PHARMACEUTICALS

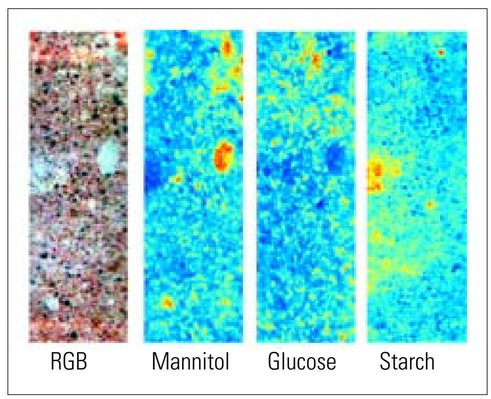
Hyperspectral and Chemical Imaging

Chemical imaging is the application of hyperspectral imaging to identify and quantify chemical components of a sample or product and its dispersion or homogeneity. Chemical imaging typically uses the near-infrared (NIR) or short-wave (SWIR) infrared ranges, which contain information about chemical bonds, in contrast to hyperspectral imaging, which uses any wavelength range, from visible to long-wave infrared. Organic chemicals that comprise most pharmaceutical products have unique spectra in the NIR and SWIR ranges. Spectral information allows identification and quantification of chemical components within a sample. Chemical imaging is used in many areas of pharmaceutical research and industry, including blending, tablet production monitoring, and counterfeit product identification. Application examples are described below.

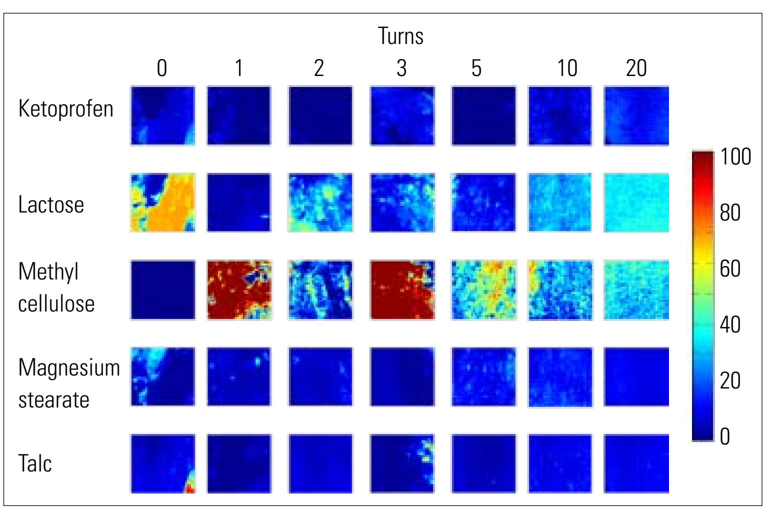
Blending

Chemical imaging is used in the pharmaceutical industry for process validation. FDA regulations require control of the drug content at various stages of the manufacturing process, including granulation and final blending. Statistical sampling for content uniformity assessment is straightforward, but in practice, there is a potential for sampling bias when only a small sample volume is extracted (Berman, 2005). Pharmaceutical companies are discovering that chemical imaging is an effective and efficient way to detect problems in blending and tableting (El-Hagrasy, 2001, Lyon, 2002).

For several years, blending has been monitored using the near-infrared region to non-invasively determine the concentration of an active ingredient in a sample (Ma, 2007). The challenge is that by taking one single-point measurement at a time (for example during one rotation of the blender), the distributions of the ingredients are not revealed. The image (below left) illustrates ideal blending. Multiple components can be predicted from the same hypercube of data. The images (below right) are calculated concentration maps of three different, poorly mixed components. They demonstrate the rich detail available from hyperspectral imaging.



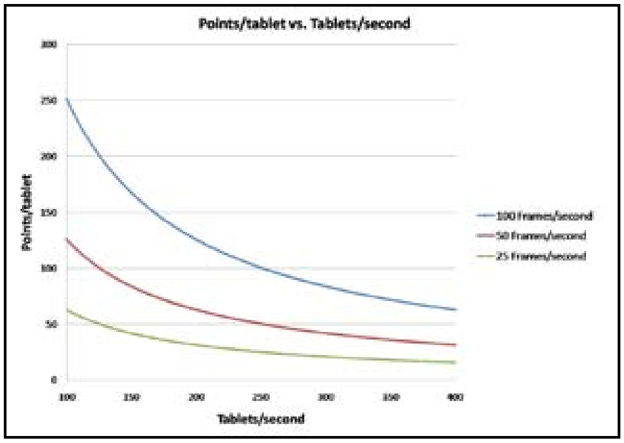
One hyperspectral image datacube can detect areas of poor blending, the location of high concentration pockets of particular constituents, as well as the progression of the blending. The predicted images for the first few turns of an experimental blend, taken after each rotation of the blender, are shown below (Kemeny, 2010).

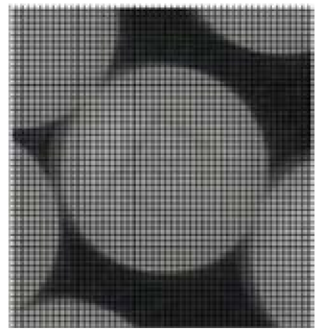


Concentration prediction images from the PLS prediction of five components. Hyperspectral images were taken prior to blending (turn 0) and after specified rotations. Coloring corresponds to a 0-100% scale of the specified component.

Tablets

Pharmaceutical tablets can be monitored on the production line with hyperspectral imaging. To establish the possible optical coverage at real production speeds, the relationship between the speed of tablets measured and the resolution of the image is plotted below in a SWIR camera example (320 pixels per sample width). For this calculation, it is assumed that the tablets are of uniform diameter and arranged in a square pattern. The hyperspectral camera operates with the push-broom method, collecting one line of sample data in each frame. At 100 frames per second, for example, it is possible to image 200 tablets per second with a spatial resolution of 125 pixels per tablet. An approximation of the image points per tablet is shown below. With fewer measurement points on each tablet, the number of tablets covered can be increased even further. As a screening tool, uncoated tablets can be measured to detect uneven distribution of ingredients, whereas coated tablets can be measured to check for potentially uncoated or unevenly coated areas.





Spatial resolution on tablet imaged with SWIR hyperspectral camera

Counterfeit Identification

Identifying counterfeit products is extremely important in the pharmaceutical industry, as the number of counterfeit drug products has grown exponentially in recent years. Counterfeit drugs have serious potential health risks to the consumer, and can also jeopardize the reputations of pharmaceutical companies. (Puchert, 2009) Hyperspectral imaging combined with chemometric data analysis is a useful method for identifying off-specification products. Hyperspectral cameras can be placed over a moving line of products to efficiently scan and report counterfeits in real-time, or products can be measured individually off-line.

