Headwall is the proud recipient of these honors and more...

Hyperspectral Imaging for Advanced Machine Vision

BENEFITS

- Non-contact detection & inspection
- Real-time product assessment
- Detect potentially harmful foreign matter
- Deployable in challenging processing environments
- Proven technology widely used in many applications

BROCHURE

VISUALIZING VALUE AT THE SPEED OF LIGHT

BACKGROUND

The global food inspection industry needs newer and more precise tools to meet stringent government regulations. From specialty crops to seafood, meat, and poultry, the food safety testing market alone is valued at a staggering $19.5 billion USD in 2021 and is projected to reach $28.6 billion by 2026.[1] This is one example where Hyperspectral Imaging (HSI) is becoming a tool that can alleviate tedious and labor-intensive tasks, as well as bring a new level of consistency to some historically subjective grading applications.

Developed originally for remote-sensing applications involving imagery from aircraft and satellites, HSI has become a commercially viable technique for industrial machine vision applications. HSI sensors act like thousands or millions of spectrometers providing chemical signatures from the reflected light at each pixel of an image. Headwall's sensors cover wavelength ranges beyond the ability of the human eye to discern, from the ultraviolet and visible (UV and VIS) to the near-infrared (VNIR, NIR, and SWIR) wavelength ranges.

Hyperspectral-imaging sensors can distinguish spectral features and detect potentially harmful foreign matter. They provide a means to sort and grade material such as food products whose value is often tied to characteristics that are often better and more consistently measured by an HSI system than by a human who is subject to fatigue or the effects of something as simple as varying amounts of coffee each day.

However, systems utilizing HSI have faced significant hurdles in industrial deployment because of the need to handle comparatively vast amounts of raw data and address the relative complexity of spectral-classification model development. Newer HSI platforms such as Headwall's award-winning Hyperspec® MV.X imaging system overcome these obstacles. The MV.X combines a high-performance imaging spectrometer with powerful embedded computing and software to create spectral-classification

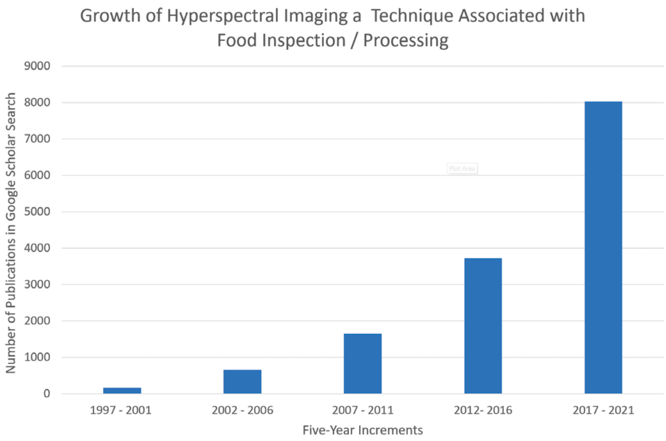

Figure 1. The growth of hyperspectral imaging as a technique in food inspection / processing is illustrated by the trend shown here in Google Scholar search results over the past 25 years.

A DIFFERENT WAY OF SEEING THINGS: WHAT IS HYPERSPECTRAL IMAGING?

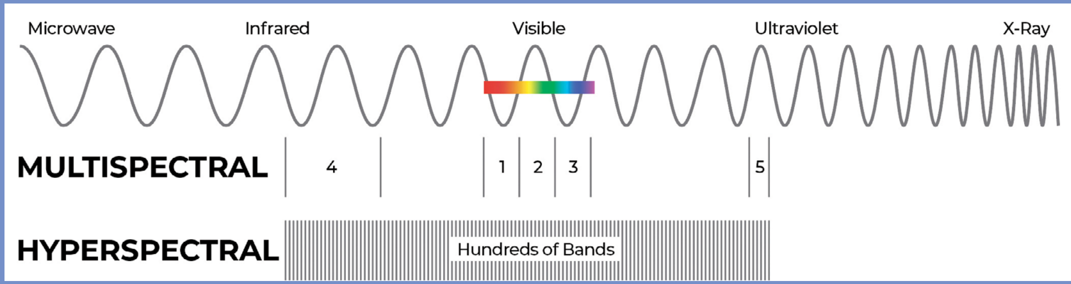

Figure 3. The full electromagnetic spectrum is shown at the top, while the color gradient represents what normal human eyes can see. Multispectral imaging uses 4 or more fairly broad bands, while Hyperspectral imaging uses hundreds or thousands of relatively narrow bands.

