Hyperspectral Imaging for

Advanced Machine Vision

From specialty crops to seafood and poultry, the global food inspection industry needs newer and more precise tools to meet stringent government regulations. The bias toward human inspectors and outdated RGB cameras is creating tremendous upside potential for the adoption of advanced high-resolution imaging systems that are simultaneously robust, affordable, and easy to deploy. This also holds true for the global recycling industry, which needs new ways to distinguish between various types of plastics.

Hyperspectral imaging represents one such tool. "HSI" was originally developed as a technology that could deliver highly resolved images from aircraft and satellites, primarily for defense purposes. But now successfully commercialized, HSI sensors from Headwall can be tuned to bands within the electromagnetic spectrum well beyond the ability of the human eye to discern. They can distinguish the chemical signatures of everything within the field of view and provide answers to challenges facing the global food inspection and recycling industries.

INTRODUCTION

The earth represents a bountiful harvest of fruits and crops that represent sustainable nourishment for our population. From citrus in Florida to coffee beans in South America, precision agriculture aided by hyperspectral imaging is providing new guidance for the planting, cultivating, and harvesting of these crops. And this thinking extends beyond crops to poultry and seafood as well.

Once harvested, our natural food products still need to be under the watchful eye of precise imaging sensors to assure wholesomeness and quality. Indeed, since entire economies depend on specialty crops, seafood, and poultry, it makes abundant sense to implement hyperspectral imaging sensors at points along high-speed inspection lines to spot anomalies, foreign material, disease characteristics, and even to 'grade' food products based on their specific spectral characteristics. With governmental oversight increasingly stringent, the investment in new tools is absolutely vital.

A NEW WAY OF LOOKING AT THINGS

The human eye, as capable as it is, can only detect images that fall into the visible light spectrum of 400 – 700 nm. There are only three colors within this range that fall under RGB (Red, Green or Blue). The food inspection industry has largely depended on humans and RGB sensors to detect problems in the stream. These would include foreign objects missed earlier in the harvesting process, and even hard-to-detect disease conditions that might be largely invisible to either of these traditional methods. Obviously the stakes are huge: consumer preference, the ability to meet new governmental regulations, and corporate shareholder value can all hinge on the precision and effectiveness of how inspection is implemented across all facets of the food industry.

'Spectral Imaging' sensors can be subdivided into two categories. *Multispectral* sensors comprise a handful of spectral bands, anywhere from 10-20; *Hyperspectral* sensors provide a much more granular look at the field of view, since they comprise literally hundreds of spectral bands. Both provide a much more complete picture of foods under inspection because they go well beyond the 'red-green-blue' paradigm so commonly and traditionally used.

An 'advanced machine vision system' for the purposes of this discussion comprises one or more spectral imaging sensors, an illumination source, and a computer that collects the image data while communicating to downstream robotics. The sensor presents image data to the computer in real time, and that image data is then sent onward to the robotics system. The robotics system interprets the image and immediately understands what to do based on algorithms and instructions. In some cases it may simply grab and delete a piece of foreign material (pass/fail). In other cases it would direct certain colorations of a product to another line for further processing (product 'grading'). For recycling applications, it can classify different yet similar-looking types of plastics along high-speed lines.

The important point is that the hyperspectral sensor is not a standalone device but rather an important and very accurate part of an entire 'advanced machine vision system.' By one estimate[1], Machine Vision has been employed in less than 20% of the applications for which it is potentially useful. So it is therefore sensible to discuss ways in which this new imaging technology can make inspection processes better and economically efficient. Spectral imaging, thanks to its unwavering accuracy, also has the ability to boost yields and reduce waste for high-value specialty crops such as nuts and berries.

The first point to note is that a hyperspectral imaging sensor is essentially a '*new set of eyes*' acting as a sentinel and standing watch over inspection lines, 24x7. Its ability to 'talk' to other elements of the system is a crucial reason hyperspectral sensing is favored as a new tool for the industry with an ability to far surpass RGB units.

The basic function of a hyperspectral or multispectral sensor is to capture individual slices of an incoming scene (though a physical slit) and to break each slice into discrete wavelength components that are then presented to a focal plane array (FPA). A diffraction grating manages the task of dispersing the image slices into discrete wavelength components. The grating is engineered with a precise groove profile to maintain spatial coherence in one dimension (the length of the image slit, in millimeters) and will cause the spatial information (the width of the slit, in microns) to diffract. This diffraction (dispersion) process allows the spectral content to transverse to known wavelength channels on the sensor.