Chemical imaging provides several advantages over older methods of identifying counterfeit pharmaceuticals. In contrast to chromatographic assays and dissolution testing, chemical imaging is fast and non-destructive. (Dubois, 2007) Researchers at the Institute of Pharmacy and Molecular Biotechnology in Germany demonstrated that near-infrared chemical imaging is an innovative, effective and non-destructive way to detect counterfeit tablets by discovering differences between amount and spatial distribution of ingredients within a genuine or counterfeit tablet. (Puchert, 2010)

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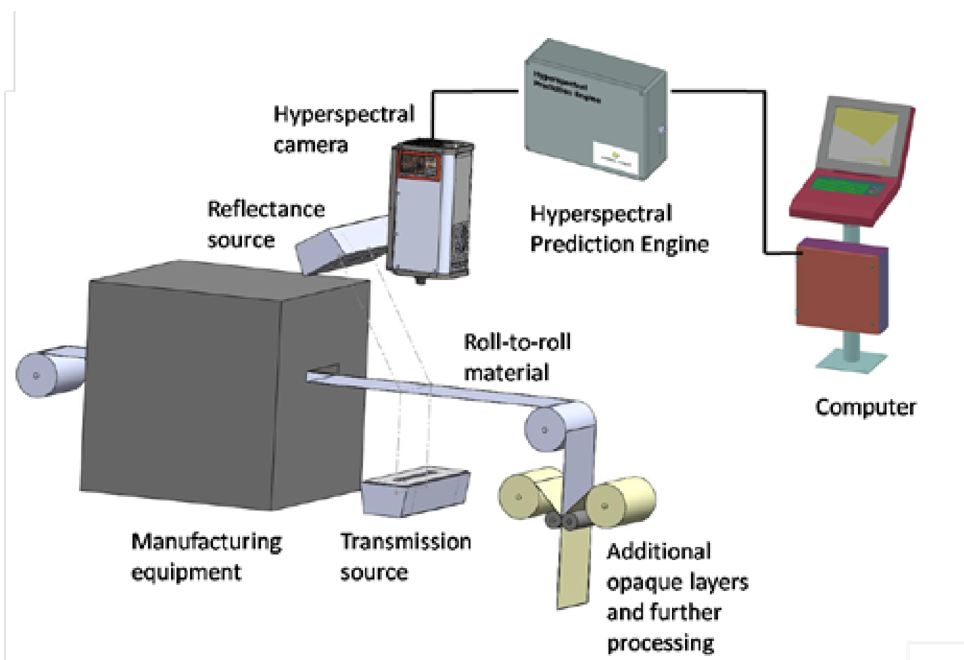
PROCESS ANALYTICAL TECHNOLOGY

Process Analytical Technology (PAT), is defined as "a system for designing, analyzing, and controlling manufacturing through timely measurements (i.e., during processing) of critical quality and performance attributes of raw and in-process materials and processes with the goal of ensuring final product quality" (FDA, 2009). The goal is for pharmaceutical industries to understand upstream factors contributing to product qualities and flaws by more efficiently evaluating and monitoring production processes rather than a singular focus on end-product inspection. The result is more efficient, effective processing, fewer rejects, and higher quality products overall.

On-line Monitoring of Continuous Manufacturing

Numerous manufactured products can be monitored during production using advanced hyperspectral imaging (HSI) technology. Middleton Research provides custom systems development and integration for monitoring myriad on-line applications, such as pharmaceutical films, patches, blends, and tablets. HSI technology is ideal for non-contact/non-destructive, on-line analysis. A push-broom camera focused on the production line images the moving product during manufacturing. By capturing both spatial and spectral information simultaneously, off-specification chemical composition, poor dispersion of ingredients and other nonconformances can be identified from spectral signatures. For many pharmaceutical products, the correct spatial location or pattern of the active ingredient within a formulation is crucial to achieve the desired effect. Immediate analysis of nonconformances during continuous manufacturing can reduce costs of manufacture compared to batch manufacturing and off-line analysis. HSI supports PAT principles by controlling for factors causing out-of-specification products.



Validation System

The hyperspectral camera, as a multi-point parallel near-infrared spectrophotometer, is validated using a protocol similar to the USP <1119>. The actual values of resolution, signal-to-noise ratio, and linearity are specific to the type of camera system, but the validation protocol uses the same NIST traceable standards with similar protocols developed for single point spectrometers.

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FOOD AND AGRICULTURE

Evaluating plant and vegetation quality is important for the production of grains, fruits and vegetables in industry, as well as tracking the effects of disease, climate changes, and other factors on natural environments. Similarly, excellent quality control monitoring is crucial in food processing, due to the potential for adverse affects on the health of entire populations. For example, outbreaks of *E. coli* in spinach and salmonella in peppers and peanut butter affected more than 20,000 people in recent years. (Maki, 2009) Hyperspectral imaging provides a means to easily inspect the entire surface of a product, significantly improving upon the random inspections made possible by pull samples and subsequent laboratory tests.

Wheat Kernel Analysis

Insect infestation is a devastating problem for various types of agricultural crops, and is considered one of the most widespread causes of crop degradation in the United States and Canada. Because government policies prohibit live insects, insect fragments, and other insect contaminants in wheat kernels, undetected insect-infested kernels can pose major economic and credibility risks for grain distributors. Hyperspectral imaging technology can be used by grain suppliers and distributors to mitigate risk of contaminated products entering the food chain. In a study conducted at the University of Manitoba, Canada, hyperspectral cameras were used to separate insect-damaged wheat kernels from healthy wheat kernels. Researchers found that scanning wheat kernels in the 1000 - 1600 nm range was an effective way to separate healthy and insect damaged kernels, with success rates between 85-100%. (Singh, 2008)

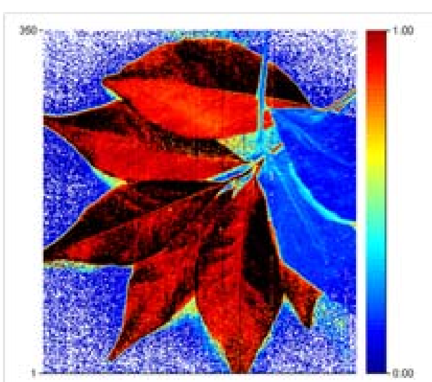
Citrus Ripeness

It is easy to detect citrus fruit ripeness and project yield when the fruit is in its more advanced stages and its color differs from that of the tree. However, it is much more difficult to do the same in earlier stages of fruit maturation. Researchers from Hokkaido University in Japan and the University of Florida used a hyperspectral camera in the 360-1042 nm range to estimate citrus yield from early stage green fruits. The results of pixel-identification tests from hyperspectral images demonstrated that 80-89% of the fruit in the validation sets were identified correctly. This information helped growers to adjust site management practices and other factors. (Okamoto, 2009)

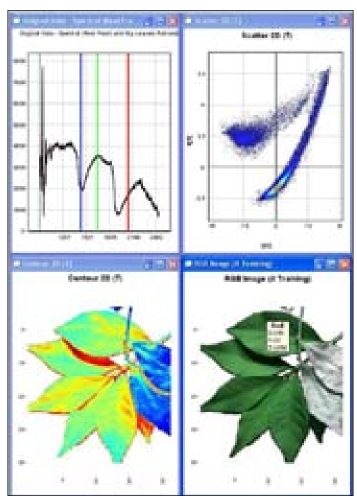
Plant Moisture Content

Fresh leaves and leaves dried to various levels were measured using a SWIR (1000 - 2500 nm range) hyperspectral camera. The samples were placed on a moving tray beneath the camera, and by line-scanning across the samples the camera measured the full spectrum of each individual point of the sample area.

The images to the right show fresh and fully dried leaves analyzed with hyperspectral software programs. From the hypercube of spectral data, the software easily differentiates the fresh and dried leaves and readily identifies not only the degree of drying but also the uneven distribution of the moisture as a consequence of drying. Similarly, plant diseases and other damaged plants can be detected in the laboratory, in a process environment for quality control, or in the field.



