WHITE PAPER:

RECENT DEVELOPMENTS IN HYPERSPECTRAL IMAGING IN INDUSTRIAL APPLICATIONS

specim

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Recent Developments in Hyperspectral Imaging in Industrial Applications

With a performance-to-cost ratio that now meets industrial demands, hyperspectral imaging has quickly become a key part of the machine vision solutions market, along with technologies such as X-ray, RGB (red, green, blue), and 3D in-line inspection. Having the option to purchase a complete solution combining a hyperspectral camera, software, and compute power from a single supplier can be a tremendous advantage. It often results in a solution that's less expensive to install, less complex to validate, and less costly to maintain.

Introduction

Though hyperspectral imaging (HSI) has been available for decades, untapped and emerging markets and use cases have catapulted the imaging method into the spotlight in recent years. Thanks to faster and cheaper sensors, HSI continues to advance due to its value in industrial and commercial marketplaces, across industries such as pharmaceuticals, food, recycling, and agriculture.

By combining imaging and spectroscopy, HSI offers many advantages over traditional systems based on X-ray, RGB, or multispectral sensors. The technique enables the development of unique spectral signatures for materials and compounds, similar to fingerprints. These spectral features can be used during inspection to locate, sort, or quantify the concentration of various materials that are invisible to common cameras or the human eye.

This white paper includes a review of a few fundamental imaging concepts, such as the electromagnetic spectrum and color imaging, to explain hyperspectral imaging and its main advantages. It also introduces successful industrial HSI applications and discusses recent developments in components that have led to more cost-effective HSI applications in industrial automation. In the end, it outlines the SpecimONE concept — a complete spectral imaging platform for sorting.

What Is Hyperspectral Imaging?

Color imaging starts with visible light, which is the segment of the electromagnetic spectrum that the human eye can view. The human eye typically can detect wavelengths from 380 to 700 nanometers (nm). The brain interprets these various wavelengths as the different colors of the rainbow, ranging from red, with the lowest energy, to violet, with the highest.

When light interacts with matter, it can be reflected, absorbed, transmitted, or in some cases re-emitted by the object. The amount of light reflected, absorbed, and so on varies, depending on the wavelength of the light and the chemical makeup of the object. Color is observed when a part of the visible related spectrum is reflected from the object's surface back to the eye or imaging device.

While a white object reflects all the wavelengths of the visible spectrum back to the eye or camera, a red object reflects only red wavelengths. If a particular color or wavelength is not reflected off an object's surface, it's most likely absorbed by or perhaps transmitted through the object's surface.

The electromagnetic spectrum describes all types of light, ranging from very long radio waves, though microwaves, infrared radiation, visible light, ultraviolet rays, and X-rays, to very short gamma rays — most of which the human eye can't see (Figure 1).

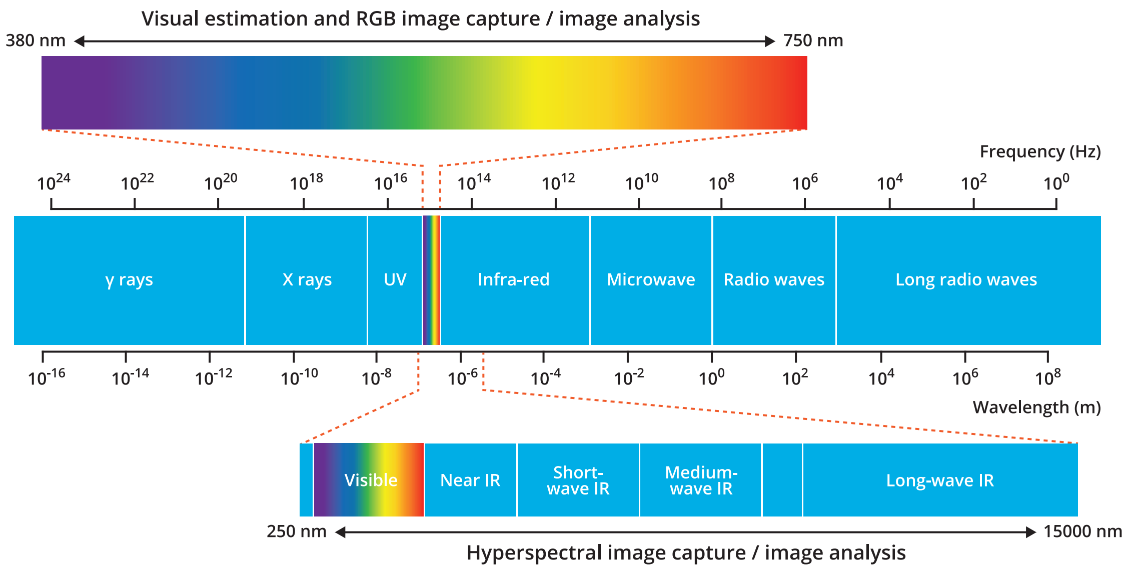


Figure 1: While a typical camera uses three visible light bands (red, green, and blue) to create images, spectral imaging makes it possible to examine how objects interact with many more bands, ranging from 250 nm to 15,000 nm and thermal infrared.