The all-reflective *push broom spectral line-scanning technology* used by Headwall captures a spectral line (X spatial and Z spectral) in each frame as shown in Figure 1 below. Sequential frames build up the Y spatial dimension. The push broom design is preferred for its ability to provide low distortion for very high spatial and spectral resolution. High throughput means high signal-to-noise and very low stray light. Because it is an all-reflective design, chromatic dispersion issues are eliminated.

When viewed though the slit of the hyperspectral sensor, all we see is the spatial strip that the slit lets through. This would be equivalent to one column of pixels depicted in Figure 2. You can still see the spatial detail in the image, but only one strip at a time.

In every slit, there are many colors. The hyperspectral system separates the light in each spatial pixel into the different colors in that pixel as shown. Each time the camera takes a picture of the slit, it gets a full frame of spectral data for each pixel. Stacking up each spectral image of the slit as we cross the scene we build up the hyperspectral data cube.

As the sensor moves left to right over the scene, Headwall's advanced hyperspectral processing software can take a set of pictures and stitch them together to acquire a full 'data cube.'

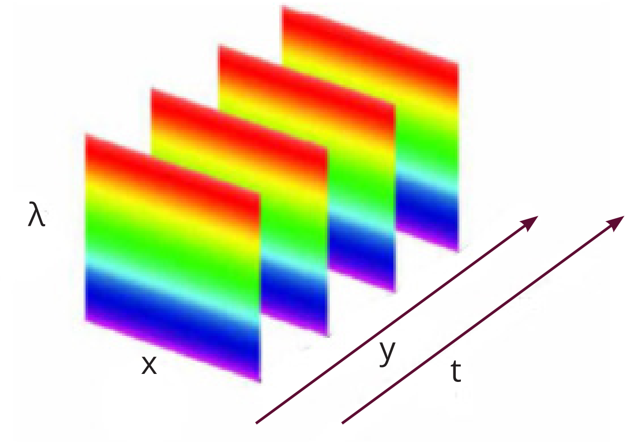


Figure 1: Depiction of Spectral Line Scanning

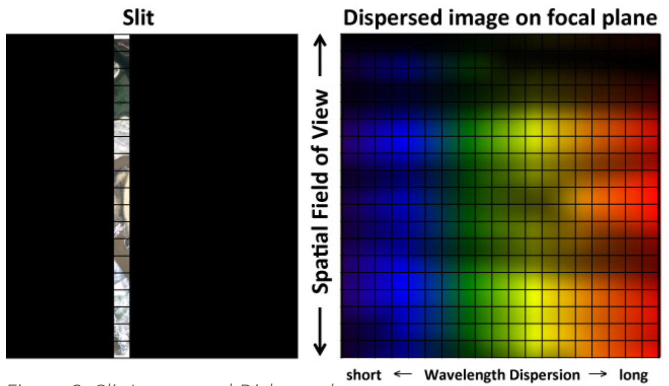


Figure 2: Slit Image and Disbursed

One characteristic of spectral imaging that makes it perfect for advanced machine vision applications is movement. Since sensors capture image data frame by frame, they naturally depend on motion to occur. The sensor either needs to move over the field of view (as it would attached to a drone or aircraft), or the field of view needs to move beneath the sensor (as it would in an advanced machine vision deployment).

The precision agriculture community is adopting hyperspectral and multispectral sensors as payloads for their drones and aircraft that fly above crop fields. A wealth of vital agricultural data is captured by these sensors, with respect to indices such as NDVI, PRI, WBI, Red Edge Ratio and more. Crop vitality, fertilization and irrigation effectiveness, and early signs of invasive species and diseases can all be seen within the hundreds of bands of a Visible-Near-Infrared (VNIR) sensor that 'sees' between 400 and 1000nm.