SBC prediction of fresh leaves (red) differentiated from the background and dry leaves (blue)



Evince principal component analysis plots of fresh and dried leaves

Production Monitoring

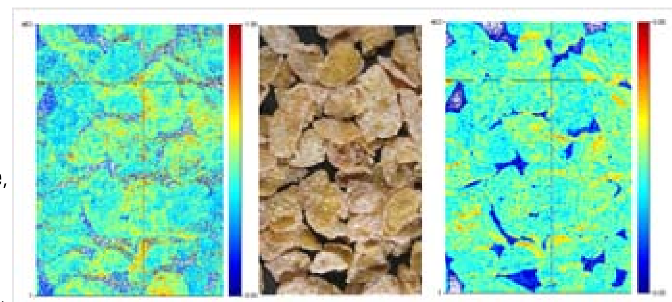
Hyperspectral imaging supports on-line monitoring of food processing by detecting differences in chemical composition, color, or moisture content, as well as recognizing shapes, patterns, defects, contaminants and spatial distribution of other relevant features. By collecting the spectrum of each individual point of the food product, a push-broom hyperspectral camera can be used to monitor the quality of the entire product line as it passes below. In this way, the contaminated or otherwise imperfect food can be easily identified and removed, ensuring better quality products. The SWIR region, capturing important spectral information from 1000 to 2500 nm, is especially powerful for differentiating components of food products, such as seen in the image shown here.

Chocolate pieces in chocolate-chip cookie. Dark chocolate candy on the right side of the image for reference.

The low heat-load from illumination and the high-speed of the push-broom hyperspectral imaging systems are ideal for on-line, non-destructive monitoring. In addition, hyperspectral imaging may be helpful in determining the cause of flawed products. Cameras can be placed over different stages of the moving production line to identify where changes in product quality occur.

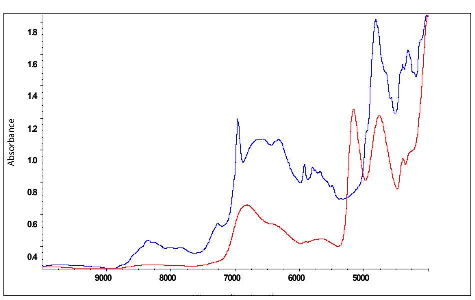
Sugar Coating

It is known that added sugar in foods is somewhat amorphous and partially recrystallizes on the product surfaces. The qualities of different sugars such as nutrition, texture, shelf-life, and dissolution behavior make the determination of amounts and distribution relevant for the manufacturing process. In this example, sugar coated corn flakes were studied. The flakes were illuminated with a halogen line light from about 10 inches, and a Model MRC-303-005-01 SWIR camera scanned the sample at 100 frames per second. The raw data was processed using the SBC algorithm (Marbach, 2002) to produce the sample images shown here.



Crystalline *Cornflakes* *Amorphous*

The algorithm requires use of the pure spectra of the ingredients that are to be predicted. Sucrose, with its characteristic sharp band around 1430 nm was used to predict crystalline sugar, and the spectrum of honey was used as an amorphous sugar model. The model materials were scanned on a FT-NIR instrument using integrating sphere optics and a Middleton Research Model MRC-912-000 Transflectance Liquid Cell accessory was used for the honey sample.



Spectra - red: honey (amorphous), blue: sucrose (crystalline)

The spectral differences between the sugars on the cereal flakes were detectable by the SWIR camera and the composition of the two ingredients predicted online. A complete SWIR camera based process system would therefore be able to determine composition and distribution and report that information to the manufacturing plant process control computer.

Detecting Apple Contamination

A recent food safety example involved visible/near infrared hyperspectral reflectance imaging for the detection of fecal contaminants on apple surfaces. The spectral differences found between the contaminated and uncontaminated surfaces provided the USDA with the basis for creating a universal algorithm to identify fecal matter on apple skins. (Liu, 2007)

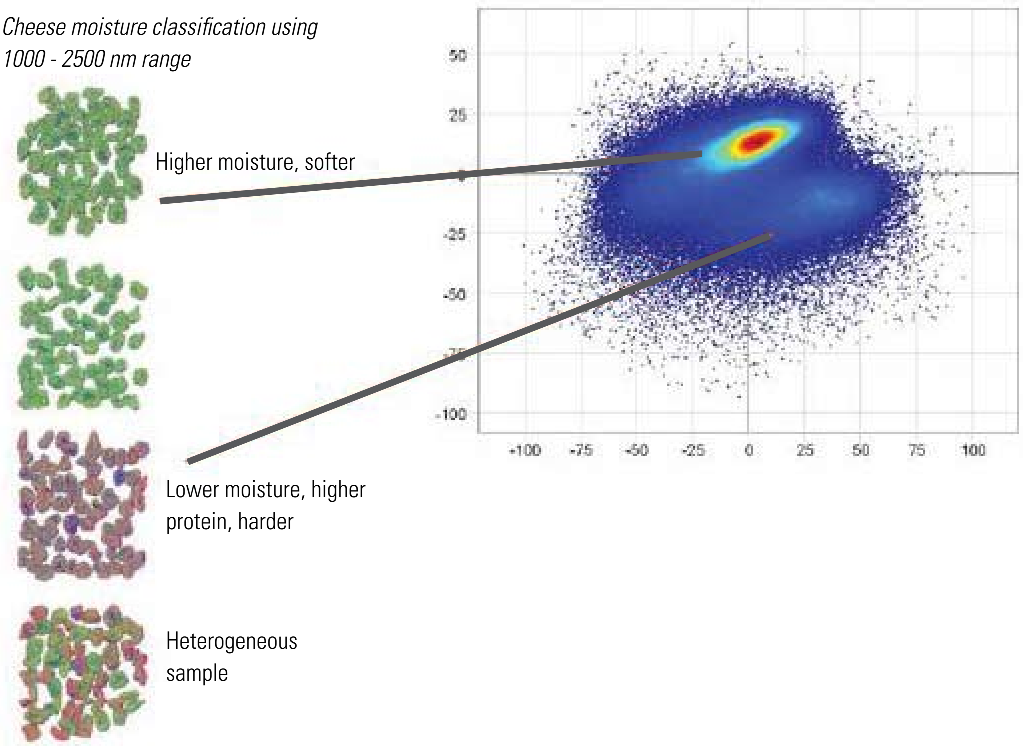
Dairy Applications

Near infrared (NIR) spectroscopy is a technique frequently used to characterize materials and products in the dairy industry. It has proven to be a valuable tool for determining various properties such as solid content, cheese ripeness and milk coagulation. Hyperspectral imaging systems extend the traditional NIR spectroscopy with high resolution imaging by providing detailed, quantifiable information on chemical composition and structural distributions within the sample.

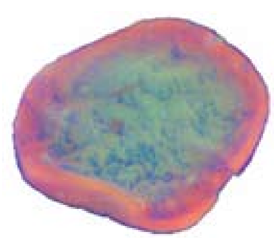
Cheese

The images shown below were collected by a short-wave infrared (SWIR) camera and depict different qualities of cheese granules. A principal component analysis (PCA) was performed on the whole image. As each pixel contains the full NIR spectrum (970-2500 nm), it is possible to distinguish samples of different chemical properties through the use of multivariate methods.