Spectroscopy is the study of light–matter interaction. It's a great tool for studying and identifying materials and defining material properties. By examining how light behaves in the target, spectroscopy recognizes materials based on unique spectral signatures. A material's spectrum defines how much light the target emits, reflects, or transmits per wavelength.

By combining the benefits of a camera and a spectrometer, hyperspectral imaging provides both spatial and spectral information. For instance, spectral imaging can enable the identification of contaminants and the amount of fat, sugar, or moisture in products. The technology analyzes a spectral response with the goal of classifying unique spectral signatures to detect features or objects in images. This allows for identification and classification of materials and provides data on distribution and areal separation.

Hyperspectral imaging involves using an imaging spectrometer, also called a hyperspectral camera, to collect spectral information. The device measures thousands or hundreds of thousands of spectra to create a massive hyperspectral data cube comprising position, wavelength, and time-related information. By doing this, hyperspectral imaging can provide answers to questions concerning "what" (based on the spectrum), "where" (based on location), and "when" (based on time; Figure 2).

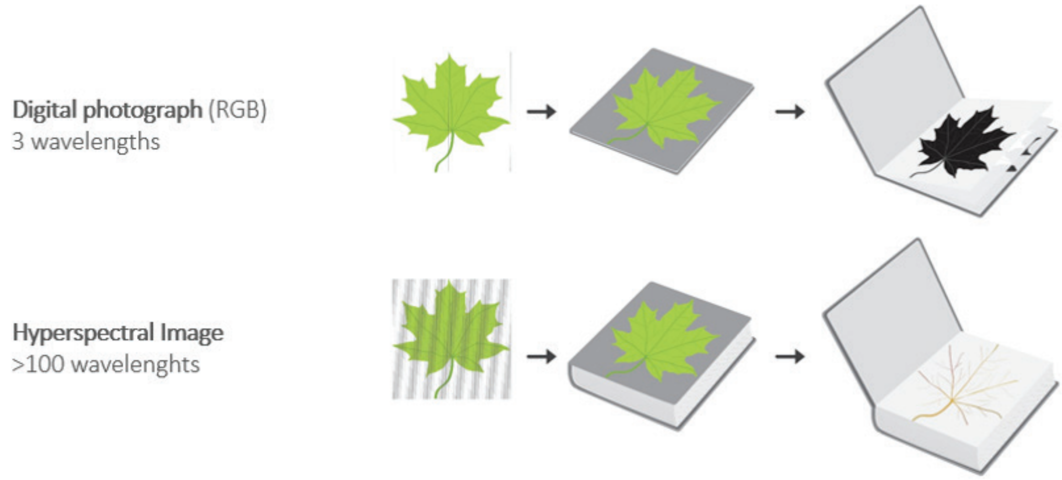


Figure 2: To match human vision, a digital photograph of a leaf (top) is created using three bands: red, green, and blue. The RGB data is comparable to a three-page pamphlet. In contrast, a hyperspectral image of a leaf (bottom) captures a spectral response from 220 wavelengths. The comparable 220-page book contains much more detailed information about the object.

What Is the Main Advantage of HSI?

HSI can differentiate within classes. A contiguous spectral signature is very distinct, has high spectral resolution, and can define very discrete spectral responses in different chemical objects or in different materials in an image.

In pharmaceutical packaging operations, multispectral imaging systems might be used to ensure that each blister in a blister pack contains a tablet or capsule. The system would use a shortwave infrared (SWIR) wavelength to penetrate the packaging to detect the tablet or capsule within.

However, if the application requires quantifying the amount of active pharmaceutical ingredient (API) that each tablet or capsule contains, HSI would be required. For instance, in a transparent blister pack, due to high spectral information content that creates a unique spectral curve for each class, hyperspectral sensors can distinguish the chemical composition of each tablet or capsule by looking at the chemical response to each wavelength. So molecular bonds between carbon and hydrogen can be identified and quantified, for example. Consequently, HSI error-proofs the process by providing quantitative data to ensure that each tablet or capsule contains the correct percentage of API, while MSI is only able to qualify that each blister contains a tablet or capsule.

What Components and Technologies Drive Industrial HSI?

While a variety of different methods for acquiring hyperspectral images exist, most industrial applications rely on camera-based systems. Such cameras generally consist of a lens, an imaging spectrograph, and an area array image sensor, which all must be optimized for the selected wavelength range.

The camera performs a type of linear scanning, dubbed push-broom, which collects full spectral and spatial information about the target line by line, forming a data cube, with each line of the spatial image data resolved across the entire sensor's worth of spectral content.

