrared and absorbance patterns in this wavelength region may also be used to differentiate between free and bound water in a substance. Consequently, HSI may be used to generate moisture distribution profile maps for products during dehydration and to investigate the effects of various drying parameters on final product quality. This would enable estimation of accurate drying end points in dairy powder production and also improve quality assurance of the final product. Moreover, HSI may be used to detect any problems in the drying process, e.g. non-uniform drying due to equipment malfunctions would be detected by non-uniform moisture profiles in a product. Examination of the surface composition of milk powders, which is known to differ from their bulk composition, is another area in which HSI may potentially be applied.

Blending

The HSI technique has an added advantage over traditional bulk quality measurement techniques in its ability to detect problems arising during processing. HSI can be used to spatially map the distribution of components within a food product during manufacturing, allowing direct qualitative comparison with control products. This would be useful in monitoring the process of blending in dairy food production, which is important since the uniformity of blending directly affects the final product quality. For example, regions of ingredient agglomeration in blended dairy products may be identified and related to inadequate blending protocols. The potential application of HSI has already been demonstrated in monitoring of blend homogeneity of powder and tablet forms in pharmaceutical processing . HSI may also be used to estimate particle size distribution during processing, enabling improved monitoring of the blending process, more accurate estimation of blending end points and enhanced insight into the behavior of dairy products during blending.

2.2 Compositional analysis

Dairy products are complex food matrices assemblies of dissolved, suspended and emulsified substances, fat in globulular and continuous forms, proteins, carbohydrates, minerals and vitamins. Traditional wet chemistry methods for compositional analysis of dairy foods are labour intensive, time consuming and require sample destruction. Numerous studies have been reported which demonstrate the effectiveness of Near- and Mid- Infrared spectroscopy for non-destructive prediction of dairy food composition(e.g. for the prediction of fat; protein and lactose). Hyperspectral imaging provides the added potential to simultaneously estimate the spatial distribution of numerous components in a sample while also predicting average compositional information. A number of authors have published work on the application of HSI to estimate the distribution and concentration of active ingredients in pharmaceutical products and its potential for prediction of the location of components such as water, fat and protein in food products has also been demonstrated. Qin and Lu have recently applied hyperspectral diffuse reflectance line scanning for rapid determination of the optical properties of turbid liquids, using the spatially resolved scattering of light in the Vis-NIR region to predict fat content in milk.

In 2006 an application of HSI to cheese products in 2006 in an article on NIR hyperspectral image regression was published. A range of 12 commercial cheese products were tested, specifically selected to span as wide a range as possible in terms of protein, fat and carbohydrate content. The average composition values on the packaging labels were used as standard reference values and a parallel set of reference values for protein and fat content was determined using standard techniques. The challenges of developing accurate calibration models using hyperspectral image data were discussed. One major issue is that reference values were only available for entire bulk samples, not at the individual pixel level! To overcome this limitation, the authors used the mean spectral response from sample images to build calibration models. Partial least squares regression (PLSR) models were developed on mean spectra subjected to various spectral pretreatments, and (considering the prediction error of the regression models) results suggested that applying a 1st derivative Savitsky-Golay smoothing was the most effective spectral pretreatment. Using this approach, a PLSR model with 2 or 4 latent variables could be used to satisfactorily predict fat, protein, and carbohydrate. Typical prediction errors of 1%–2% for protein and fat, and 2%–3% for carbohydrate were obtained, which were greater than the errors in the reference measurements (0.14% protein and 0.41% fat) but similar to results reported for other NIR spectrometers.

The regression models developed on mean spectra and bulk reference values were then applied to pixel spectra for each hyperspectral image studied, to generate prediction maps showing the distribution of each component as estimated by the calibration model. **Figure 4** shows the false colour maps for the 2-latent variable PLSR models for prediction of protein (green), fat (red) and carbohydrate (blue) on the 12 individual cheese samples studied. For comparison purposes, the false colour of the combination of expected values of the three ingredients was depicted in a smaller rectangle below each prediction image. Colour intensities were scaled such that the ranges of protein, fat and carbohydrate contained in the calibration set were mapped to the full scale values of red, green and blue. The colour matching between expected and predicted values was quite good, indicating the usefulness of HSI in prediction of mean composition. Some inhomogeneous regions are noticeable as changes in colouration of the images, which in some cases do not appear to be uniformly distributed; these may indicate areas of non-uniform fat and protein distribution, which may in turn be related to processing parameters involved in the production of the selected cheeses.