Cheese moisture classification using 1000 - 2500 nm range



The PCA score scatter plot shows two clusters of observations (pixels) separating the two major types of granules. In this case, the granules were analyzed for solid content, moisture and protein. In the picture, the first three principal components were assigned to red-blue-green colors. The greenish granules show low solid content, high moisture and low protein. The reddish granules show higher solid content and more protein.



The image at the right shows a pseudo-colored image of a cross section of a cottage cheese granule created from a NIR image of the first three principal components. The image was created in Evince hyperspectral analysis software and shows the differences in both physical and chemical structure at the surface of the granule.

Predicting Mushroom Quality

Hyperspectral imaging technology was also used by researchers in Dublin, Ireland for quality prediction of white mushroom slices at varying storage temperatures. The mushroom slices were measured with a push-broom line-scanning HSI instrument in the VNIR wavelength range to determine moisture content, color and texture. The results from this study could be used to develop a non-destructive monitoring system for sliced mushrooms in a production setting. (Gowen, 2008)

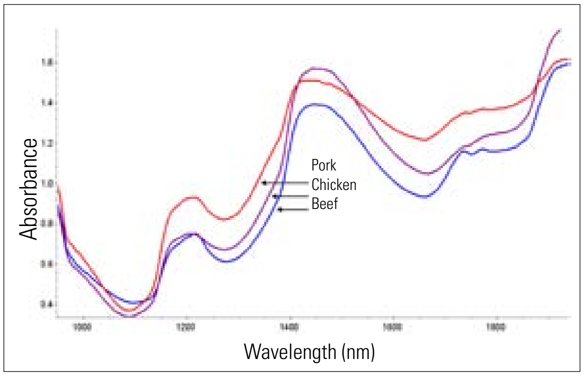
Classifying Grades of Tea

Researchers at Jiangsu University in Zhenjiang, China used hyperspectral imaging to analyze internal and external attributes of tea leaves, such as texture and color. The analysis resulted in a non-destructive tea classification model that differentiates five grades of green tea. (Zhao, 2009)

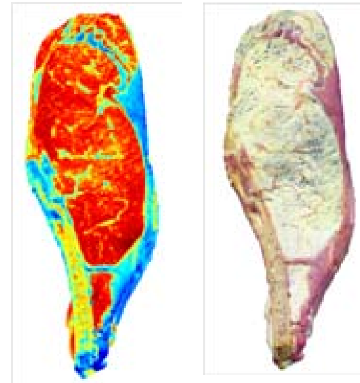
Meat

Hyperspectral imaging can be used to analyze various qualities of meat, such as tenderness, fat, protein and moisture content.

The image to the right was obtained from a SWIR hyperspectral camera in reflectance mode. It shows the spectral variation of different components of a beef steak (fat, muscle, and bone) following a Principal Component Analysis calculation.



SWIR spectra of pork, chicken, and beef



Hyperspectral PCA analysis and pseudo-color RGB image of steak

From top to bottom: Hyperspectral and RGB images of pork, beef, and chicken

Three types of ground meat (pork, beef, and chicken) were also imaged and found to be spectrally distinct. A hyperspectral image of the samples and their average spectra are shown here. From the false-color hyperspectral information in the far left image, clear color differences between the meat types are readily apparent. For some samples, the VNIR and VIS wavelength ranges are also useful for detecting differences in meat characteristics.

Grading Turkey and Ham

Another application of interest is predicting the quality of ham and turkey. Using hyperspectral imaging technology to examine the amount of brine injected in the meat, prediction models were created to accurately and non-invasively estimate ham quality. Researchers at the College of Dublin, Ireland explained that the highest quality ham is cut from a single muscle, which requires less brine injection to produce an acceptable yield. It is known that the more brine meat contains, the lower its quality. The only complication in judging the quality is that despite differing levels of brine content, all grades of ham appear very similar to the naked eye. Using HISI to examine the brine content in the meat slices, researchers were able to classify varying grades of both turkey and ham despite their similar appearance. (Jackman, 2009)

Detecting Diseased Chicken

The USDA has also used hyperspectral imaging to solve meat quality control issues. United States law requires the post-mortem inspection of each chicken by the Food Safety Inspection Service, and the USDA has found that reflectance imaging is a good technique to identify localized diseases/defects. Diseased, bruised or otherwise unwholesome carcasses pose a serious health threat to consumers, so that accurate identification and separation of these carcasses are vital. Hyperspectral imaging in the NIR region has been used to separate good tissue from damaged or tumor-afflicted tissue to ensure that disease carrying poultry carcasses do not reach the processing stage and are subsequently distributed for human consumption. Given such successful results, the USDA is currently investigating other areas in agriculture and food where hyperspectral imaging could be used for grading and inspection. (Park, 2008)

Predicting Meat Tenderness

Researchers at the University of Nebraska, Lincoln used a push-broom hyperspectral imaging system as a non-destructive way to predict the tenderness of cooked beef from the hyperspectral images of uncooked steaks. In this study, a total of sixty-one different beef steaks, in varying cut, were imaged. After imaging and prediction, the steaks were cooked and Warner-Bratzler shear (WBS) force values were gathered as tenderness references. The model predicted each piece of meat according to three tenderness categories: tender, intermediate, or tough. Hyperspectral imaging allowed the researchers to predict the tenderness of meat with 96.4% accuracy. (Naganathan, 2008)

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PHOTOVOLTAICS / SEMICONDUCTORS

Mass-produced electronics such as photovoltaics and semiconductors require efficient methods of manufacture and quality control. Hyperspectral imaging (HSI) can provide this non-contact, on-line monitoring and can be used to identify off-specification products based on thin film characteristics and material composition. HSI can also be used in the same way in a research lab or on a smaller scale. One advantage of push-broom hyperspectral imaging cameras over other monitoring devices is the low light exposure required to image the sample. Because only one line of the sample is illuminated at a time and imaged rapidly, the risk of damaging the material with a high heat-load is significantly reduced.

Solar Cell Quality Control

Researchers at East China Normal University in Shanghai have developed a hyperspectral imaging system that is used to identify cracks and characterize other contaminants and defects early in the production cycle of solar cells. Hyperspectral images capture the diffuse light reflectance to distinguish cracks on polished specular surfaces. (Li, 2010). Film thickness measurement during production is another important HSI application.

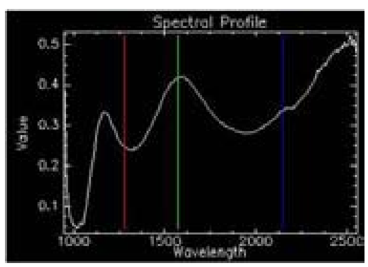
Thin Film Measurement Using Spectral Interference Fringes

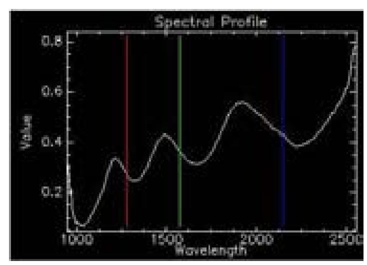
Thin film characterization, including film thickness, refractive index, reflectivity and homogeneity, is important for photovoltaics and semiconductors, as these factors greatly affect the performance of the product. Single point spectral-photometric and spatial uniformity measurements are also critical in these processes. By understanding the interaction between the thin film and light, the characteristics of the thin film can be determined using the interference pattern (or fringes) created from the partial reflection/transmission of the thin film surfaces. The thickness of a thin film can be calculated if both the angle of incidence and refractive index are known. Both sides of the thin film reflect light and have a phase relationship dependent on the two optical path lengths. The phase relationship creates an interference pattern that can be used to calculate the thickness of the thin film using the equation below. This equation assumes a constant index of refraction; more complex formulas can be used in cases of significant changes in the refractive index as a function of wavelength.

