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The power of in-line metrology using machine vision

Precision in-line metrology, or measurement, is an important application of machine vision in manufacturing environments.

Using machine vision components, manufacturers can develop in-line setups that measure the dimensions or geometries of products or their features in real time. When thoughtfully designed and tested, the systems produce repeatable and reliable measurements of 100% of products during the manufacturing process.

And because in-line vision-based metrology systems operate without physically contacting a part, there is little risk of accidental damage.

In addition to helping manufacturers meet their customers' expectations for quality, the systems highlight problems in production.

When implementing in-line metrology applications, however, engineers must pay attention to some unique implementation challenges, writes Machine Vision Expert David Dechow in the cover story in this *Vision Systems Design* supplement. Dechow's instructional tutorial discusses these challenges and how engineers can overcome them in their system designs.

It's worth the effort. As the speed and resolution of cameras and sensors increases and software becomes more sophisticated, engineers likely will have more options to consider when designing in-line metrology systems that deliver precise and repeatable results.

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Keys to deploying machine vision in precision in-line measurement applications in manufacturing

Explore the challenges and best practices that ensure accurate, reliable measurements using metrology systems integrated directly into the production process.

DAVID DECHOW

Machine vision tasks like quality inspection, identification, and robotic guidance might be the first to come to mind when considering this valuable technology in industrial automation. Just as important though is machine vision's capability to perform precision, in-line metrology or measurement.

Automated, non-contact measurement, however, can present some unique implementation challenges in the execution of a robust and reliable application. This discussion will cover a few of these sometimes-overlooked key issues and some best practices that can help ensure application success.

Automated imaging is used in many off-line or laboratory metrology systems, too. However, this discussion focuses on systems integrated directly in the manufacturing process to deliver measurements of every part produced to help improve production efficiency and quality.

Non-contact vs. contact-based measurement

It might be obvious to mention that machine vision uses imaging technologies. Understanding the impact of this is critical when executing non-contact metrology using imaging. Differences between contact- and non-contact measurements are simple to describe but can be difficult to overcome, and in many cases, the results produced by these two techniques will not be aligned.

A view from the surface

Regardless of the machine vision component used, an acquired image (grayscale, color, or even 3D) contains only a view of object features that generally face the imaging device. Where a manual measurement

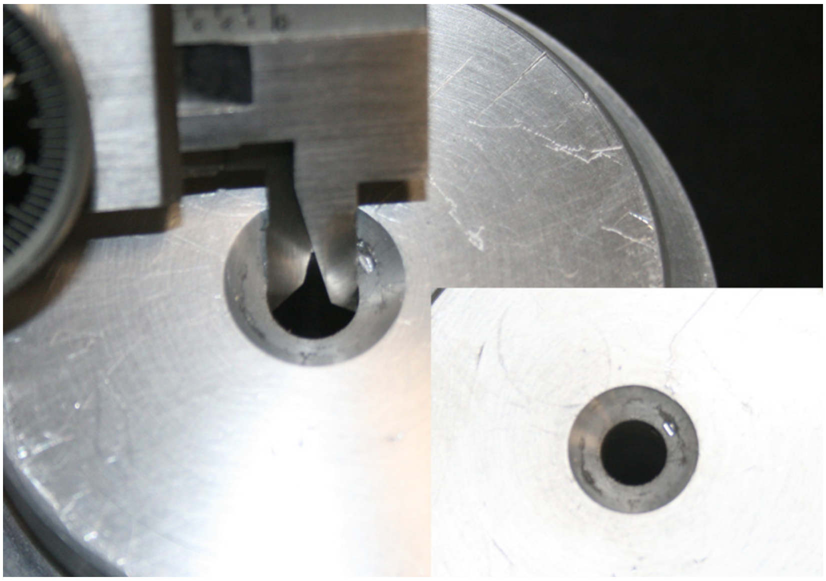


FIGURE 1. Caliper Measure: Physical gauge tools measure surfaces, such as the inner diameter of this bore hole, while imaging systems measure visible surface edges. It is important to be know the differences that may exist in these two measurements for a given part. *(Credit: David Dechow)*

tool will have contact with, for example, the sides of an object at the measurement points, non-contact measurement must rely on visible edges of related features. Take, for example, measurement of the diameter of a machined hole or "bore hole" in a part.