The human eye, as capable as it is, can only detect images that fall into the visible-light spectrum roughly between 400 nm and 700 nm. There are only three colors within this range that fall under broad RGB (Red, Green or Blue) regions, and each person's color sensitivity and perception varies to a surprisingly wide degree. Humans have trouble distinguishing the difference between a red-green mixture and a pure yellow.

models and extract actionable results in real time then send instructions over the local network to take action along the production line or the Industrial Internet of Things (IIoT) to collect monitoring and control data.

Machine learning and artificial intelligence powered software such as perClass® MIRA assists in building classification models and helps enable runtime processing. Model development is very intuitive, and the browser-based interface of the MV.X is also very simple, allowing for remote control and maintenance of the system by a range of users with different levels of expertise.

Packaged in a compact, dust, and watertight housing, the IP-rated MV.X system is designed to be used in machine vision, quality monitoring, and process analytical applications both within and outside of production environments.

The streamlined workflow is designed for efficiency and each stage is intuitive for the operator. Updating a classification model MV.X workflow involves simply uploading the new model into the online MV.X systems positioned over the flow of goods. Building new models can be done using a small MV.X scanning stage for offline development of classification model.

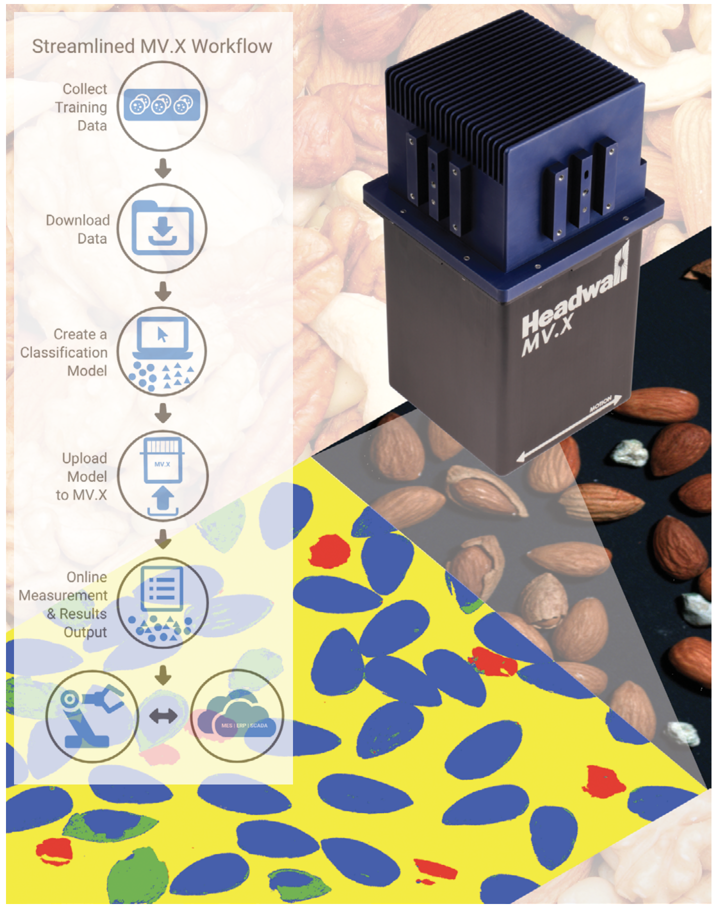

Figure 2. New hyperspectral imaging systems such as Headwall's Hyperspec® MV.X incorporate sensor, embedded-processing capability, enhanced connectivity, and an intuitive workflow in compact, rugged form factors suitable for challenging environments such as food-processing lines.