$$d = m / (2 D_n \sqrt{(n^2 - \sin^2\theta)})$$

Where:

d = film thickness
m = number of fringes in wavelength region
n = refractive index
θ = angle of incidence
D_n = wavelength region used (λ_1 - λ_2, in wavenumbers)





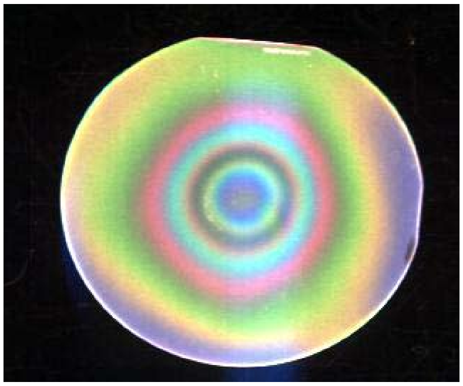
The same measurement and calculation of thickness can be performed using hyperspectral push-broom type cameras, covering the whole surface of the samples, as described in the next example.

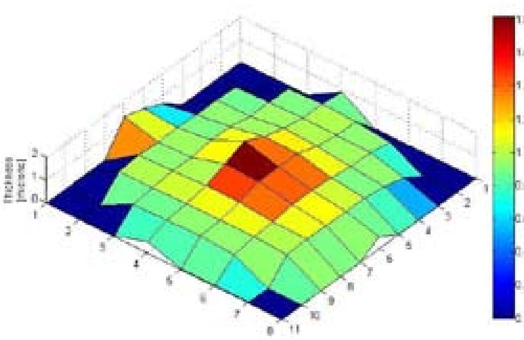
Full Surface Thickness Measurement

As an example, a 4-inch diameter silicon wafer with a thin but non-uniform diamond coating was placed on the linear sample stage of a SWIR spectral camera system. Typical near infrared spectra obtained from the various points on the wafer showed a strong interference pattern. Interference peaks were further apart for the thinner layer areas as shown in the first spectrum above, whereas the thicker layer produced fringes closer together as seen in the second spectrum.

Thickness was calculated using the generic formula shown earlier. The diamond coating on the wafer used in this example was very uneven. The following surface plot displays a grid of varied thicknesses, indicating that the layer at the center of this wafer is much thicker than the area towards the edges.

To obtain optimal results for different film thicknesses, it is important to use the appropriate wavelength range. A variety of imaging cameras, optics and sources are available for spectral regions from the UV to the long-wave infrared. Middleton Research staff can help with the selection of appropriate equipment for a specific application and integrate the system with the necessary hardware components, software and prediction methods.





Diamond coating thickness

Non-Imaging Multi-Channel Arrangements

Some applications call for the measurement of thickness data at different discrete points rather than the full image surface. In order to measure multiple discrete thickness values simultaneously, a hyperspectral line camera can be fitted with a multi-arm fiber bundle, with each arm positioned at different sampling points predetermined by the application requirements. A range of up to 100 measurement points can be covered with different fiber bundle assemblies while the length of the fibers can be selected to accommodate the particular industrial setting.

From Lab to Process

An important advantage of hyperspectral imaging is that the same camera can be tested and calibrated in the laboratory and then transferred to the production line to monitor the manufacturing process. This will streamline the transition to efficient, cost-saving on-line quality monitoring. In an on-line application, it is advantageous to calculate and display results at the frame rate of the camera output. To effectively manage the voluminous data generated from continuously moving samples, the data is transformed online, producing compressed data results. The Middleton Research High-Speed Prediction Engine™ is an optimized, dedicated real-time parallel calculating device. It includes an input specific to the type of camera used, options for taking reference measurements, and a simple Ethernet output for the thickness results. Please see the Complete Systems chapter for more information.

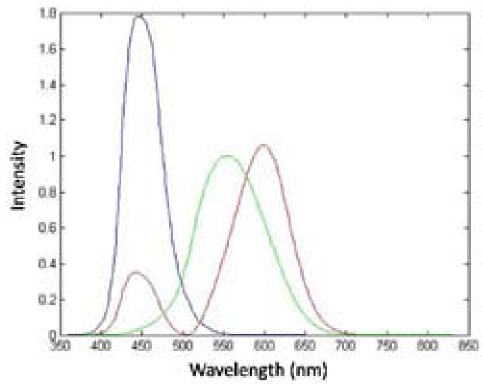
References

Li, Q., et al. (2010). Detection of physical defects in solar cells by hyperspectral imaging technology. *Optics & Laser Technology, 42* (2010), 1010-1013.

COLOR INSPECTION

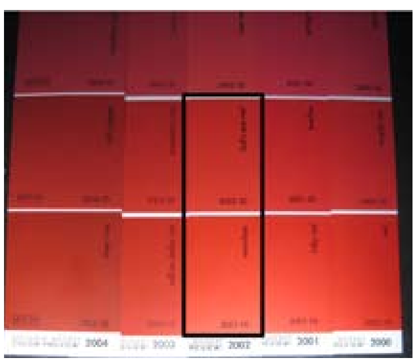
In-process and Laboratory Color Monitoring

Color monitoring and sorting are key processes in numerous industries including textiles, cosmetics, food, printing, and building materials. In-process monitoring of these products during manufacturing is possible with push-broom hyperspectral imaging (HSI) cameras. In fact, if the samples are moving, such as roll-to-roll textiles or food products on a conveyor belt, push-broom imaging is the only way to obtain hyperspectral measurements without interrupting the continuous production process. Because hyperspectral cameras view the moving material one line at a time and cover the entire surface of the product stream, they are ideal for high-speed in-process quality control applications in manufacturing environments. Color inspection can also be performed on single objects and in the research lab, and includes a wide range of items such as art work, paint products, custom signs or posters, embroidery, quilts, and colorful antiques. Samples can be placed on a moving tray below the camera and full spectrum color measurements can be collected in only a few seconds without damaging the sample from high illumination and potential heat load.

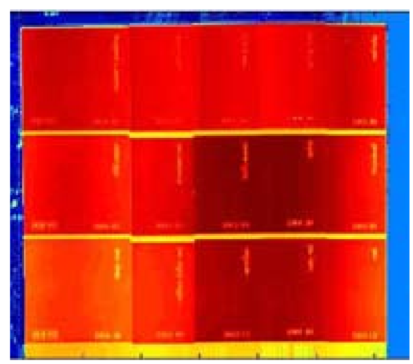


Color Component Measurement

As shown in the images below, red paint color swatches were measured with a visible hyperspectral camera (model HS-V8E) and processed to compute CIE 1976 (L*, a*, b*) color space dimensions. The color coordinates were calculated based on all wavelength points to distinguish the similar colors. Shades of red towards the higher end of the visible wavelength spectrum are typically more difficult for the human eye to differentiate, as shown in the standard RGB camera image.



RGB image



Plot of b-color dimension

The three Lab components (L*, a*, and b*) can often display differences between colors that are indistinguishable to the human eye. For example, the "Bull's Eye Red" and "Vermilion" swatches (boxed in the RGB image) are almost indistinguishable to the naked eye, but in the measured and calculated b dimension, the swatches were clearly separated. Each color space dimension accentuates dissimilarities differently, so calculating all three can greatly improve upon the color differentiation observed by the human eye alone.