Along a high-speed line, the same level of meaningful data can be collected to positively impact the inspection process. Frame-rates and field-of-view characteristics are such that the sensors are more than capable of monitoring wide lines operating at high speeds. The high

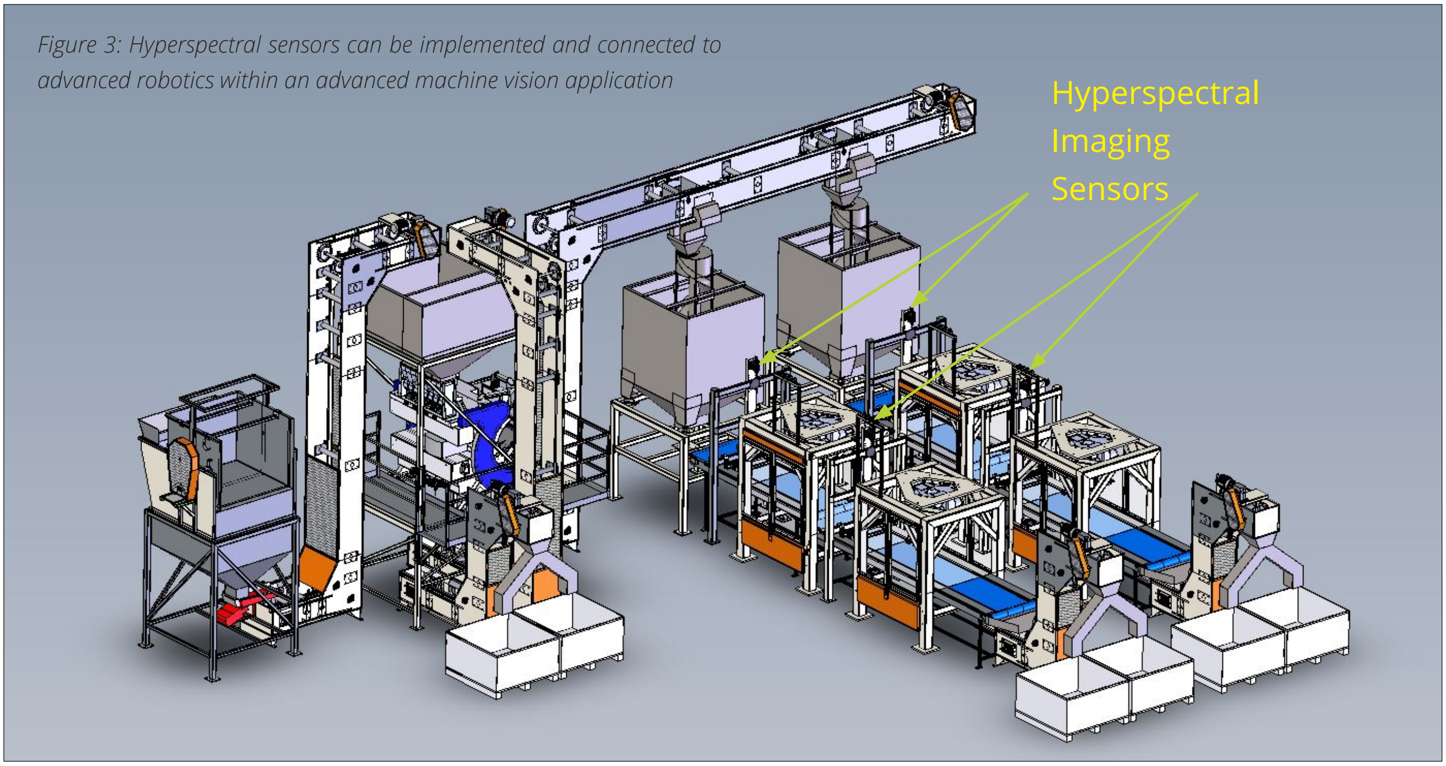
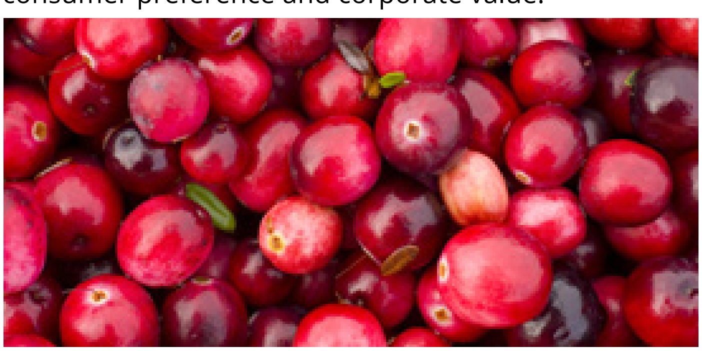


Figure 3: Hyperspectral sensors can be implemented and connected to advanced robotics within an advanced machine vision application

level of discrimination afforded by hyperspectral imaging means that even hard-to-distinguish anomalies are seen and managed. Obviously a blueberry in a field of strawberries is easy to spot. But what about very vague chemical differences between crops or recycled materials? Only hyperspectral can distinguish these impossible-to-see differences.