Relative motion between camera and test object enables line-by-line image acquisition, as products move from one process step to the next in-line, such as on conveyor belts. A hyperspectral camera mounted above a conveyor belt records line-by-line images of the objects passing underneath (Figure 3). In addition, relevant illumination is required, continuously covering the spectral range of the camera.

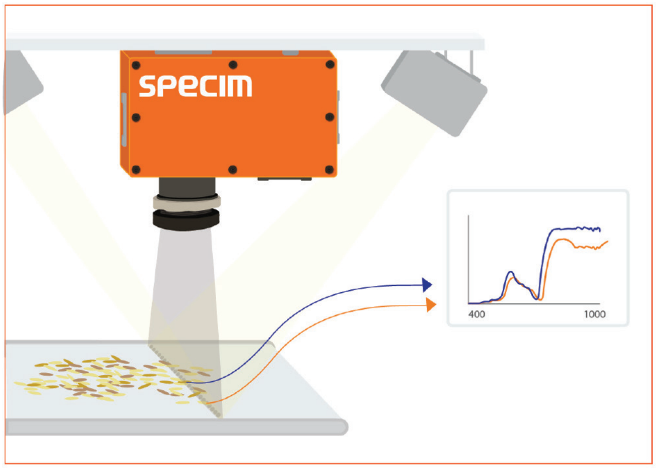


Figure 3: High data quality and fast operation make this push-broom hyperspectral camera suitable for a variety of different environments.

When recording a normal black-and-white image, the objective projects the target to a camera sensor, which records the image. Using the book analogy from Figure 2, the result would be a one-page black-and-white leaflet. Adding an imaging spectrograph as in Figure 3 enables hyperspectral data to be recorded. It gives sorting machine builders and system integrators a technology that obtains chemical information across the full product stream in real time. Thus hyperspectral imaging improves chemical grading and foreign material detection by identifying a range of characteristics simultaneously with a single camera.

Successful Industrial HSI Use Cases

With a performance-to-cost ratio that now meets industrial demands, HSI has quickly become part of a machine vision solutions market that also includes technologies such as X-ray, RGB, and 3D in-line inspection. Consequently, use of HSI has expanded across industries such as pharmaceuticals, food, recycling, and agriculture, to name just a few sectors where hyperspectral imaging already supplies reliable and cost-effective automation solutions.

Pharmaceutical Qualitative Analysis

HSI is ideal for performing both qualitative and quantitative online chemical analysis with high reliability to avoid the potentially catastrophic effects of incorrectly packaged pharmaceuticals. Figure 4 shows real-time qualitative HSI analysis being used to sort paracetamol tablets, aspirin tablets, and ibuprofen capsules.

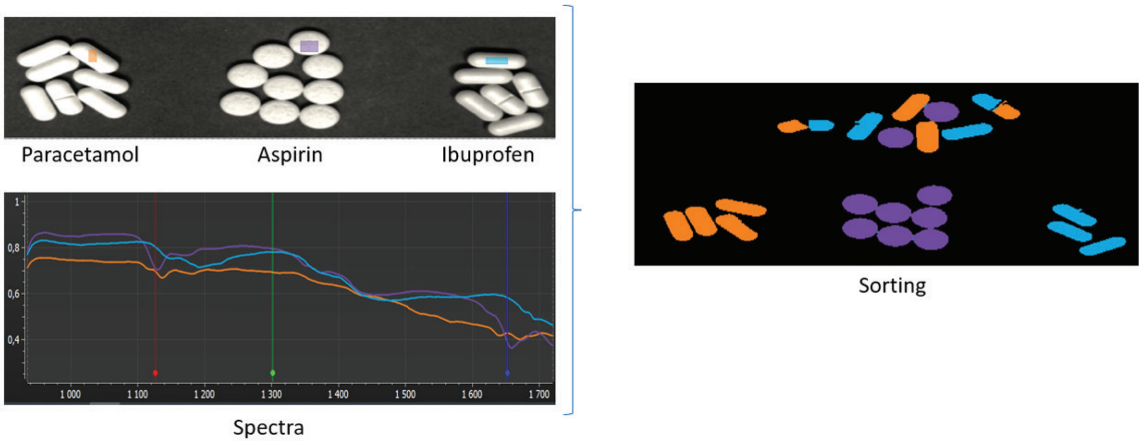


Figure 4: This spectral analysis of paracetamol, aspirin, and ibuprofen shows that each has a unique spectral signature that can be used for reliable sorting.

Each has a unique spectral signature. Paracetamol is here depicted in orange; aspirin is purple and Ibuprofen is blue. After analysis of the spectral library and determination of the spectral signature for each, a statistical model is applied to the image. The technology easily distinguishes between the three APIs to deliver reliable sorting.