ASSURING WHOLESOMENESS AND QUALITY

Once harvested, natural food products need to be under the watchful eye of precise imaging sensors to assure wholesomeness and quality. Some entire economies depend on specialty crops, seafood, and poultry. So, it makes sense to implement hyperspectral imaging sensors at points along high-

Nevertheless, the food-inspection industry has depended on humans and RGB sensors to detect problems and grade products for centuries. 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.

The stakes are high: 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 four to dozens; whereas hyperspectral sensors provide a much more granular (i.e., high spectral resolution) look, since they can capture literally hundreds or thousands of spectral bands at a time. Hyperspectral imaging sensors provide a much more complete picture of foods under inspection because they go well beyond the simple RGB or multispectral paradigms and can also provide spatial information such as locations of areas of interest.

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, an investment in new, more effective tools is absolutely vital.

SYSTEM DESIGN

An 'advanced' machine-vision system may comprise one or more spectral imaging sensors, a suitable illumination source, and a computer that collects the image data while communicating to downstream robotics. The sensor sends image data to the computer (that may be embedded within the sensor itself) in real time, and the processed data is then sent onward to the robotics system. The robotics system interprets the data and immediately understands what to do, based on algorithms and instructions. It may simply grab and delete a piece of foreign material (pass/fail). In other cases it could 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, Machine Vision has been employed in less than 20% of the applications for which it is potentially useful.[2] Therefore, it is sensible to discuss ways in which this powerful imaging technology can make inspection processes better and economically more efficient. Hyperspectral 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 HSI sensor can be thought of as a 'new set of eyes' acting as a sentinel standing watch over inspection lines, 24 hours a day, seven days a week if needed. 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 sensor is to capture individual slices of an incoming scene though a physical slit in the case of a 'pushbroom' design 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) and 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'. Sequential frames build up the Y spatial dimension. The pushbroom design is preferred for its ability to provide low distortion at very high spatial and spectral resolution. High throughput means a high signal-to-noise ratio 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. 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 HSI system separates the light in each spatial pixel into the different colors in that pixel. 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

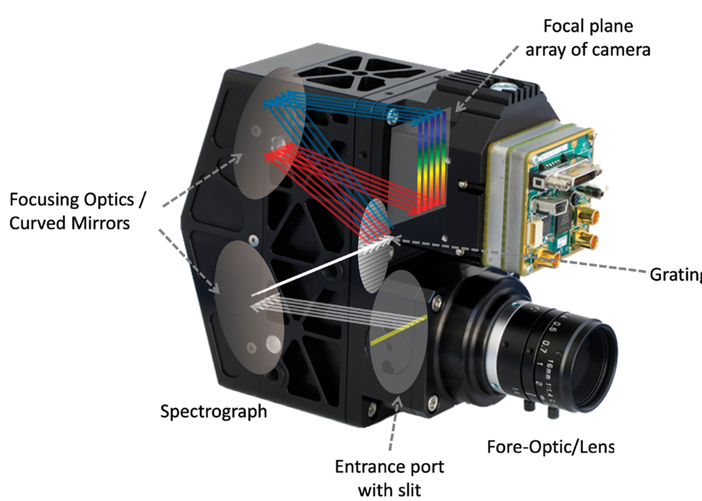

Figure 4. Headwall's hyperspectral sensors capture images one line at a time with full spectral information at each pixel. Uniquely amongst manufacturers, Headwall designs and manufactures its own holographic diffraction gratings and spectrographs.

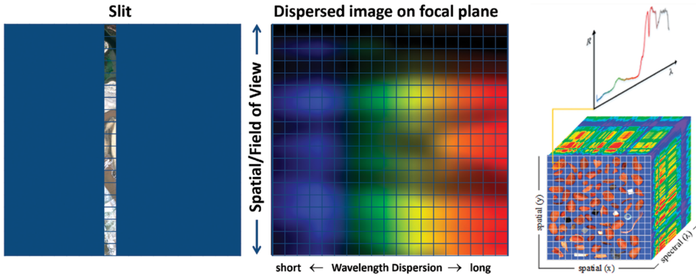

Figure 5. Hyperspectral data is captured in the X and Y spatial dimension as well as the Z spectral dimension.