Ocean Spray® uses hyperspectral imaging sensors to effectively 'grade' cranberries as they are being inspected. Based on the data collected by the sensor, this global leader of cranberry-based products can determine which berries will go into juices, spreadable fruit, and wholesome packaged snacks (their popular Craisins®) based on very specific algorithms and software analysis. Armed with this data, Ocean Spray can greatly reduce waste since more berries are being used. Although the cranberries are all varying degrees of 'red,' this level of discrimination gives Ocean Spray a new tool that boosts inspection efficiency and ultimately boosts consumer preference and corporate value.



SENSOR DESIGN

Although hyperspectral imaging sensors are sometimes referred to as 'cameras,' they are truthfully a marriage of spectrometers and cameras, as depicted in Figure 4 below.

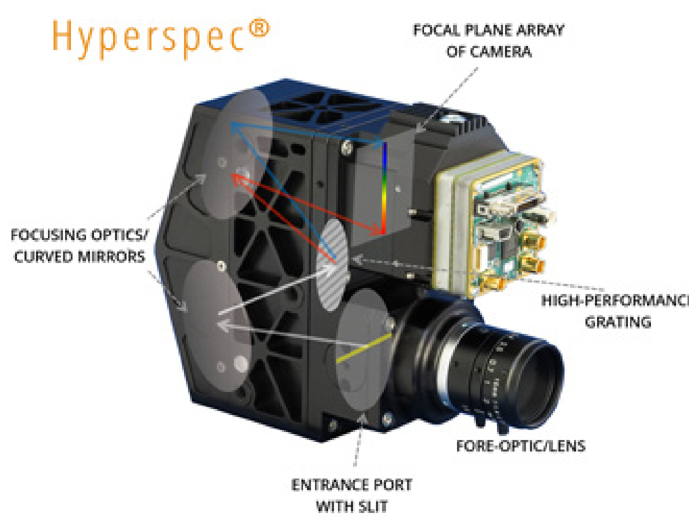


Figure 4: Cutaway illustration of a hyperspectral image sensor.

Headwall's sensors are based on an all-reflective design having no moving parts or potentially offending transmissive optics. This is accomplished through the use of diffraction gratings (Figure 5) that manage the incoming light passing through the image slit. The gratings are not only exceptionally precise, but they are small and light. This allows the instruments themselves to be small and light for easy deployment anywhere. The objective of the sensor is to present a very high-resolution slit image to the camera's focal plane array (FPA). The use of diffraction gratings helps in measureable ways, from high signal-to-noise ratios to high spatial and spectral resolution across the field of view. The gratings themselves are all master quality, not replicates, which means exact repeatability from one sensor to the next. This is a crucial distinction when a machine vision application calls for several instruments all tuned precisely the same.

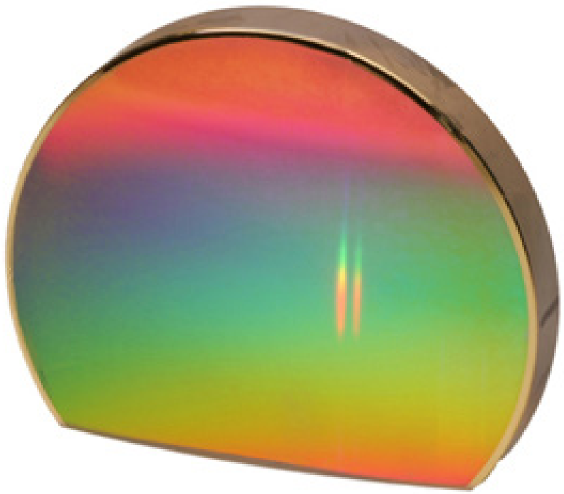


Figure 5: A holographic diffraction grating manages incoming light presented to the camera FPA.

Figure 6: Hyperspec INSPECTOR encloses a precise spectral imaging sensor within a robust enclosure.

A food inspection line can be an unforgiving environment for sensitive instruments. Headwall's Hyperspec INSPECTOR (Figure 6) packages the sensor along with storage and software within an industrialized, rugged enclosure that is suited for the rigors of the food-inspection environment.