A caliper or bore gage could be used to physically contact and measure the diameter of the bore at a point below the surface. However, an image from above the part measures only the edges of the hole at the surface of the part. Important questions are:

- Do these measurements represent the same exact thing physically?
- If not, is there a consistent relationship that reconciles any measurement differences?

This is a simple example of an underlying challenge that impacts almost any measurement application.

The impact of part presentation

In a broader sense, part presentation and related production variations play a similar and perhaps more challenging role in contact/non-contact measurement disparities. Take, for example, the circular bore hole described earlier. When the face of that hole is perpendicular to the imaging system, the feature appears correctly as a circle in the image. However, if the part surface tilts even slightly, the circle will turn into an ellipse visually, impacting the measurement. This presentation problem can occur in nearly any in-line measurement regardless of the object or feature to be measured.

This issue is often more noticeable when performing measurements on a backlit part, and even the use of telecentric or "gauging" lenses does not overcome the potential error. With imaging for non-contact measurement, one must first mitigate all possible variation in part presentation, then understand that in almost any situation, any remaining part and/or presentation variation will introduce some stack-up error in the measurements.

An understanding of these underlying factors in non-contact measurement serves as a good starting point for success in machine vision in-line measurement, but there are several other points to consider in the practical implementation of image-based metrology.

Successful imaging for measurement using machine vision

From the discussions above, it might be apparent that the success of an in-line system rests with the implementation of correct and sometimes creative part imaging. What works best is often unique to a specific use case. However, certain best practices offer a foundation for getting the best imaging results. An important starting point for this discussion is a review of the concepts and language of the metrics of measurement.

Measurement metrics—precision, accuracy, trueness

Measurement results are commonly evaluated based on these fundamental and related measurement science concepts. It is important to clearly understand what the terms mean and how they impact the approach you take to designing machine vision measurement applications.

Precision is how close the values of a specific measurement are to each other over many executions. It is closely related to "repeatability" and "reproducibility." In an in-line measurement application, precision is arguably the most important metric to consider as it indicates how trusted the reported measurement will be over time.

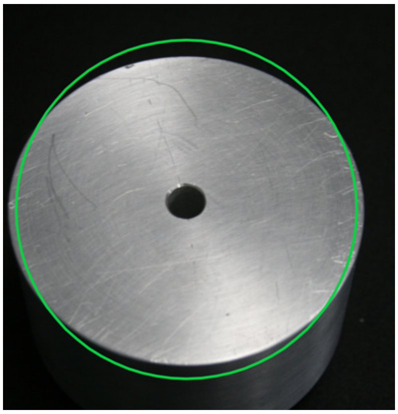


FIGURE 2. Part presentation can impact the representation of an object or feature in an image. In this case a circle being observed as an oval due to part tilt. *(Credit: David Dechow)*

A common way to express precision is as the standard deviation (SD) of a set of measurement values with a lower SD indicating higher precision. However, averaging the data may not tell the whole story for in-line measurement. For many applications, the most useful metric is a basic range of measurement values over time. Because most in-line systems not only collect data but also must provide decisions regarding in- and out-of-tolerance parts, the extremes of a range can be used to reasonably predict the system's capability to reliably pass and fail parts with minimum false rejects and few or no escapes.

But what about accuracy and trueness? Trueness is how close the mean of the measurement is to a real value. A measurement that is accurate has both high precision and high trueness. These values may be less practical for in-line systems because the "real value" that determines these metrics can be somewhat ambiguous or even variable in the production environment. However, a non-contact measurement system that has very high precision usually can implement a fixed bias in the measurement to bring the results in line with a stated true value.

Imaging specification for metrology

The basic image formation specification related to system precision in machine vision metrology is the spatial resolution of the acquired image. Spatial resolution is the estimated or measured size of an individual pixel (the smallest unit of imaging in a camera) in real-world units. Simply put, with a sensor that contains 1000 pixels in the horizontal direction, and optics that produce a field of view that is 1 inch in width, a single pixel would represent 0.001 inch in the resulting image. By dictating the selected sensor pixel count and/or the size of the imaging field of view, the spatial resolution can be specified to meet the needs of the application. But what are the needs of the application?