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

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 (when attached to a drone or aircraft in remote-sensing applications), or the field of view needs to move beneath the sensor (when in an advanced machine vision deployment).

The precision agriculture community has adopted both hyperspectral and multispectral sensors as payloads for 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 many 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 400nm and 1000nm.

Along a high-speed conveyor, the same level of meaningful data can be collected to positively impact the inspection process. The sensors are more than capable of monitoring wide lines operating at high speeds. The high level of discrimination afforded by HSI means that even hard-to-distinguish anomalies are seen and managed. A blueberry in a field of strawberries is easy to spot, but what about minute color or chemical differences within the same crop or within similar-appearing recycled materials? Only hyperspectral can distinguish these impossible-to-see differences.

EXAMPLES

Ocean Spray® uses HSI 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 packaged snacks 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.

Approximately 70 million tons of oranges are produced per year worldwide. About a third of the total tonnage is processed, with the rest being consumed as fresh fruit.[3] Sweetness and acidity are among the most important quality parameters monitored by orange processors. Sweetness, or the concentration of soluble solids is of particular importance. Commonly reported in degrees Brix (°Brix), it is a key quality factor in assessing the grade of the product delivered into the processing facility. Results are used to calculate the value of the delivered fruit and are directly tied to costs and profitability. The measurement traditionally requires obtaining a representative sample from the delivered, then juicing and analyizing with a laboratory refractometer. The process of obtaining results can be slow and labor intensive.

A world-leader in processing and selling orange juice has deployed Headwall's latest HSI system to calculate and predict the sweetness of incoming fruit without direct contact in order to send each truckload to the proper destination. The HSI system rapidly collects highly resolved data from each load of oranges passing under the sensor. Processing this

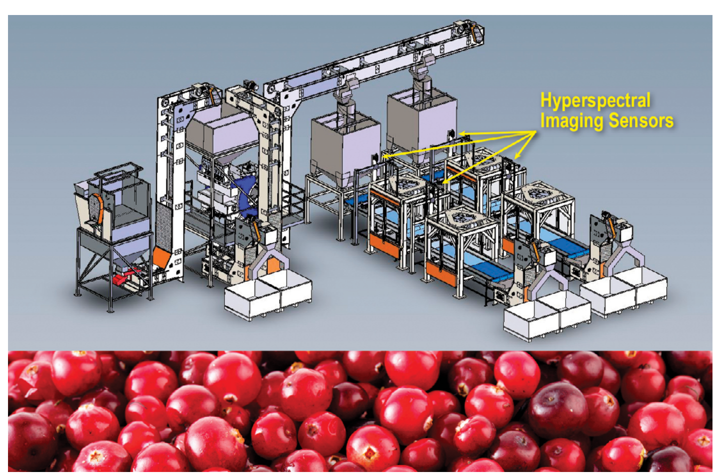

Figure 6. Hyperspectral sensors can be implemented and connected to advanced robotics within an existing processing / inspection line.

Figure 7. Hyperspectral imaging is a non-contact technique that can enable incoming citrus fruit to be delivered to the right destination based on a fast yet accurate prediction of sweetness. One large citrus processing company enjoys significant return on their initial investment.

data in real time and applying statistical analysis algorithms developed by Headwall, the system delivers a predicted °Brix value at the end of the scan. Entire truck loads can be scanned in minutes and the results sent to production control stations. Real-time results help speed up receiving operations, optimize decision making and deliver significant ROI.

New legal requirements in Western Europe set strong maximum permissible values for pyrrolizidine alkaloids (PA) in parsley. Contamination by groundsel (senecio vulgaris) that contains PA, as well as by creeping thistle that contains sharp thorns can reduce the real and perceived value of a parsley harvest. HSI offers a way to differentiate amongst the product and undesired weeds.