ILLUMINATION

Since spectral imaging sensors measure and analyze reflected light, illumination is an important consideration. It is an issue that has many facets and technical solutions, but the overall objective is to provide the field of view with an extremely uniform, consistent, 'cold' form of illumination that is simultaneously robust and economical.

For the VNIR range of 400-1000nm, Quartz Tungsten Halogen (QTH) represents one such illumination technology while newer LED light sources are seen as another. Bundled optical fiber also presents a uniform light source. Much of what interests the food-inspection industry 'reflects' at ranges beyond the visible, which cuts out at around 700nm. So having a light source covering either side of this point is vital.

Beyond being 'cold,' robust, and uniform, the light source needs to fully traverse the width of the inspection line. This edge-to-edge capability takes advantage of the wide field-of-view of the sensor, allowing inspected product to be seen not only directly beneath the sensor itself but off to the edges. There's no regimentation in a high-speed food inspection line because product is everywhere...along the edges, bunched together, and so on.

Although there are many illumination choices, Headwall presents customers with options that are robust, affordable, and matched to the spectral requirements of the application. Longevity of the light source is also key, since many food-inspection lines run around the clock.

Since we earlier saw that the sensor is building a 'cube' of image data one slice at a time, the illumination itself is a very thin strip. The region of interest (the 'slit image') is what needs to be illuminated as shown below in Figure 7. You will also note the presence of a white reflectance target used to calibrate the sensor prior to actual operation. This is a crucial step because the sensor is collecting image data that a downstream robotics system (vacuum, air knives, or similar) will use to segregate 'good' from 'bad.' As a producer of complete machine vision solutions, Headwall has a keen understanding of illumination and the trade-offs that each application may encounter. The objective is always to present the right kind of light at the right intensity, exactly where it's needed. Also, it is important that documentation exists providing wavelengths and intensity of light across the field of projection, uniformity of the light, and degradation across standard distances. This way, the exact positioning of the sensor relative to the line can be determined should some adjustment on the architecture of the line be necessary.

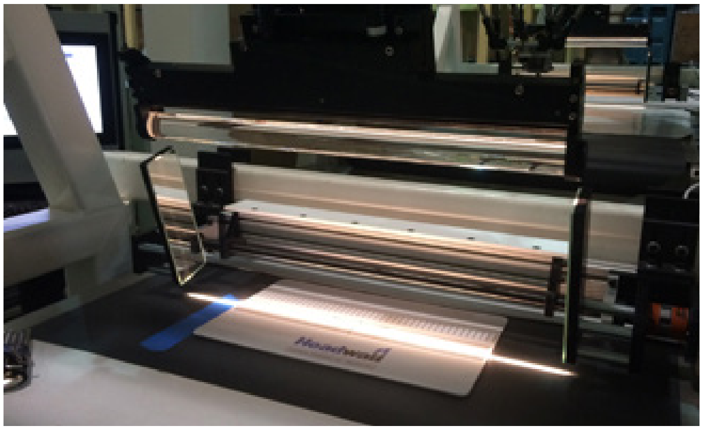


Figure 7: Illuminating the field of view beneath the hyperspectral sensor. (courtesy Bratney Companies)

ROBOTICS

Robotic subsystems (Figure 8) are a natural element of many advanced machine vision line applications. The ability to eliminate and discriminate rests with the ability of the sensor and robotic system to communicate rapidly and faithfully, in real time. Hyperspec® sensors from Headwall often run well in excess of 200 frames per second, meaning that they are well suited from both an operational and economic standpoint to work with high-speed lines and the robotic systems embedded within them.

The machine vision industry understands that the wherewithal to integrate a wide range of subsystems into a seamless and continuously running line demands that communication protocols be industry-standard and fast.

Gigabit Ethernet is often used to tie everything together from a data-flow perspective. The hyperspectral sensors and computers that manage the incoming data all work with Gigabit Ethernet, but also other very fast communication links such as USB and CamerLink.

The optical precision of a robotics system is crucial in all cases, but especially in situations where piece-size is small. The inspection of berries and nuts, for example, demands millimeter precision so the robotic arm targets only 'fail' examples as defined by the upstream sensor system. Also, ease of recovery from vision failure is important, with the cost of downtime running thousands of dollars per minute in some cases. If machine vision is broken, the line stops. Since it's incumbent that the sensor and robotics system be tied together through software, manufacturers of both elements are able to accommodate this through common languages and control electronics.