As a gauge, the smallest unit of measurement (some exceptions noted later) in a machine vision system is a single pixel. As with any measurement system, to make a repeatable and reliable measurement, one must use a gauge where (as a rule of thumb) the smallest measurement unit is one tenth of the required measurement tolerance band. This can be referred to as the gauge resolution. In the example I just described, the system with a 0.001 inch/pixel spatial/gauge resolution could be estimated to be precise for a measurement of approximately +/- 0.005 inch (a tolerance band of 0.01 inch, or ten times the gauge unit).

Sometimes these calculations might result in a surprisingly high number of pixels being necessary to make non-contact measurement reliable and repeatable with reproducible results for a given application. It is unwise and usually unsuccessful to make compromises in spatial resolution. The only guaranteed configuration is achieved with creative specification of imaging devices along with the use of measurement tools and algorithms appropriate for the application.

The lure of high-resolution imaging

Advances in sensor and camera technologies have resulted in the availability of increasingly higher-resolution imaging for machine vision applications. This allows users to achieve necessary spatial resolutions with larger fields of view. While this approach is compelling in some use cases, the benefit comes with some disadvantages. One that is often overlooked is the challenge of lighting and imaging angles with larger fields of view. Providing uniform illumination or illumination with critical geometry can be difficult over large viewing areas. Optics with wide imaging angles, if used to obtain a larger field of view, also impact image quality with respect to feature extraction for metrology. One option is to use multiple cameras if appropriate.

High-resolution imaging though is a very acceptable option if these and other possible obstacles are overcome in the imaging design. Some applications also might benefit from the use of algorithms that expand the gaging resolution of the system.

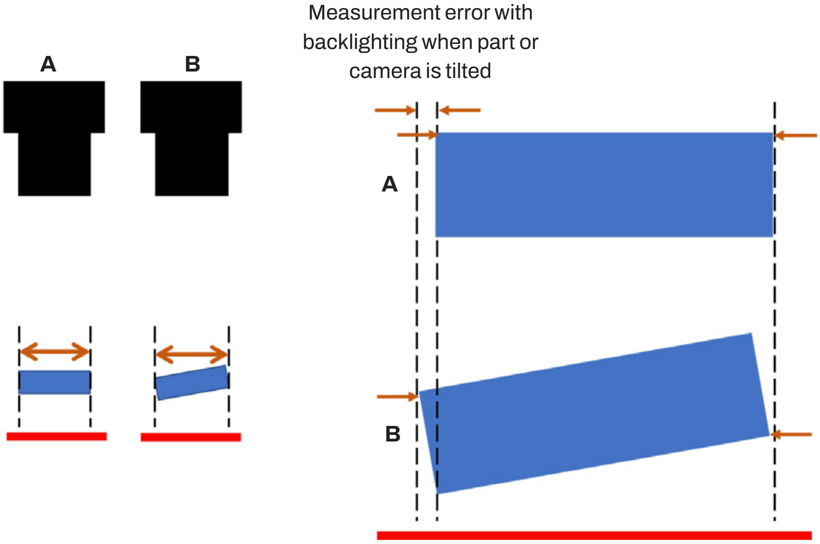


FIGURE 3. Backlighting is a common imaging technique in machine vision and often is associated with applications for measurement. It's important to recognize, however, the potential error introduced due to part presentation or camera orientation with some types of parts. With backlit objects, the image is of a profile or "shadow" of the part. As such, if the object tilts so that it is not perpendicular to the camera, features beyond the surface of the part will become part of the visible profile. The amount of error depends on the part geometry, depth (relative to the camera view), and angle of offset from perpendicular. This contribution to measurement error, if present, is difficult to overcome with imaging techniques, and typically cannot be accounted for in calibration of software. *(Credit: David Dechow)*

Expanding resolution algorithmically

Sometimes improved gaging resolution is possible beyond the spatial resolution of an imaging system by using algorithms that report features to “sub-pixel” repeatability. Some examples would be gradient edge analysis, regressions such as circle or line fitting, and connectivity in some cases. The result is that the smallest unit of measurement, or gauge resolution, can be less than a single pixel, which could impact the necessary pixel count or field of view (FOV) size. In specification, the expected sub-pixel capability should be very conservatively included (if at all) with the understanding that while the sub-pixel capability can be estimated in advance, it can only be confirmed by testing the system with actual parts and images to empirically determine capability.