Headwall's sensors are based on an all-reflective design having no moving parts or potentially offending transmissive optics. This is accomplished by using small and light holographic diffraction gratings that manage the incoming light. This allows the instruments themselves to be small and light for easy deployment anywhere.

Headwall is the only spectral sensor manufacturer that also makes its own diffraction gratings. Since the fundamental optical performance of the sensor is a function of the grating, this capability represents true differentiation.

The Visible-Near-Infrared range (VNIR) covers from 400 nm to 1000 nm and the Extended VNIR range covers from 550 nm to 1700nm. The Near-Infrared range (NIR) collects image data from 900 nm to 1700nm, while the Shortwave-Infrared range (SWIR) covers from 900 nm to 2500nm. Since material 'reflects light' at certain points within these ranges, it is important to first define the signatures themselves. Then, through algorithms, the sensor is able to characterize material or detect anything not precisely defined as 'good.' Not only with respect to foreign material, but also hard-to-distinguish 'grading' differences from one berry to another or from one nut to another. This is a very valuable characteristic of hyperspectral imaging, since it has a level of specificity that goes far beyond more traditional RGB sensors.

A food inspection line can be an unforgiving environment for sensitive instruments. Headwall's Hyperspec® MV.X sensor is rugged and packaged in an IP-rated enclosure suited for the rigors of the food-inspection environment.

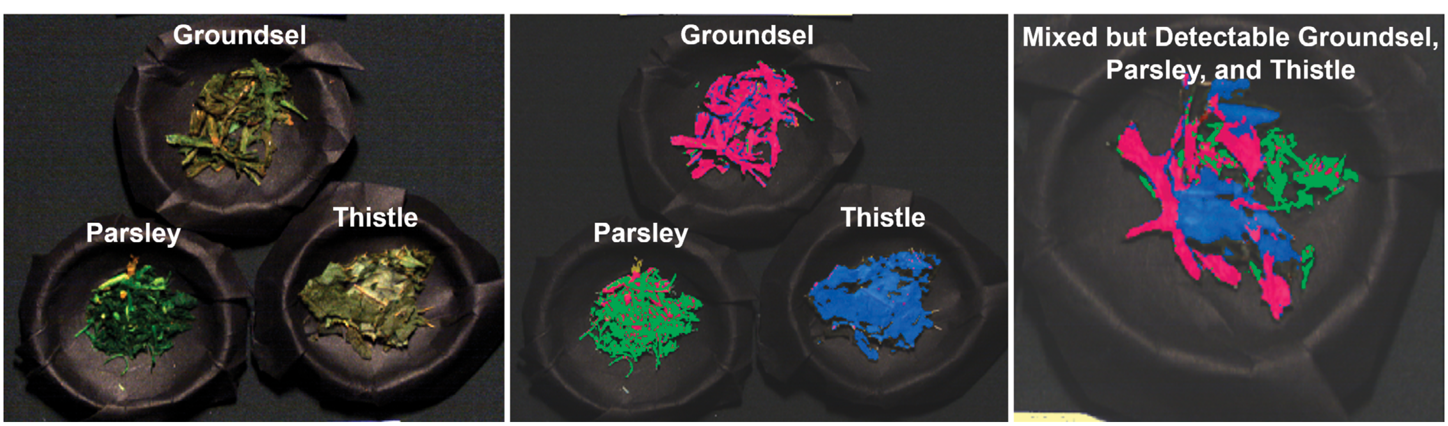

Figure 8. Hyperspectral imaging can distinguish amongst genuine product and contaminants or adulteration. Here you can clearly see parsley in false-color green and unwanted groundsel in magenta and thistle in blue.

Figure 9. Optimized broadband lighting allows the highest quality hyperspectral imaging data to be captured. Important considerations include uniformity of coverage, wavelength range, and robust construction.

LIGHT MATTERS

Since HSI 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 sensor's field of view with an extremely uniform, consistent form of illumination that is simultaneously robust and economical.