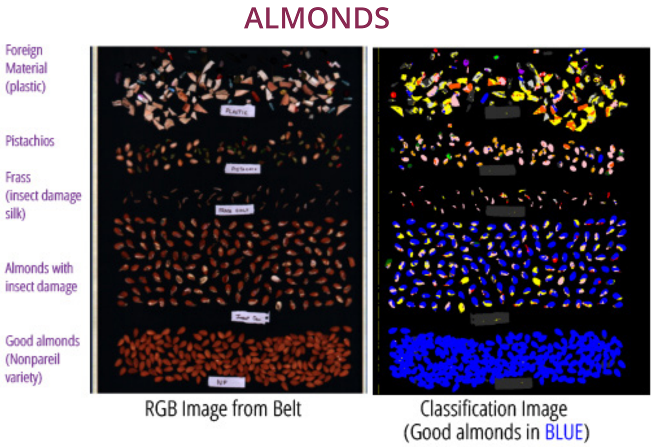
Figure 8: Robotic subsystem represents an integral part of the machine vision system and must communicate seamlessly and in real-time with the hyperspectral sensor, using industry-standard protocols.

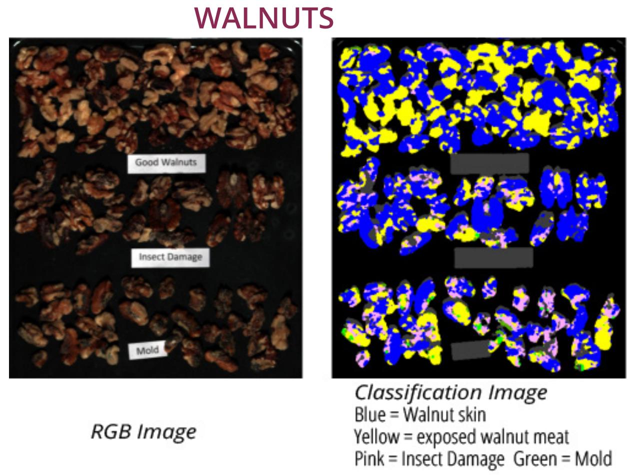
DATA COLLECTION

Inspecting specialty crops such as nuts and berries involves looking at vastly similar-looking items with small degrees of variability. This is why dividing the signal or image into upwards of 300 'hyperspectral' channels is a benefit to the industry. With hyperspectral machine-vision technology in place, "even the slightest variation in color or tone can be distinguished," according to Mr. Dave Ewald, Director of Marketing and Customer Service at Bratney Companies (Des Moines, IA). "Infractions or defects are not always detectable by visual means, so this allows us to basically 'see the unseen.'"

As an integrator of high-quality, high-performance pick & sort systems for the food industry, Bratney understands the challenges its customers face:. "In an increasingly challenging industry, they want engineered, disruptive technologies that put them ahead and keep them there," said Ewald. "Our ability to integrate the best third-party solutions out there into seamless, end-to-end machine vision systems has always been a focal point for us," he concluded.

Using almonds and walnuts as examples, the illustrations in Figure 9 show the clear distinction between an RGB image





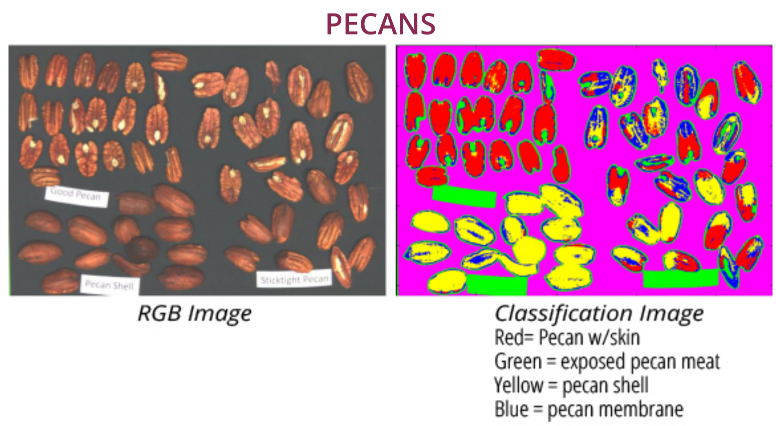


Figure 9: Hyperspectral imaging provides a much higher degree of discrimination, especially with items with similar coloration. Algorithm-based software represents the 'instruction set' the sensor uses to do its classification. (courtesy: Bratney Companies)