The impact of optics and illumination

Successful imaging relies on creative use of optics and lighting. A complete discussion of best practices with these components in machine vision is beyond the scope of this discussion, but the impact of these components is still important. As a broad statement, the image must produce the best possible contrast for the extraction of the features to be measured with the lowest possible distortion. Specialty optics like telecentric lenses may be one option. Illumination components must highlight features with consistency in the face of part and presentation variation. In all cases, successful machine vision image formation requires experimentation, both in the lab and on the floor, to ensure the correct component selection.

Achieving and measuring performance

Use all the right analysis tools

No discussion of image analysis can even begin without a reminder of one of the most basic machine vision paradigms: no software tools or applications can “fix” or overcome a bad image. Where necessary, tune or optimize the image sparingly but ensure the quality of the image first and then use analysis tools for exactly their purpose: the extraction and analysis of features in an image.

Most machine vision software libraries and applications have tools or algorithms targeted for measurement or metrology. These often have the capability to use multiple points to produce a result thereby “smoothing” the effect of small physical variations in the features. Some algorithms are not well indicated for measuring though. Generalized “search” tools can find features but must be used carefully as the tool might “fit” the result to a pretrained model without regard for localized variations that could impact the feature position. Note that these tools do not provide measurement information, but only search confidence, and they rarely are effective alone. Binary tools might not be practical in some cases either as consistency of the thresholding can change the geometry of the reported object or “blob.” Meanwhile, 3D imaging systems for metrology implement their own somewhat specialized but effective tools. And, while deep learning models can be trained to segment targeted features, measurement of those features is best performed with direct analysis tools.

Calibration of the camera(s) in a metrology application is not absolutely required but benefits of calibration include:

- the ability to present real-world measurement results
- correction of image perspective for more precise measurements
- the ability to correlate images from multiple cameras

Calibration performed with a specific calibration article usually is an available function of any machine vision system or software.

Machine vision components and systems that acquire 3D data also are effective in some measurement applications. Systems using 3D range from very simple to very complex to integrate, but in some cases, 3D might be the only option. In the application of 3D measurement, it’s important to note that all the aforementioned measurement metrics and considerations still apply. It might be valuable to seek out expert assistance with 3D imaging, depending on your level of experience.

Error: static and dynamic

When testing a system to evaluate performance metrics, static and dynamic data collection help clarify the source of error in a machine vision measurement system. Static testing is performed by acquiring multiple images of the same part while it is in a static fixed position. The static test reveals the

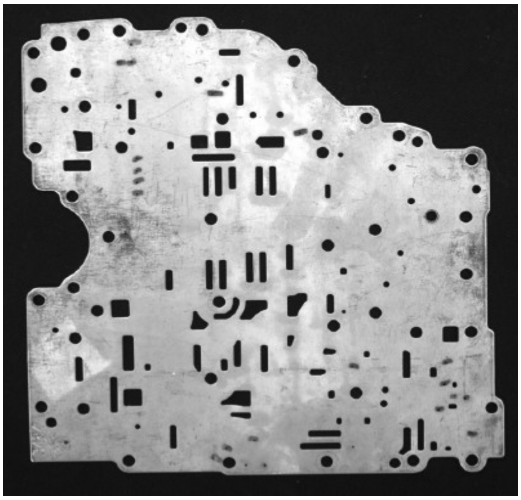


FIGURE 4. In contrast to physical gauging, non-contact metrology using machine vision must rely on surface features as imaged perpendicular to the sensor, as is clearly represented on this automotive transmission plate. *(Credit: David Dechow)*

fundamental measurement capability of the machine vision components and software. With this knowledge as the starting point, additional testing of the measurements with dynamic part presentation over a large sample set reveals the contribution to error produced by the automation in the overall measurement system analysis. Usually, this error is larger than the error obtained in static testing.

Ultimately the dynamic testing results reflect the expected performance of the system. Some error stack-up from the automation and part handling process might be mitigated if better static results can be obtained by adjusting the imaging or optimizing the analysis performance. In many cases, though, the dynamic error may have to be improved in the mechanical part of the system including improvements to part handling and presentation.