Pharmaceutical Quantitative Analysis

HSI is often used for quantitative data analyses in the pharmaceutical industry, such as quantifying the amount of API that each tablet or capsule contains. Since May 2022, Sea Vision has been using a Specim FX series hyperspectral camera in its HarleNIR tablet inspection system (Figure 5). The application uses HSI in the near infrared (NIR) range to distinguish the chemical composition of each tablet in a blister pack. By identifying tablets with incorrect APIs or dosages, the system ensures 100% chemical quality control using nondestructive classification and quantification methods. If the API is paracetamol, another signal could be used to measure lactose (excipient). After establishing a ground truth calibration with a large set of tens of samples with known concentrations of each ingredient, the system can develop a regression model to perform this type of analysis consistently and accurately. HSI can measure moisture content in the same fashion.

In such applications, it's important to remember that HSI is a surface measurement method, especially when working in reflectance. That means penetration depth depends on the sample. For instance, penetration depths can range from about 1 millimeter maximum to as little as a few tenths of a micron. When performing quantitative analysis of samples, analysts must assume that the surface of each tablet is representative of what each tablet contains in sum.[2]

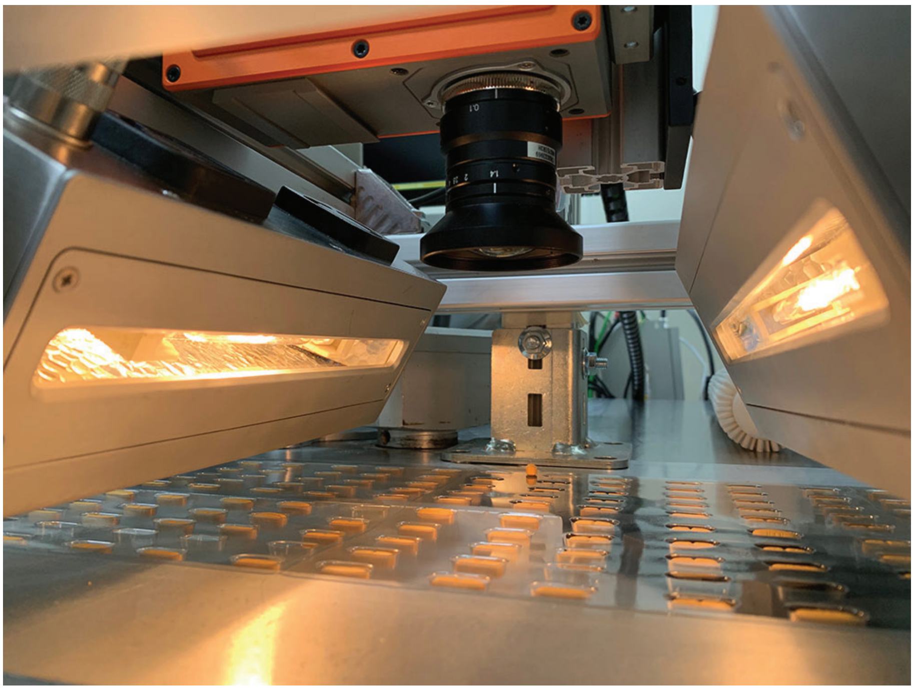


Figure 5: HarleNIR uses HSI to perform a chemical composition inspection on pharmaceutical products during production. HSI is used to qualitatively distinguish products based on API content, identify drugs with different APIs and dosages, and quantitatively measure API uniformity distribution.

Pharmaceutical Powder Analysis

HSI is also well suited for visual inspection of powder blends to determine lyophilizate quality, identify fraud, and evaluate the homogeneity of certain mixtures. Also, when it's time to ship an API from one place to another, both the powder and its moisture content need to be accurately scrutinized.

Powder blends can be analyzed using a hyperspectral camera in the NIR wavelength range. Many powders in the pharmaceutical industry are indistinguishable by visual inspection because they are white. HSI can be used to scan samples without contact, in a fast and nondestructive way, to identify unmixed powders and various blends to build models for compound identification, and thus to assess blend homogeneity or content uniformity.

Classification models can also be developed. Such models, when combined with spectral analysis, make it possible to label different areas of a hyperspectral image according to their chemical composition. The software can then assign false colors to each pixel of the image, allowing the user to quickly identify the location of the various chemical compounds.
These models can also improve the understanding of powder blending processes. In the case of powder blending, optimal mixing times can be defined, with an end-process identification when blend homogeneity is reached.[3]

Phenotyping in Vertical Farming

Phenotyping, a vital process in crop improvement, is another application where HSI is frequently used. By measuring the concentration of compounds such as chlorophyll and water in vegetation, analysts can develop models to determine the health of plants. This is especially useful in the vertical farming industry, where HSI is often combined with RGB and thermal cameras, as well as light intensity sensors, in plant monitoring systems mounted above or beside vegetation.

A hyperspectral camera mounted above plants in a greenhouse can monitor how a plant is growing in terms of size and can also chemically determine if the plant has a deficiency of, for example, nitrogen, phosphorus, or potassium. HSI technology helps vertical farming operations achieve yield increases up to 100x while using 98% less soil and 95% less water than traditional farming (Figure 6).