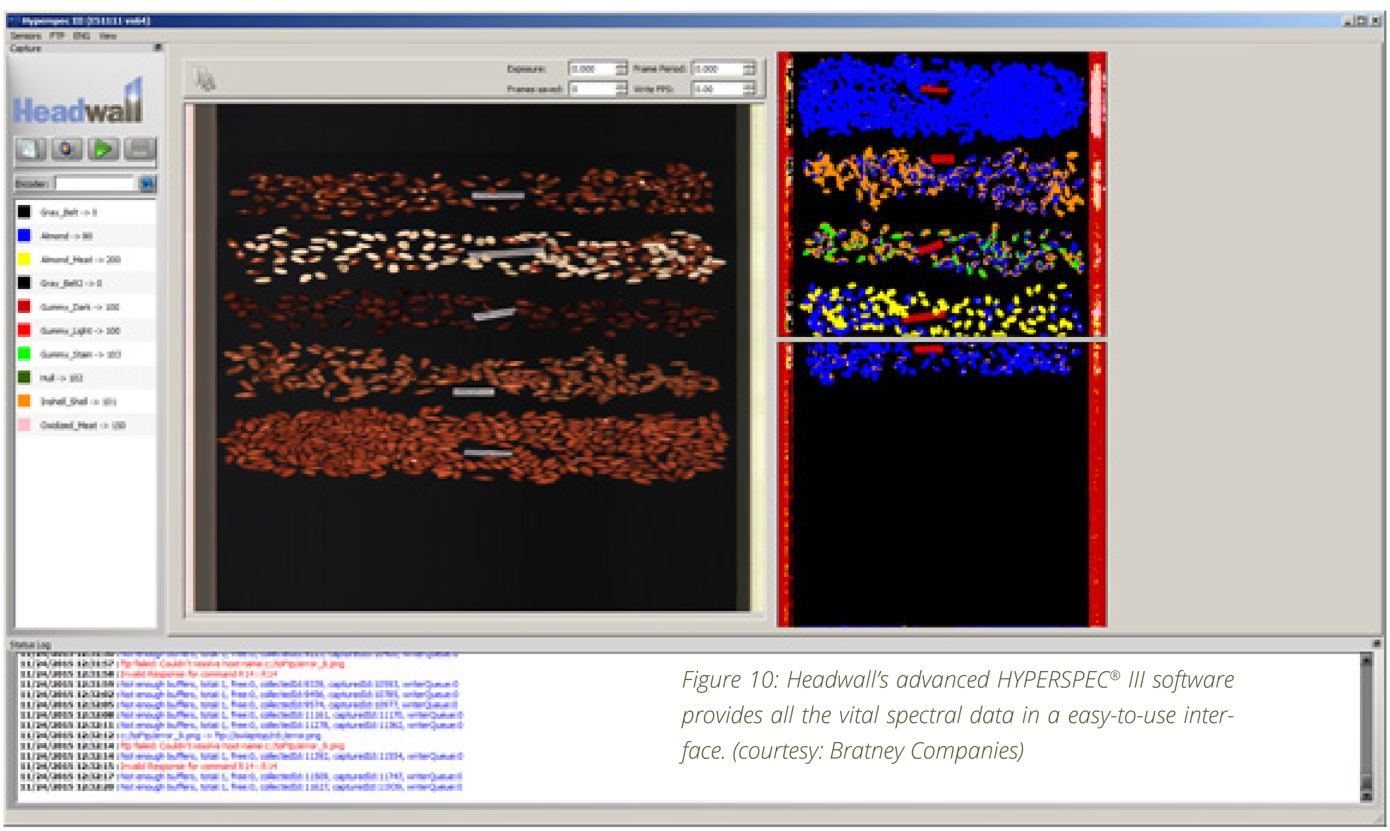


Figure 10: Headwall's advanced HYPERSPEC® III software provides all the vital spectral data in a easy-to-use interface. (courtesy: Bratney Companies)

and a hyperspectrally classified one. With this data, quality and wholesomeness decisions are easier to make.