Making it work

There are, of course, many other important technical issues and considerations when it comes to implementing successful machine vision based in-line measurement systems. Hopefully this discussion has provided some insight into the specification and implementation process and encourages you to use machine vision in this important industrial automation application. ◎

David Dechow is automation solutions architect for Motion Automation Intelligence (Birmingham, AL); https://ai.motion.com.

What is event-based vision sensing?

Cameras with event-based vision, or neuromorphic sensing, enable fast imaging by focusing only on changes in their field of view.

HEIKO SEITZ

In industrial image processing, cameras with traditional, image-based sensors have been the proven tool for inspection, quality control and process monitoring for decades. However, especially in dynamic scenes and fast production processes, conventional image sensors generate enormous amounts of data at high frame rates and sensor resolutions, while static images are unable to capture valuable information about changes over time. In order to obtain the desired motion information, high-performance image processing systems must process the flood of data, which requires enormous hardware resources.

Now imagine an industrial camera with a temporal resolution of around 10,000 images per second that captures even the fastest movements almost seamlessly and generates only a percentage of the data of a conventional camera. The exact name of this sensor technology is 'event-based vision sensor', or EVS for short.

Neuromorphic sensing technology—inspired by human brain

Once again, cutting-edge technology takes its inspiration from nature. The photoreceptors in human eyes continuously pick up light stimuli and send signals to the brain, which processes them, reacting in particular to changes such as differences in brightness, contrast and movement, while uniform input is often filtered out. This means that we automatically focus on movements instead of constantly re-recognizing every detail of our environment. This allows our brain to process relevant information quickly without being flooded with unnecessary data. To replicate this ability, Prophesee (Paris, France) has collaborated with Sony (Tokyo, Japan) to develop an event-based vision sensor (EVS) with special pixel electronics.

The key aspect of the solution is that no complete 2D images with unnecessary static data are generated. Instead, changes beyond a defined threshold value trigger events. These events are signalled individually and in real time, without being bound to a fixed time grid (cf. frame rate). The minimum time span between two pixel events is an important characteristic of this sensor and is referred to as 'temporal resolution'. It lies in the microsecond range and therefore enables ultra-fast and almost 'gapless' sensing of movements in a time window of 1 millisecond or less, which would correspond to a frame rate of 10,000 images per second of a classic industrial camera. While these image-based cameras always transmit the full amount of data from the entire sensor surface, an event-based sensor often only generates a very small amount of data in the same period of time—a major reason for their impressive speed.

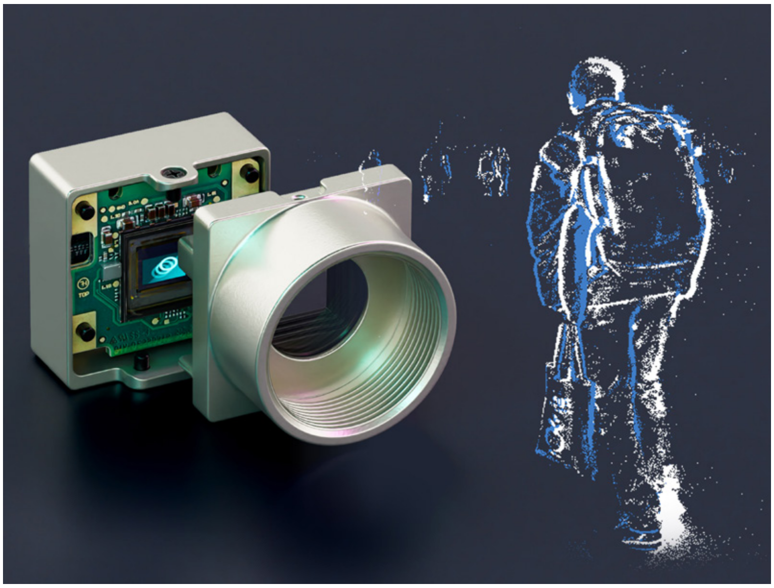


FIGURE 1. The amount of data generated by the event-based sensor is based on activity in the field of view (FOV) and automatically adapts as scene conditions change. *(Credit: IDS Imaging Development Systems)*

Only changes instead of complete images

Engineers of image processing systems no longer have to compromise between high frame rates and large amounts of redundant data to capture fast events. The amount of data generated by the EVS sensor is based on activity in the field of view (FOV) and automatically adapts as scene conditions change. Each pixel only sends information when something changes in its FOV—not according to a predetermined frame rate. This leads to a high-resolution sequence (stream) of events instead of a rigid image series with fixed frame rates. The movement data also contains valuable clues from which a lot more information can be derived. This is information that conventional cameras with a fixed frame rate are unable to capture due to their low and fixed sampling rate, or which is lost in a large amount of redundant data due to the nature of their output.