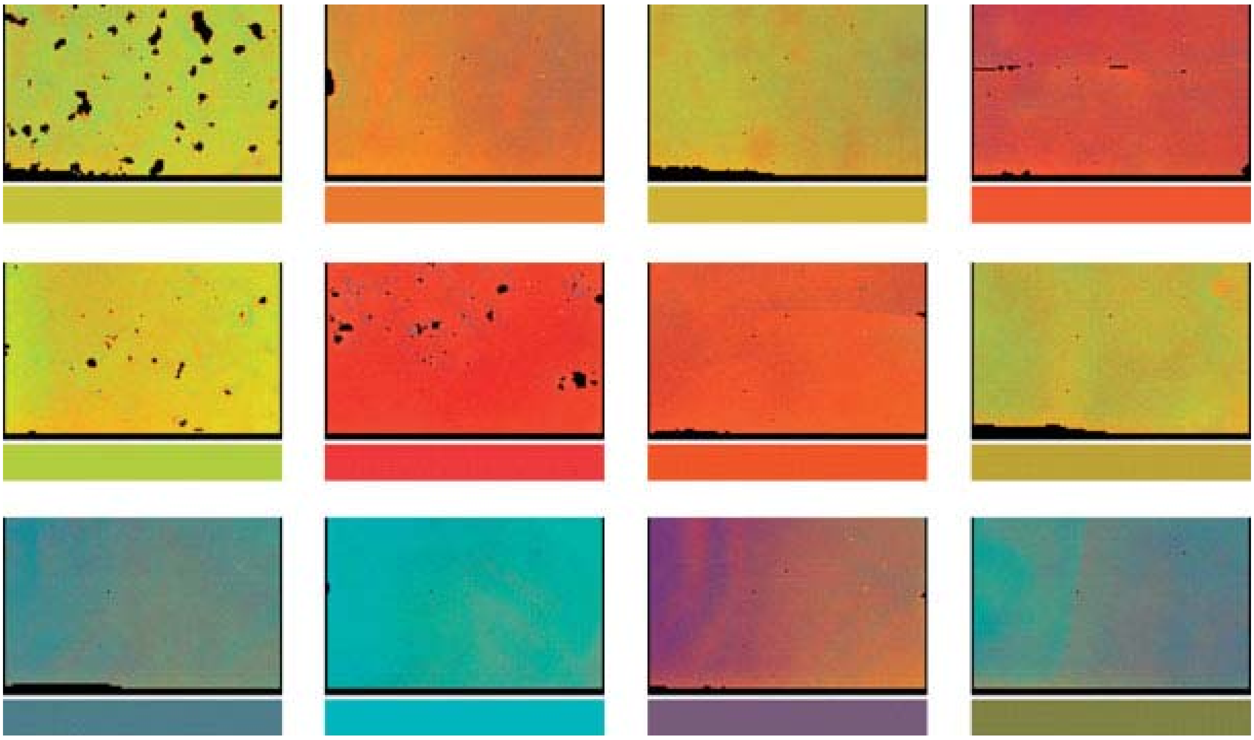

Figure 4: False colour concentration prediction maps for 2 component first derivative spectra models of 12 different cheeses A smaller rectangle below each prediction map indicates the target 'colour' expected. Rectangular cheese regions are 209 x 320 pixels in size corresponding approximately to 50 x 62 mm^2. (BURGER & GELADI 2006).

2.3 Prediction of functional properties

The expression "functional properties" is a broad term in food science, collectively given to factors that describe properties of foods relating to their quality. Functional properties of foods are intrinsically related to their composition and structure; consequently, processing methods that alter dairy product composition and structure directly affect their functional properties. Potential applications of NIR spectroscopy and conventional RGB imaging have been reported for the prediction of functional properties of dairy products; some examples include: turbidity and viscosity of milk; free oil formation and meltability of cheese. Other optical techniques reported for monitoring structural changes related to functional properties in dairy products include confocal laser scanning microscopy, scanning and transmission electron microscopy and magnetic resonance imaging.

Control of functional properties in dairy products demands an understanding of where the constituent components (e.g. fat, protein) are located in relation to each other, and how they are modified during processing. HSI presents a relatively low cost method for examining the distribution of components within a sample, which may be useful in monitoring the development of functional properties during processing. Hyperspectral imaging would enable improved image contrast not available with RGB imaging, and provide additional insights as to the effect of underlying composition distribution on functional properties. One example where HSI may be particularly useful is in NIR monitoring of free oil production in cheese, as oil is semi-transparent to visible light captured in RGB imaging. Functional properties of milk powders, including flowability and particle size distribution could also potentially be evaluated using hyperspectral imaging, since these properties directly relate to the concentration and size of constituents in the powders expressed as light scattering differences, which may be examined using HSI.