Since ease-of-use is paramount and steep and rapid learning curves are necessary, Headwall's Hyperspec III software (Figure 10) is intuitive and packed with functions that allow users to modify and adapt their inspection processes based on what the sensors see. The algorithm-based process pinpoints the spectral characteristics users might encounter. For example, almonds with insect damage are nearly indistinguishable from 'good' almonds under RGB analysis. But the same scene classified hyperspectrally will call attention to the damaged ones, which can be eliminated by the downstream robotic system.

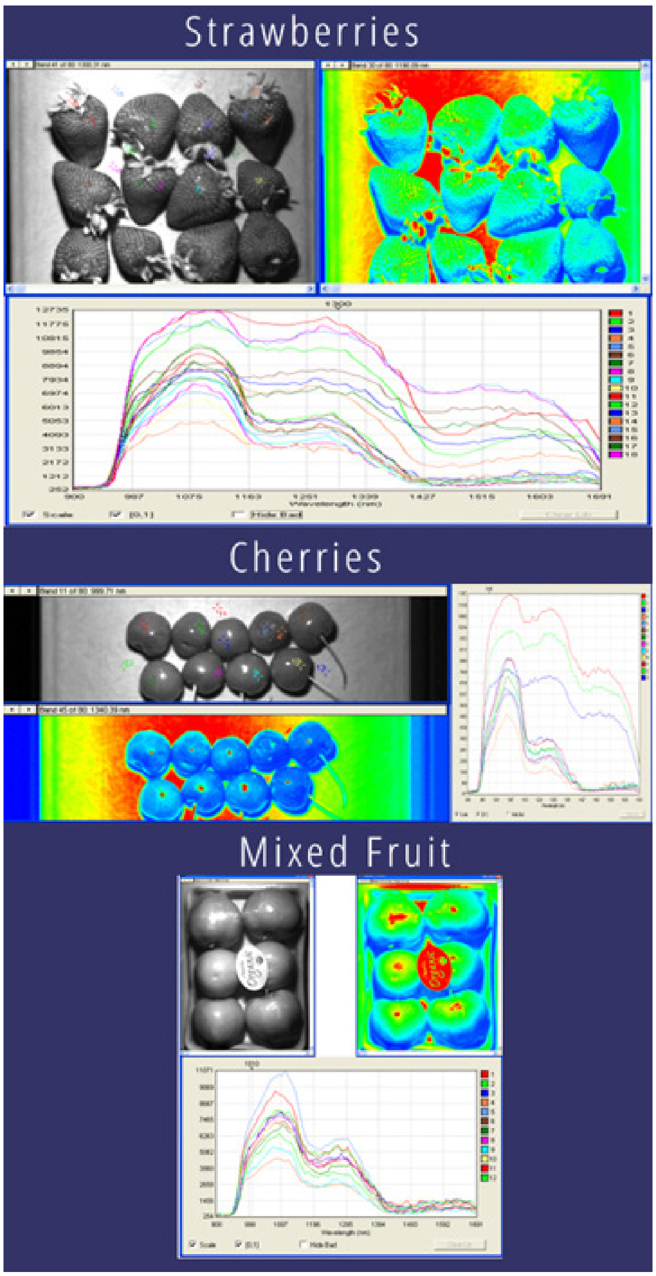


Figure 11: Hyperspectral classification of different fruit types.

Similarly, mold on walnuts can be classified and 'seen' hyperspectrally. The result is a far higher level of quality and wholesomeness, which results in greater consumer preference and shareholder value. Product recalls can be a very damaging (and costly) event for packaged foods, so the ability to implement a new set of eyes such as hyperspectral represents a level of inspection precision previously reserved for military and defense applications.

Hyperspectral imaging is also beneficial for the inspection of poultry and seafood as well. Headwall has been awarded an exclusive licensing agreement with the USDA Agricultural Research Service (ARS) for the use of hyperspectral imaging in the inspection of poultry. Fecal material in poultry is exceptionally difficult to distinguish through normal means but is quite noticeable through the use of hyperspectral imaging. Not only is the inspection process more thorough, but portions of each bird (profit-rich claws, for example) can be salvaged.

The ability to distinguish histamine levels within seafood is also possible with hyperspectral imaging.

REFERENCE

(1) Hornberg, Alexander (2006). Handbook of Machine Vision. Wiley-VCH. p. 694. ISBN 978-3-527-40584-8.

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BRATNEY COMPANIES
Integrating Innovative Solutions

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