As contrast changes are less apparent on evenly illuminated surfaces, but primarily on object edges, the visualization of an event stream is comparable to a 2D camera image processed by an edge detector. EVS sensors therefore already support recognizing motion patterns and directions very efficiently. The time between detected events can directly be used to calculate the speed at which an object is moving—and all this without having to process many unnecessary images. This could be advantageous for autonomous vehicles or for applications in robotics where movements require immediate reactions. The extremely high precision at pixel level is also particularly helpful for analyzing fast movements, such as in industry or sports technology. Reducing unnecessary data also means lower memory requirements and therefore more efficient processing.

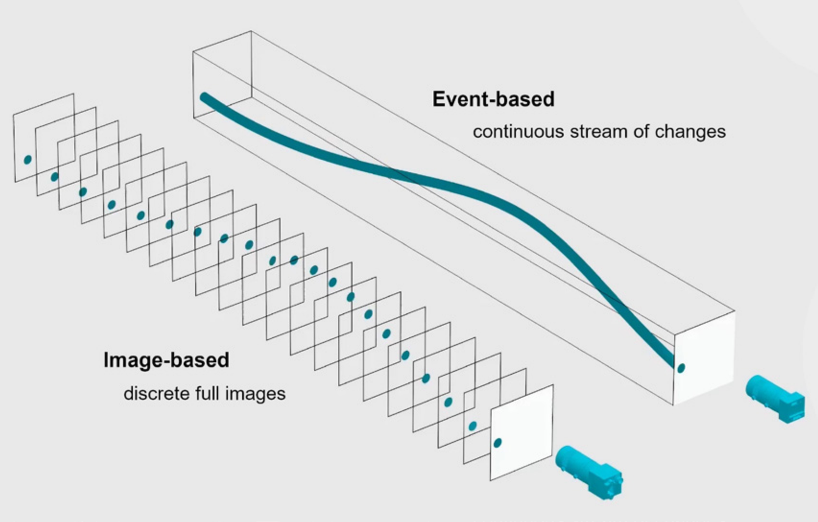


FIGURE 2. While image-based cameras are limited in their sampling rate and therefore only capture real movements discretely and with gaps, event-based sensors generate an almost loss- and latency-free event stream of the changes. *(Credit: IDS Imaging Development Systems)*