2.4 Classification

Accurate classification is critical for pricing, authentication and categorization of dairy products. Products may be classed based on their geographical origin, composition, functional properties, maturity and on manufacturing methods used in their production; for example, milk and cream products are priced based on their fat content. Therefore, rapid and accurate classification techniques would represent an economic benefit for producers. The multivariate nature of dairy product classification, combined with the knowledge that many dairy food components exhibit characteristic light absorbance and scattering behavior in the NIR make NIR spectroscopy well suited to many classification tasks. Multispectral imaging has been employed in the classification of blue cheeses based on product type and producer using a custom made system capable of recording images at 8-wavebands in the UV-Vis-NIR wavelength regions.

Hyperspectral imaging offers exciting new opportunities in object classification, based on spatial and spectral properties of samples. This method is particularly well suited to the classification of cheese products, where distribution and concentration of ingredients is a key grading parameter. In order to demonstrate the potential of HSI in classification of cheese products, a hyperspectral image of 12 pieces of high fat and low fat cheese slices (purchased from ‘Marks and Spencer retail outlet, Dublin), arranged on a piece of black cardboard were obtained using a pushbroom hyperspectral imaging system operating in the wavelength region 400 – 1000 nm. For comparison, an RGB image of the cheese samples studied (obtained using a digital camera) was acquired, shown in **Figure 5a**; all cheese samples appear similar in colour and appearance. However, looking at the mean HSI spectral profiles of each product, it is evident that the full fat product reflects more light in the visible (500 – 950 nm) wavelength range. These spectral features may be used to classify each pixel of the hyperspectral image into one of two or more groups. In the present case a spectral angle mapping algorithm, which compared the similarity of the spectrum of each pixel in the hyperspectral image with the mean spectra shown in **Figure 5b**, was applied and each pixel was classified as full fat or half fat depending on it's similarity to each mean spectrum. Although the algorithm correctly classified most pixels, some edge regions in the half fat samples were misclassified, possibly due to lighting in-homogeneities at edge regions.

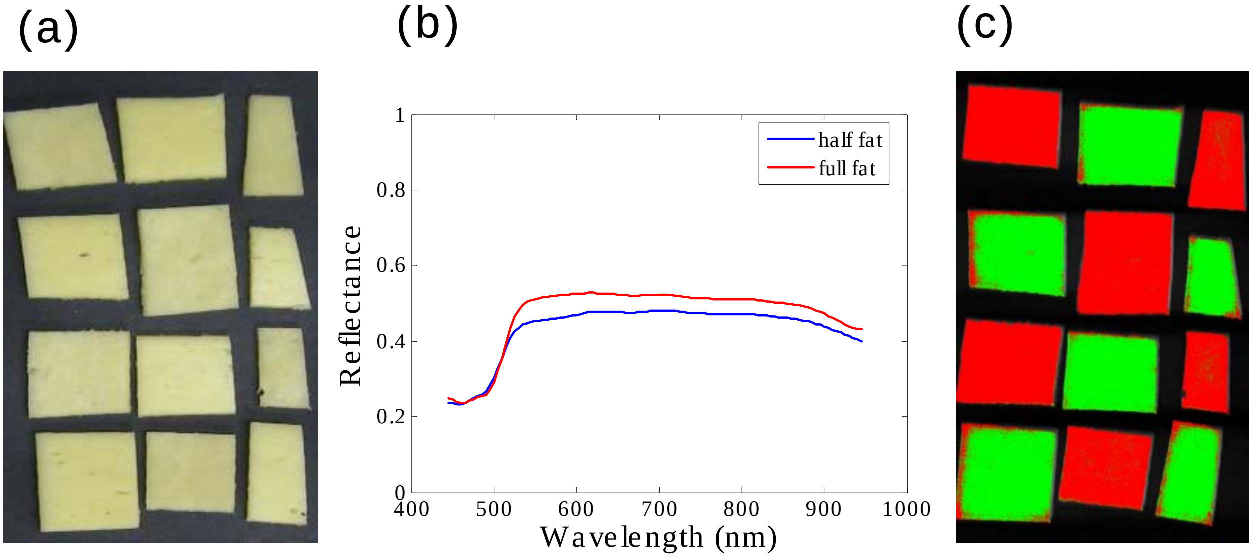

Figure 5a: RGB image of cheese samples studied; (b) Mean spectral of half and full fat cheese samples; (c) cheese classification map (red = half fat, green = full fat) obtained using Spectral Angle Mapper algorithm.