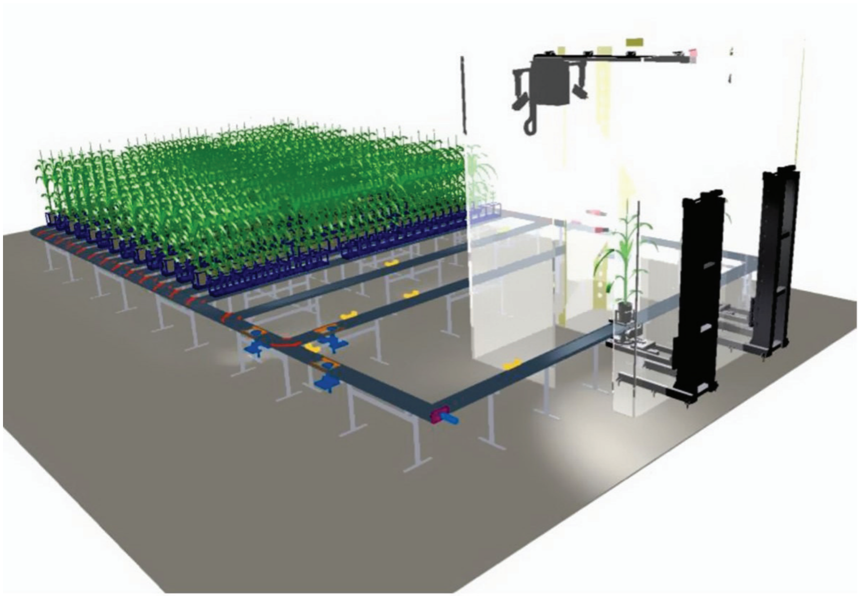


Figure 6: HSI technology in a phenotyping facility.

A case in point is the Italian vertical farming company Agricola Moderna, which sells leafy greens and salads to supermarkets. Its platform uses several types of sensors, including HSI, to monitor nitrogen, phosphorus, and potassium levels instead of using the alternative solution: a slow and expensive chemical analysis of crops.

After months of market research, discussions, and thought, Agricola Moderna chose Specim as its hyperspectral camera supplier. The company learned about Specim from its collaboration with the University of Milan, where it has its phenotyping platform. After several comparisons, Agricola Moderna decided that the Specim FX10e was the best device for its needs, and the price was competitive.[4]

Food Sorting and Quality Inspection

Quality control is crucial in the food industry. Monitoring a product's nutritive property contributes to protecting and increasing a brand reputation. Strelen Control Systems GmbH uses a Specim FX series hyperspectral camera in its Safe-Ident Sort system, which sorts out foreign objects from nuts prior to processing. By using HSI technology to identify empty shells and other foreign objects to avoid contamination, Ortlieb Organic in Bensheim, Germany, minimizes the risk of product recalls and the associated loss of reputation.

Reliably differentiating nuts from their shells at high speed is extremely challenging due to only minor variations in their brown tones. But HSI makes it easy to distinguish nuts from shells and can even differentiate between distinct types of nuts, such as almonds, hazelnuts, walnuts, cashews, macadamia nuts, and peanuts, because each has a uniquely identifiable spectral response.[5]

Software quickly analyzes the hyperspectral images and reliably recognizes all spectra that do not correspond to the expected nut type. Shells, remains of shells, plastic parts, nuts infected with mold, and other contaminants are identified, and 32 high-precision nozzles blow these unwanted objects into a reject container with targeted air blasts as they fall. Only the desired nuts land undisturbed in a collecting container for further processing (Figure 7).