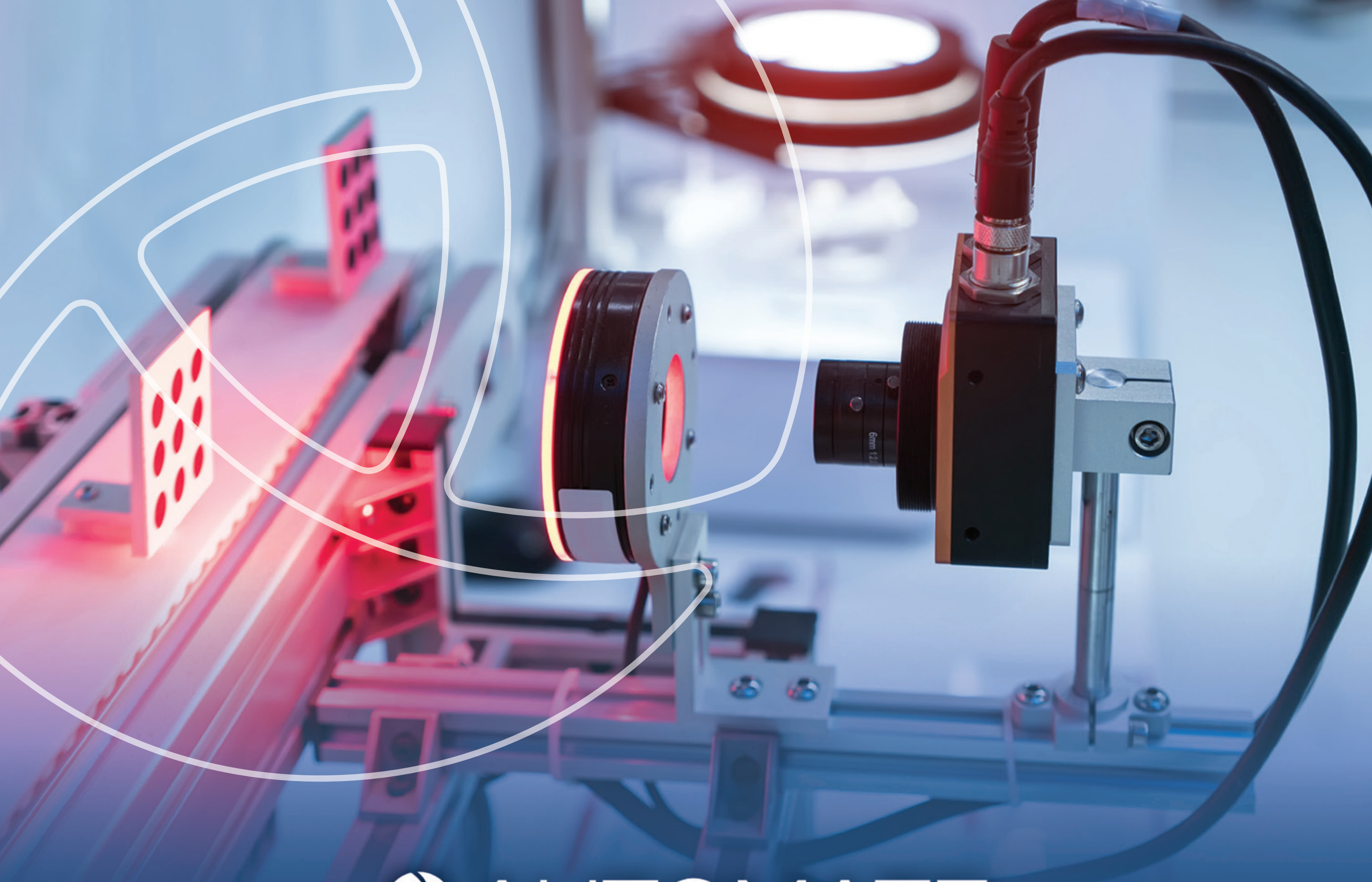
New temporal dimension

Time stamps of the pixel events with microsecond accuracy open up completely new application possibilities. If the location and time of several nodes are correlated over a specified time range in a 3D visualization, a motion path emerges, which in turn leads to a better understanding of how objects move. Speed information can also be easily extracted from this without complex image processing.

Event data offers additional interesting analysis options when creating slow motion recordings. By sorting the captured pixel events into a temporal grid and generating complete sensor images from them, slow-motion videos emerge with a variable ‘exposure time’. The playback speed also remains variable afterwards: from real time (super slow motion with one image per event) to real movement speed (at approx. 1 image per 33 ms) to an overall image that summarizes all captured events in a still image and thus makes the complete movement path visible. This enables detailed temporal motion analyzes without having to perform complex calculations and with minimal data volume and low resource consumption with unprecedented efficiency.

New approach to image processing

But in order to use this new sensor information, developers have to completely rethink their approach and adopt new, alternative software approaches. Of course, the event data can be divided into classic frames to process them like conventional images. However, this method is not exactly optimal, as it does not take advantage of the actual event data, and its high temporal precision for fast movements and efficient processing of sparse data, which also reduces energy consumption. Using appropriate functions, tools and algorithm patterns, users can extract and process movements,



times and structures quickly and efficiently from the event data. However, these cannot be found in any of the known generic standard vision frameworks today.

However, Prophesee and Sony, the manufacturers of the new sensor technology, have already established a corresponding processing method and made all the helpful functions available in a software development kit, the Metavision SDK, together with detailed documentation and numerous samples.