2.5 Safety testing

In order to assure product safety and compliance with food regulatory standards, there is a need for rapid monitoring systems sensitive to low levels of microbial contamination in food production. One of the major successful applications of hyperspectral imaging in food monitoring has been in safety testing of poultry products; an on-line system for detection of fecal and ingesta contamination has been developed. More recently, HSI has been proposed for identification of specific microbial contaminants, suggesting that HSI may be a useful tool for studying the growth of microbial colonies. HSI may prove useful in safety testing of dairy products throughout the various processing stages: from raw milk, to processed milk products, and on to the classification of waste products. The potential of HSI in detection of contamination on dairy foods and identification of pathogenic micro-organisms would be useful at both the laboratory and process monitoring scales. At the lab scale, changes in appearance of dairy products occurring as the product reaches the end of its shelf life, such as the growth of moulds, may potentially be monitored using HSI, leading to the development of early detection systems using HSI. The potential use of HSI in product classification as outlined in the previous section may be useful in authentication of dairy products, ensuring their traceability. The HSI technique may also be useful for monitoring adulteration in dairy products, offering consumer protection against products containing substituted non-dairy ingredients.

HSI may also find potential application in foreign body detection for the safety assurance of dairy products. As an example, a slice of cheese contaminated with a 3 mm shard of plastic was imaged using a pushbroom NIR hyperspectral imaging system operating in the wavelength range 950 – 1650 nm. A digital RGB image of the cheese is shown (**Figure 6a**), in which the plastic shard, although visible (placed in the upper right hand region of the cheese slice), may be difficult to distinguish from the cheese background. The mean reflectance spectra of the cheese and plastic are also shown (**Figure 6b**), and spectral differences are apparent; the plastic contaminant exhibits a sharp absorption band at around 1170 nm. Principal component analysis was applied to the hyperspectral image, and the resultant second component principal component image is shown (**Figure 6c**). This principal component image, which represents a linear combination of the image at all wavelengths (>100) imaged, shows up the contamination with far greater contrast than the RGB image. This simple example demonstrates the potential of HSI for foreign body contaminant detection in dairy foods.

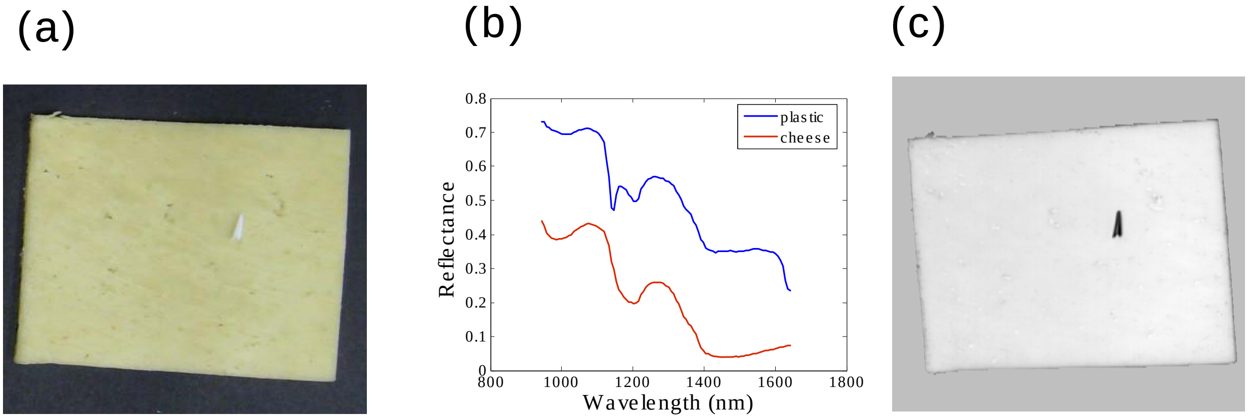

Figure 6a: RGB image of cheese and plastic shard contamination; (b) mean spectra of cheese region and plastic region; (c) image obtained after applying principal component analysis to hyperspectral image of cheese with plastic contamination (plastic contamination appears as dark region on cheese sample).

3 Conclusions

Hyperspectral imaging offers new possibilities to researchers and producers in food science; by combining spectroscopy and imaging, this tool can be used for mapping distribution of constituents over the surface of a sample. This capability may be useful for dairy food analysis at the laboratory research scale and further the development of both laboratory and online monitoring technologies in the dairy industry. Future improvements in precision and speed in hyperspectral imaging are likely to arise with improved lighting systems, higher quality photometric sensors and faster hardware. As hyperspectral imaging continues to emerge as a tool for food quality and safety analysis, and with new systems offering much faster image acquisition and processing times than ever before, the potential role for this technology in the monitoring and control of dairy food processes seems very promising. It is anticipated that the number of applications of this technology to problems in the dairy industry will increase rapidly in the coming years.