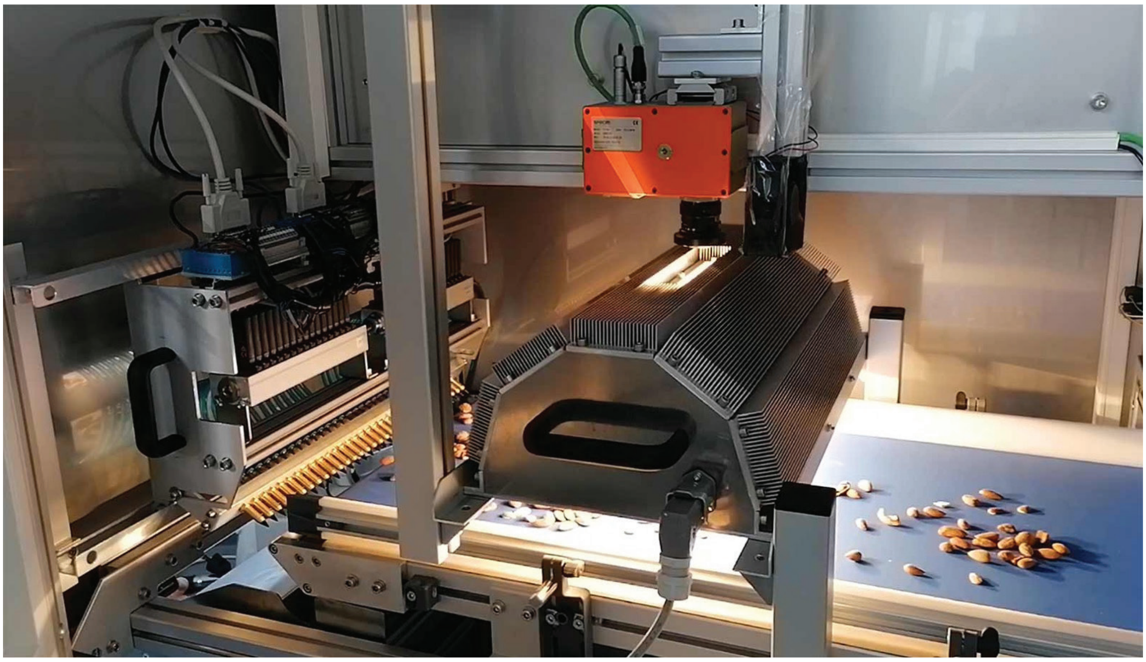


Figure 7: The Specim FX10 hyperspectral camera was chosen for this nut sorting application because it covers many wavelengths, including NIR (near infrared) wavelengths, which are relevant for the task.

Grading Proteins in the Food Industry

Another critical HSI application in the food industry is monitoring the nutritive properties of products, including the fat and moisture content of meat, which consumers often scrutinize with care. Specim conducted a study using 10 minced meat samples from Atria (Seinäjoki, Finland). Specim ordered measurements from a third-party laboratory, Seilab, to validate the fat and moisture content of the samples.

The researchers used a Specim FX17 hyperspectral camera and a regression model built and calibrated on eight samples and applied to the two remaining ones to determine the fat and moisture contents of each sample. The regression model results, shown in Figure 8, demonstrate that the Specim FX17 camera is a suitable tool for precisely measuring the fat and moisture content of minced meat.

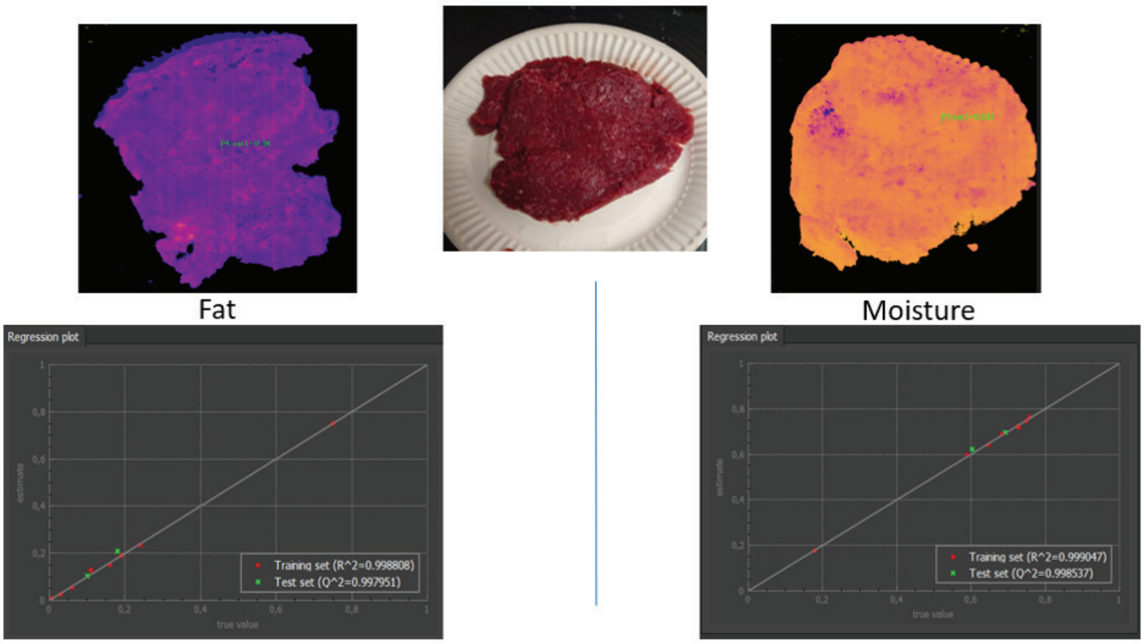


Figure 8: With the Specim FX17, it is possible to use regression models to determine the moisture and fat content of minced meat.

In addition to measuring fat content, hyperspectral imaging is suitable for measuring its distribution. Meat processors rely on the Specim FX17 in machine vision systems to provide crucial and accurate fat quantification data. This fast and nondestructive technology is also suitable for detecting other properties, such as moisture and freshness. Furthermore, the technology can sort out contaminants, such as pieces of wood and plastic. The Specim FX17 is a perfect tool for industrial quality control.