For the VNIR spectral range, Quartz Tungsten Halogen (QTH) represents one such illumination technology while newer LED light sources may be seen as another albeit less mature alternative. Bundled optical fiber can also help create 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 as cool as possible, 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. In a high-speed food inspection line product could be everywhere…along the edges or bunched together on the conveyor belt.

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

We mentioned earlier 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. 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 of the architecture of the line be necessary.

ROBOTICS

Robotic subsystems are a natural element of many advanced machine vision processing-line applications. The ability to discriminate and eliminate depends on the ability of the sensor and robotic system to communicate rapidly and faithfully, in real time. Hyperspec® sensors from Headwall 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 HSI systems and computers that manage the incoming data all work with Gigabit Ethernet, but also other very fast communication links such as CameraLink.

Figure 10. Robotic subsystems represent an integral part of machine-vision systems. Hyperspectral systems can communicate using industry-standard protocols to enable real-time actions along the line.

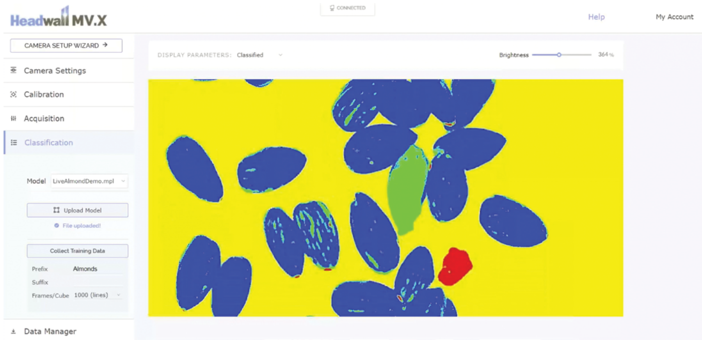

Figure 11. Intuitive software can enable straightforward operation of even the most sophisticated HSI system.

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 imaging systems are 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.

DATA COLLECTION & PROCESSING

Inspecting specialty crops such as nuts and berries involves looking at vastly similar-looking items with small degrees of variability. With hyperspectral machine-vision technology in place, even the slightest variation in color or tone can be distinguished. Since ease-of-use is paramount, Headwall's software including perClass Mira® is intuitive and contains 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 using HSI will call attention to the damaged ones, that can be eliminated by the downstream robotic system.

The combination of innovative sensors, software, and workflow allows a growing number of users access to HSI with true solutions that use spectral data to not only detect contamination, but also to 'grade' products so that less is wasted and more is converted to revenue. Hyperspectral imaging unlocks that possibility within the machine vision industry.

CONCLUSION

Hyperspectral imaging sensors represent a new technology for the machine vision industry, where precision far beyond RGB is necessary. Food inspection is a key application. New-generation sensors are small and rugged for use in harsh environments such as those found in food inspection facilities. Reproducibility from one instrument to the next is a critical requirement where inspection accuracy across numerous lines must be maintained.

Headwall's diffractive optics approach allows inspection lines to be wide and fast. Hyperspectral sensors are able to 'see' with unmatched discrimination and specificity because they collect data across hundreds of spectral bands. This means not only distinguishing good from bad, but also the ability to 'grade' products more accurately. Software not only manages the operation of the sensor, but it also provides the key post-processing tasks involved with diagnosing the hyperspectral data in an intuitive, straightforward manner.

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[1] Markets and Markets report, Food Safety Testing Market by Target Tested (Pathogens, Pesticides, GMOs, Mycotoxin, and Allergens), Technology (Traditional and Rapid), Food Tested (Meat, Poultry, Seafood, Dairy, Processed Foods, and Fruits & Vegetables), and Region - Forecast to 2026; published May 2021

[2] Handbook of Machine Vision, Hornberg, A., 2006; Wiley-VCH, ISBN 978-3-527-40584-8

[3] Orange Book, Tetra Pak, published and maintained online, https://orangebook.tetrapak.com

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