Counterfeit Credit Card Detection

Hyperspectral imaging color inspection technology can distinguish counterfeit credit cards from real credit cards. As counterfeiting technology improves, credit card companies are continually developing more complex and costly holograms to mitigate risk. As an alternative, hyperspectral imaging can be applied as a cost-effective, non-destructive way to verify the authenticity of a credit card hologram. Researchers at the National Electronics and Computer Technology Center in Pathumthanit, Thailand, used hyperspectral imaging technology to effectively identify whether the embossed hologram on a credit card was genuine. Although a hologram can be replicated to appear identical to a genuine hologram, hyperspectral imaging can detect differences in the microscopic detail and key color characteristics. (Sumriddetchkajorn, 2008)

Analysis of Historic Documents

Since aging and document damage is not always visible to the naked eye, HSI technology can be used to evaluate the condition of historic documents by assessing the amount of stain and chemical deterioration of the documents. Researchers at the University of Winnipeg, Canada, demonstrated that hyperspectral imaging improved their ability to evaluate the extent of damage to a historic treaty. By more accurately assessing the state of preservation of historic documents, researchers were able to improve their conservation methods. (Goltz, 2010)

Measuring True Color and Pattern

While there are many different devices to identify the precise color of an object, hyperspectral color imaging is the only technology capable of recognizing the color coordinates of many different sections of a pattern. This feature of hyperspectral imaging is important for the quality control of artifacts with complex patterns where the color of each part of the image is equally important, such as printed textiles or artwork.

References

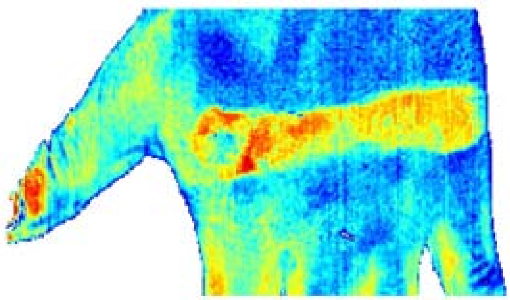
Goltz, D., et al. (2010). Assessing stains on historical documents using hyperspectral imaging. *Journal of Cultural Heritage, 11* (2010), 19-26.

Sumriddetchkajorn, S., & Intaravanne, Y. (2008). Hyperspectral imaging-based credit card verifier structure with adaptive learning. *Applied Optics, 47* (35), 6594-6600.

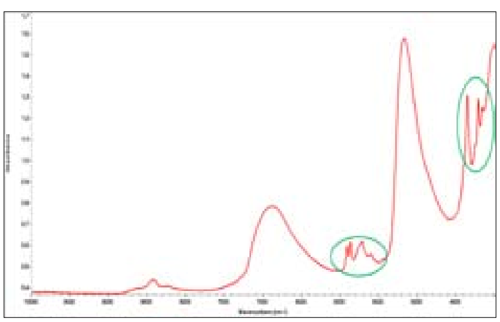
COSMETICS

A SWIR camera based hyperspectral imaging system was used to identify the location and evaluate the absorption of different cosmetics. For the experiments, several different hand lotions were sequentially rubbed in the shape of a strip on the subject's hand and scanned one at a time. The hand was cleaned with isopropyl alcohol before and between lotion applications to normalize the amount of oil on the surface of the skin. The volunteer placed the lotion-covered hand on a moving sample tray which passed beneath the camera. At 100 fps, each scan took about 6 seconds. ChemaDAQ™ software, included in the SisuCHEMA™ hyperspectral imaging system, was used to collect the images and control the camera.

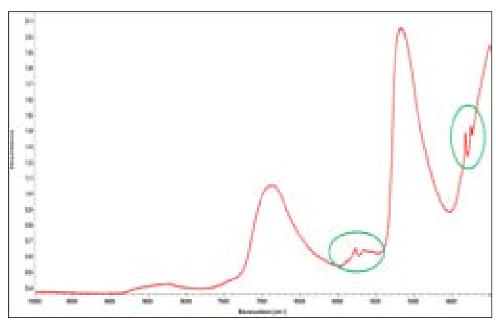
The spectral image below shows the location of the applied lotion based on its spectral differences from the skin.



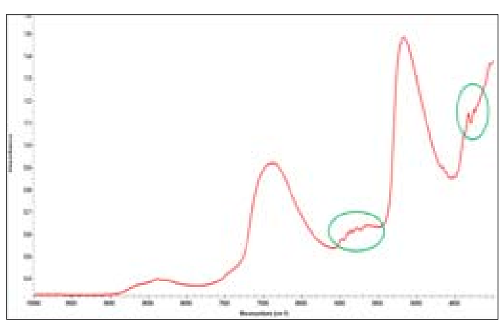
The spectra reveal differences between the lotions. The following spectra represent facial night cream, moisturizer, and sunscreen. The graphs show that around 5750 cm^{-1} and 4250 cm^{-1} (see circled areas), there are spectral differences that indicate a decreasing presence of oil from the first to the third spectrum. Furthermore, the results indicate that those characteristic wavelengths are appropriate to predict the location, the amount, and the absorption of the respective products.



Night cream



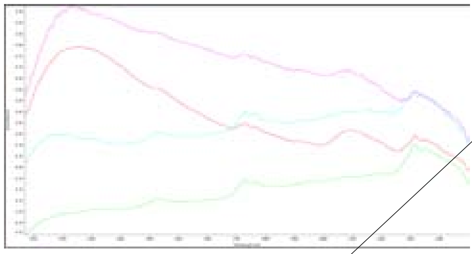
Moisturizer



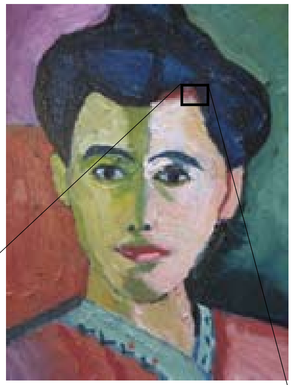
Sunscreen

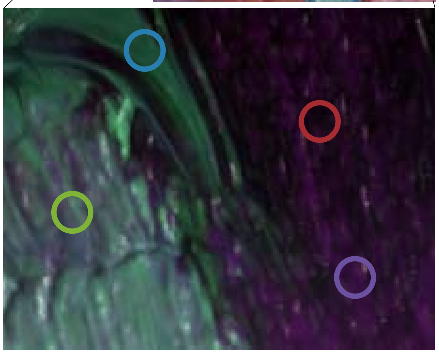
ART

Hyperspectral imaging (HSI) has been used to evaluate, document and analyze art objects (Kubik, 2007). Numerous characteristics can be determined from the HSI measurements, such as age, authenticity, and original color values for restoration purposes.