Hyperspectral imaging offers cost reductions and allows companies to quickly adapt to new regulations by providing real-time information about the manufacturing process.6 HSI is also useful for grading chicken fillets. The meat is white, the fat is white, the cartilage is white. But a hyperspectral camera can easily distinguish these components and separate them because of their varying spectral signatures. Fish and other foods can also be inspected using HSI.

Sorting Waste for Recycling

The production of genuine plastics is directly related to the price of oil and has a high negative impact on the environment. The recent increase in the price of oil, as well as the enforcement of new environmentally friendly rules, makes plastics recycling more attractive. However, recycling is traditionally costly, and the separation of recyclable polymers from the waste stream can be time-consuming. While the labeling of plastic resins and hand sorting have proven to be cumbersome and error-prone, HSI has recently proven itself in these applications. By analyzing the chemical composition of plastic resin, new, fast, and affordable hyperspectral cameras can make plastic sorting and recycling more viable.

Many Specim FX series hyperspectral cameras are used in recycling plants for sorting different types of plastics because they are fast, affordable, and cover an extensive spectral range. For instance, the Specim FX50 is the only hyperspectral camera on the market covering the full MWIR spectral range of 2.7 to 5.3 µm. The camera enables even black plastics sorting, which is impossible with conventional imaging techniques.

Specim studies have included measurement, analysis, and classification of samples of PE, ABS, PVC, PS, PA, PP, PC, and PET, which are the most commonly recycled plastics. Mostly white or transparent samples have been measured in the Specim laboratory. To demonstrate the power of the Specim FX50, additional carbon black samples were measured. Depending on the application requirements, different cameras can be used.[7]

PLASTICS	FX10	FX17	SWIR	FX50**
PE	YES*	YES*	YES*	YES*
ABS	MODERATE	YES	YES	YES
PVC	MODERATE	YES	YES	YES
PS	MODERATE	YES	YES	YES
PA	MODERATE	YES	YES	YES
PP	NO	YES	YES	YES
PC	NO	NO	YES	MODERATE
PET	MODERATE	YES	YES	YES

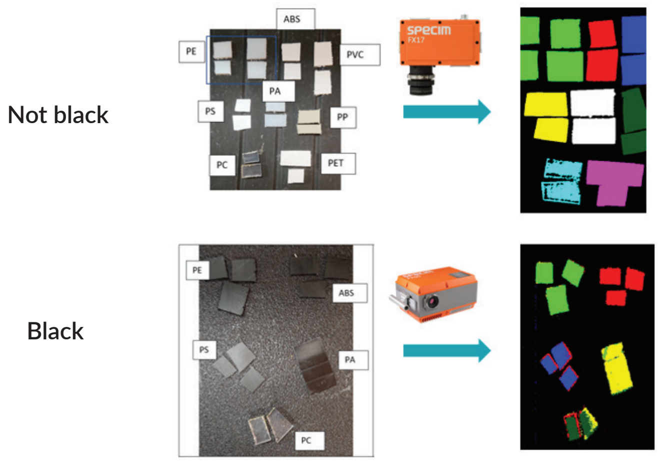
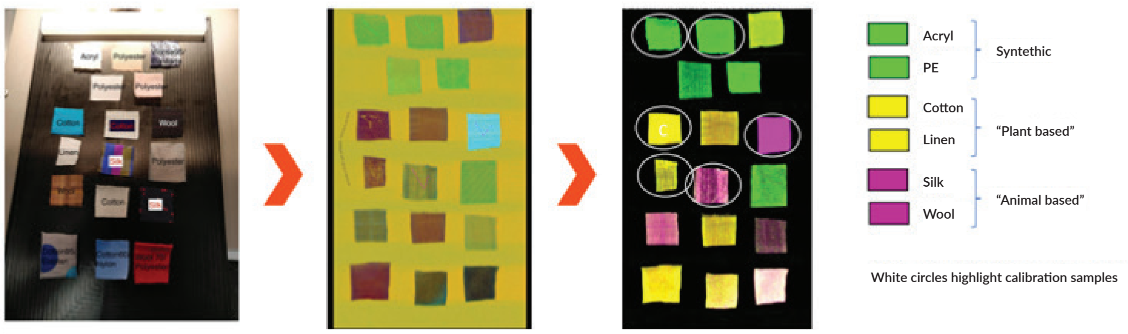


Figure 9: The Specim FX50 can sort mixed plastic waste of all types, regardless of color.

Automated Textile Sorting for Recycling and Industrial Laundry Applications

EU guidelines for fabric recycling concern global textile reuse, and HSI stands poised to be a key enabler of this industry for the benefit of the environment. Manual sorting methods are costly and slow and require special knowledge of textiles for reliable identification and separation of diverse types of fibers and substances. In addition, sorting blended fabrics based solely on appearance is almost impossible without the aid of HSI.

NIR hyperspectral cameras offer a solution. Different textiles have individual spectral characteristics that can be used for fabric classification. Fabrics can be natural fibers such as cotton and wool, synthetic fibers such as polyester, or a mixture of types. Because these disparate materials vary in chemical and molecular structure, they react differently to electromagnetic waves of different wavelengths. HSI allows the unique spectral characteristics to be used for fabric classification, forming the basis for automated textile sorting (Figure 10).



Picture of the samples | Preprocessed data | Prediction data

Figure 10: HSI can deliver quantitative information about the proportions of synthetic and natural fibers in blended fabrics.

If the dying lotion is based on carbon black, black fabrics may present a problem similar to the one presented by black plastics. However, if the dye does not involve such chemicals, the Specim FX17 would be perfectly appropriate to sort all textiles, regardless of color, even black.

Another difficulty is the differentiation of different substances when they are damp or wet. By using wet and dry material to train the system, operators can develop classification algorithms that provide usable results. Sorting dry material is much more effective. Multilayer textiles remain a challenge.

Working in the wavelength range from 900 to 1700 nm, the Specim FX17 offers a solution for textile classification, except for a few synthetics such as black polyester and black nylon. Thanks to other features, such as an excellent peak signal-to-noise ratio of 1000:1 and high throughput, which leads to accurate and fast sorting, the FX17 has proven to be an excellent sensor for use in textile sorting.[8]

What Are the Key Challenges in Industrial HSI Applications?

HSI applications have a reputation for being complicated. To achieve good results, system developers must overcome traditional challenges, such as determining proper wavelengths, selecting a camera with suitable spectral and spatial resolution, and choosing appropriate lighting, with adequate intensity at key wavelengths. Calibration is also a critical step in spectral imaging, to make sure you have a good bright white calibration and a good dark or black calibration.

Because a hyperspectral data cube is a large piece of data, decisions on local or remote image storage and data output can impact the speed of the application, which must keep pace with production. Often, only short time spans, in the range of a few milliseconds, are available for calculating results from acquired images. For example, meeting accuracy requirements in high-speed sorting applications demands fast analysis of incoming images and tight integration with rejection mechanisms or blowout unit controllers.

Making the right software choice for evaluating hyperspectral images is equally important. Because HSI generally requires a high level of physical understanding, it is even more critical that the analysis software's development environment is as intuitive as possible and supports easy establishment of material classifications. In automated environments, it's not enough to create an analysis and show an image. Rather, features must be extracted, classes of interest isolated, and results output during the process.

Likewise, the HSI compute platform must have satisfactory performance and the required interfaces to supply a fast and stable link to higher-level system controllers. In many cases, the necessary components — the hyperspectral camera, the software, and the evaluation computer — all come from different suppliers. Implementation, updates, or changes in the event of a fault can therefore be time-consuming and difficult.

How Can These Challenges Be Overcome?

Relying on disparate suppliers for a hyperspectral camera, software, and compute components is a massive problem for developers. The best way to overcome the associated issues is to purchase a complete, powerful solution that combines a camera, software, and compute power from a single supplier.

Such a hyperspectral imaging solution should be designed to significantly simplify HSI deployments in industrial applications such as sorting and inspection. The solution should include easy-to-use tools that decrease development time and reduce overall system costs while offering flexible model optimization for detecting different types of materials to increase the number of potential use cases.

In high-throughput operations, achieving high performance requires careful consideration of the speed at which the objects being imaged travel. Be sure to select an HSI system with an adequate frame rate and processing latency. Accuracy is also important. More accuracy enables higher rates of detection of smaller objects, which increases the return on investment. Consider HSI camera optical parameters and available bands carefully to achieve the accuracy required for the application.

Specim — All-in-One Spectral Imaging Provider

Specim offers a complete spectral imaging platform for analyzing and sorting. SpecimONE includes the industry-proven Specim FX series hyperspectral camera, SpecimCUBE processing hardware, and SpecimINSIGHT, an offline software tool. With SpecimONE, machine builders, vision systems integrators, and OEMs can classify different materials based on their spectral signatures off-line and apply the classification models to an in-line system in real time. Specim's proprietary platform guarantees full compatibility and seamless operation between Specim FX cameras, modeling systems, and real-time software tools with a single point of contact.

Together with the flexibility of hyperspectral imaging technology, the SpecimONE platform enables an unlimited number of applications and delivers a shorter time to market. Connect with us for an application evaluation and let us show you how HSI can improve your industrial inspection applications today.

About the Author

Mathieu Marmion, a senior application specialist at Specim, Spectral Imaging, holds a double MSc degree in electrical engineering (from INP in Grenoble, France, and from NTNU in Trondheim, Norway), as well as a PhD in physical geography (University of Oulu, Finland). Marmion has been employed at Specim for the last 11 years. He was a technical sales engineer and a sales manager before becoming a lead application specialist.

Notes

1. "Landcover Mapping Using Hyperspectral Imagery and Deep Learning," ArcGIS Developers, 2022, https://developers.arcgis.com/python/samples/landcover-classification-using-hyperspectral-imagery-and-deep-learning.
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