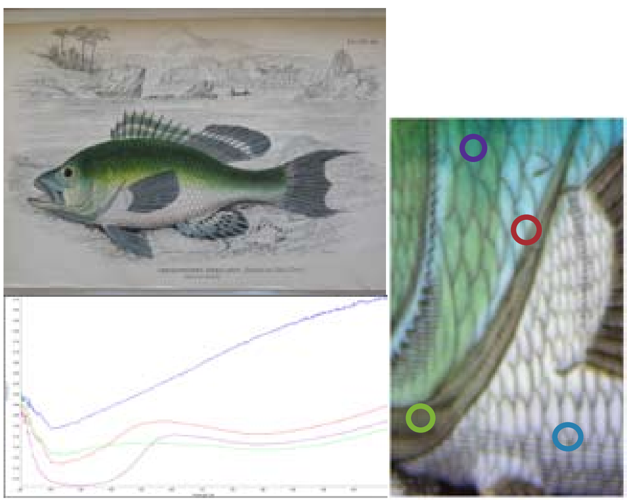
HSI measurements can facilitate documentation of museum inventory by providing documentation of true CIE color coordinates with high spatial resolution in order to track ultraviolet and oxidative degradation. Color standards are used to assure that the proper coordinates are established using the same geometry and illumination levels.





Hyperspectral image of indicated detail of oil painting measured with a SWIR camera. Color-coordinated spectra of circled areas shown above.

Leonardo da Vinci's Mona Lisa was analyzed in recent years using hyperspectral imaging to determine fading and other pigment changes. The HSI data was used to calculate the original color image, as it would have appeared at the time the painting was created. It also revealed other painting details modified by da Vinci and subsequent restorations (Bryner, 2007). The spectra of Leonardo's famous Madonna of the Yarnwinder is accessible online. (Laboratorio Spettroscopia Immagini, 2005)



Detailed hyperspectral image of artwork measured with a VNIR camera. Color-coordinated spectra of circled areas shown above.

Identification of art forgery is another important hyperspectral imaging application. HSI can go beyond evaluation of the style, pattern and other telltale signs of the artist, to detect chemicals, paints and substrates that were used. In some cases the materials readily available today are fundamentally different from those used by the old masters and can readily lead to detection of a newer than stated work.

Near infrared light penetrates deeper into the surface than visible light. In some cases the near-infrared scan of artwork can reveal a prior version beneath the outer image due to modifications by the artist or others.

Inks, pigments and watermarks of historic documents can be evaluated using chemometric methods, the legibility of documents enhanced, damages, such as gall ink corrosion or presence and the type of mold established. (Padoan, 2008)

References

Bryner, J. (2007). 25 secrets of Mona Lisa revealed. http://www.livescience.com/history/071018-mona-lisa.html

Kubik, M. (2007). Hyperspectral Imaging: A new technique for the non invasive study of artworks. *Physical Techniques in the Study of Art, Archeology and Cultural Heritage, Volume 2*, Amsterdam.

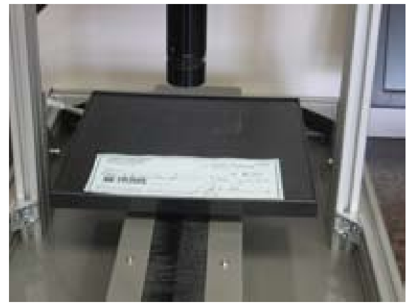
Laboratorio Spettroscopia Immagini. (2005). Results of measurements using a hyper-spectral scanner. http://www.ifac.cnr.it/webcubview/demo/leofull.php

Padoan, R., et al. (2008). Quantitative hyperspectral imaging of historic documents. *9th International Conference on NDT of Art*, Jerusalem, Israel.

FORENSICS

Hyperspectral Imaging in Forensics

Hyperspectral imaging combined with multivariate statistics is an approach to microanalysis that makes maximum use of the large amount of data in forensics analysis. VNIR, SWIR, Raman and thermal emission spectroscopy have been used to aid in forensic sciences. Several papers in the literature demonstrate the power of combining spectroscopic specificity with the rich information of hyperspectral imaging.



A check imaged with a high-magnification VNIR lens

Application Examples

One study examined the efficacy of hyperspectral imaging-enabled microscopes to identify chemical signatures in simulated bioagent materials. Hyperspectral imaging successfully identified particles with trace elements that would have been missed with a more traditional approach to forensic microanalysis. (Brewer, 2008)

Victim detection from hyperspectral images was performed using chemometric processing of the infrared hyperspectral data. Infrared hyperspectral images provided a complete picture of the surrounding environment, facilitating victim detection. (DeCubber, 2009)

Raman chemical imaging (RCI) has been used to detect and identify explosives in contaminated fingerprints. Bright-field imaging was used to identify regions of interest within a fingerprint, which was then examined to determine chemical composition using RCI and fluorescence imaging. Explosives in contaminated fingerprints were identified this way and their spatial distributions obtained. Identification of explosives was obtained using Pearson's cosine cross-correlation technique using the characteristic region (500 – 1850 cm^{-1}) of the spectrum. This study shows the ability to identify explosives non-destructively so that the fingerprint remains intact for further biometric analysis. (Emmons, 2009)

Hyperspectral imaging in the VNIR region can be used to identify document forgeries. Falsified documents can usually be identified from the spectra of critical parts of documents to discern real differences in inks that otherwise appear identical to the human eye. Slight, but well-defined spectral differences can be resolved using principal component analysis (PCA) as shown here.

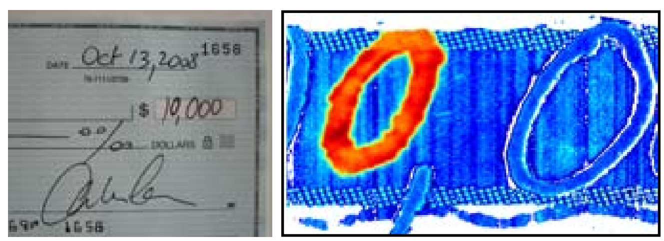


Photo and PCA processed VNIR hyperspectral image of an altered check, indicating very good discrimination of the zero added with a different ink

Investigate Crime Scenes

Hyperspectral imaging color inspection technology has been used to enhance visualization of bloodstains on dark surfaces in crime scene investigations. While DNA and similar analysis processes can assist in determining the biological source of the stains, they cannot determine the pattern of the bloodstain if it is not visually obvious. Researchers at the National Criminal Justice Reference Service found that knowing how the bloodstains were formed, as interpreted by their patterns, was often more important than evidence from DNA testing. After extensive study, these researchers found that hyperspectral imaging was a good solution for recognizing the presence of blood and analyzing the stain patterns, without destroying crucial information. (DeForest, 2009)

References

Brewer, L., et al. (2008). Forensic analysis of bioagents by X-ray and TOF-SIMS hyperspectral imaging. *Forensic Science International*, 179. 98-106.

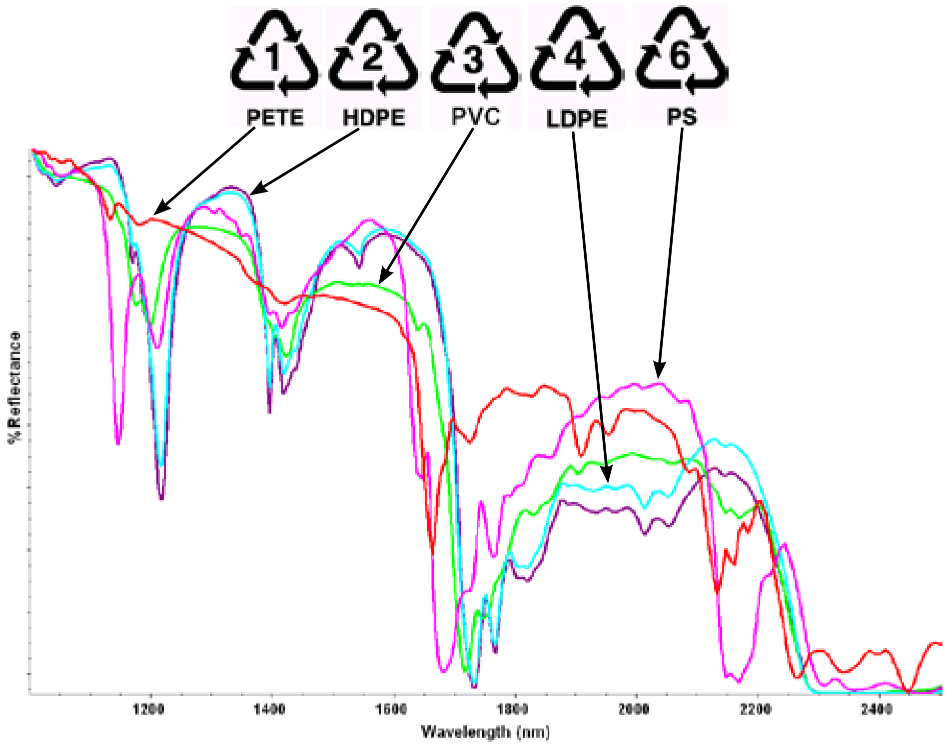
DeCubber, G. & Marton, G. (2009). Human Victim Detection. *Royal Military Academy Publication.*

De Forest, P., et al. (2009). Blood on black-enhanced visualization of bloodstains on dark surfaces. *Report submitted to the U.S. Department of Justice under award number 2006-DN-BX-K026.*

Emmons, E., et al. (2009). Raman Chemical Imaging of Explosive-Contaminated Fingerprints. *Applied Spectroscopy*, 63 (11).

RECYCLING AND WASTE MANAGEMENT

Recycling plants can reduce costs and improve production quality by replacing manual sorting with efficient machine-based methods. Sorting machines and methods include weighing, magnets and spectroscopic identification. A hyperspectral imaging (HSI) camera can be placed directly over a sorting line to measure all the recycled items as they move through. The HSI push-broom camera measures a line of spatial points at one time. The spectral information from each point can be transferred to a computer and processed in real-time for material identification. The spectra of several types of plastic (PETE, HDPE, PVC, LDPE, and PS) are shown here. Both the SWIR (1000 - 2500 nm) and NIR (1000 - 1700 nm) wavelength ranges are useful for identifying recyclable plastics.



Recycling Application

Researchers at Degli Studi University of Rome, Italy examined the problem of ceramic glass, which, when mixed with recyclable glass, reduces production quality and increases costs. Because ceramic glass is very similar in appearance to recyclable glass, inadvertent mixing is quite common. The study demonstrated that with hyperspectral imaging technology, distinctions can be made between recyclable glass and ceramic glass in both visible and near infrared wavelength ranges. (Bonifazi, 2006)

Waste Management Application

Hazardous waste site inspection is expensive, labor intensive, time-consuming, and is often conducted manually. Researchers at the University of South Carolina and Texas A&M University demonstrated that hyperspectral imaging technology shows excellent promise for detecting surface anomalies at hazardous waste sites as an indication of hazardous material leakage. Rapid identification of hazardous waste leakage enables remedial work to occur, potentially minimizing damage and maintaining the integrity of the storage sites. (Jensen, 2003)

References

Bonifazi, G., & Serranti, S. (2006). Imaging spectroscopy based strategies for ceramic glass contaminants removal in glass recycling. *Waste Management, 26* (2006), 627-639.

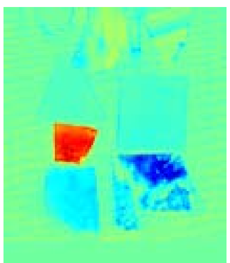
Jensen, R., et al. (2003). 2002 Hyperspectral analysis of hazardous waste sites on the Savannah River site. Prepared for the U.S. Department of Energy under contract number DE-AC09-96SR18500.

INORGANICS AND MINERALS

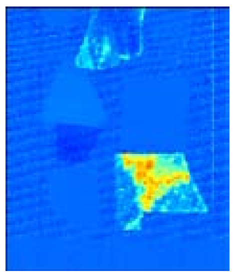
Applications

Hyperspectral imaging can be used to map surface mineral distributions via remote sensing / airborne technology. The SWIR, VNIR or thermal IR wavelength ranges provide useful spectral information for differentiating these types of materials. The SisuROCK™ is a system targeted to mineral identification from geological core samples. For more information about SisuROCK, please refer to the Complete Systems chapter or contact Middleton Research.

Hyperspectral imaging can be used to analyze many different inorganic materials. In this example, multiple samples of various minerals used to mimic jade were measured with a SWIR hyperspectral camera (1000 – 2500 nm) and compared with similar measurements of authentic jade (Burmese jadeite). The components were predicted with the SBC hyperspectral image analysis method. (Marbach, 2007)



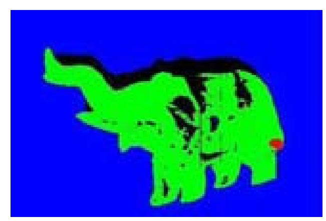
Jadeite



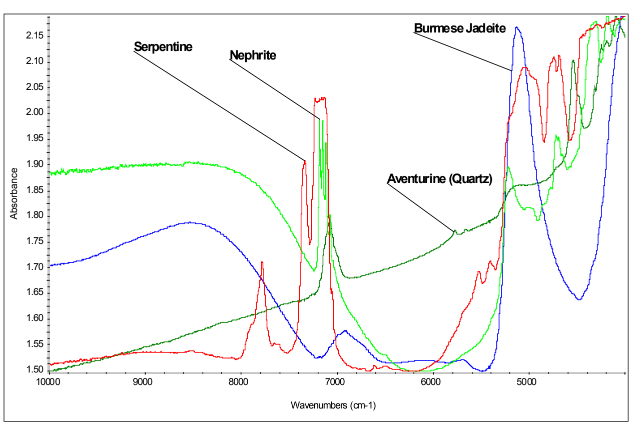
Nephrite

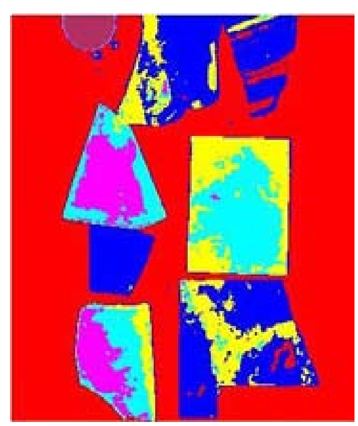
The image on the far left shows the relative intensity of the predicted jadeite – red indicates a higher intensity. The next image shows the relative intensity of predicted nephrite. Both images include several pieces of imitation jade.

HSI was also used to obtain another image of a jade artifact that contained a small repair (photo on right). The red part of the hyperspectral prediction image (far right) clearly identified the repair as chemically different from the inorganic material comprising the bulk of the statuette. Different minerals show very different spectral characteristics in the SWIR wavelength range for example and this allows the identification of minerals.



Other inorganic and mineral applications for hyperspectral imaging technology, such as examining soil properties, identifying different minerals remotely, on the ground, and even inside mines, can be performed in the SWIR, VNIR and the LWIR regions.





Reference

Marbach, R. (2007). Multivariate calibration a science-based method part 1. *Pharmaceutical Manufacturing*, 42-47.