Applications in the quality sector

The capabilities of neuromorphic sensors can also play an important role in quality assurance and improvement. This is particularly true in applications where accuracy, speed and efficiency are required for error detection. The added value of being able to detect the smallest object and material changes in pixel size and in real time is evident, for example, when monitoring machines and processes. Thanks to the high temporal resolution, which extends into low microsecond range, even high-frequency movements such as vibrations or acoustic signals can be visualized. An analysis reveals unusual patterns (e.g. due to wear, malfunctions) at an early stage, which can lead to damage or production downtime.

> Event-based sensors do not capture complete images, but only pixel changes over time.

As they only notice movements or contrasts, neuromorphic sensors are much less affected by lighting changes, making them far superior to conventional image processing systems in highly varying lighting conditions (e.g. reflections, shadows). When it comes to fast defect detection, process monitoring or inspections in difficult conditions, quality assurance processes can only benefit from the capabilities of neuromorphic sensors.

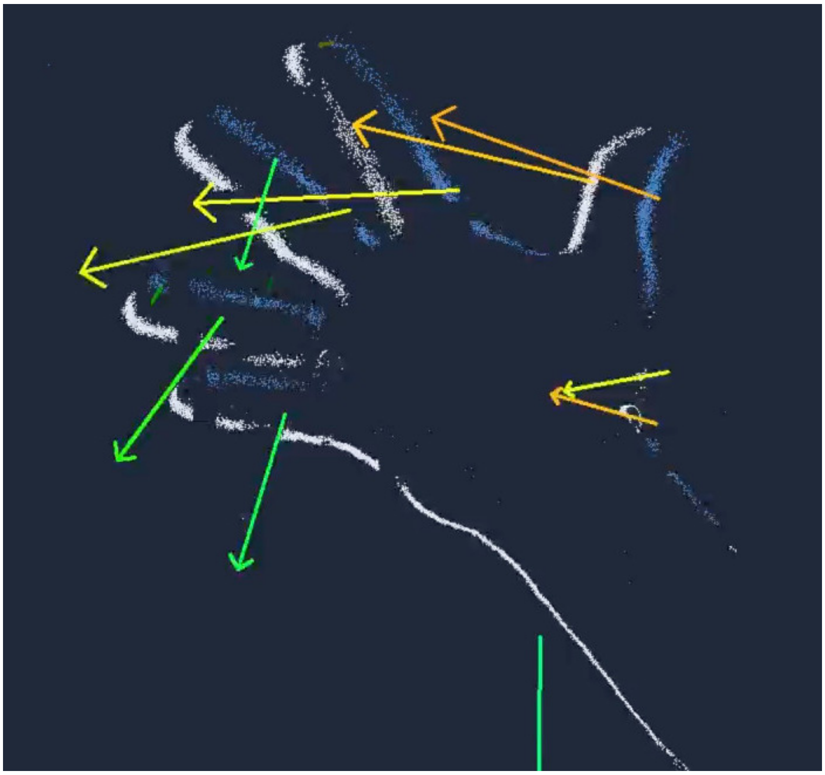


FIGURE 3. Event-based data already provides the raw information needed to analyze the location, direction and speed of pixels and objects. (This is visualized in the image with motion vectors.) *(Credit: IDS Imaging Development Systems}*

The new must-have camera technology?

Event-based sensors do not capture complete images, but only pixel changes over time. However, they can dynamically compose different types of images, providing applications with significantly more motion information than cameras with conventional image sensors. Therefore, the technologies do not compete with each other. Event-based sensors are definitely not a replacement for traditional image-based cameras or even AI-based image processing, but rather a complementary technology that opens up new possibilities when it comes to motion detection. In various applications, a single sensor type or type of data is not sufficient. A combination of different technologies is often necessary to optimize an application. Event-based cameras are therefore interesting and profitable components for fast motion analysis, robotics, autonomous systems and industrial quality assurance, and their full potential is far from being exhausted. ◎

Heiko Seitz is an engineer at IDS Imaging Development Systems, Obersulm, Germany; www.ids-imaging.us.

Rotor Technologies developing giant ag drone

A remotely piloted helicopter is outfitted with all the equipment it needs to effectively function, including cameras, sensors, LiDAR, GPS, and an onboard computer system.

JIM TATUM

Rotor Technologies (Nashua, NH, USA) has developed a drone for agricultural applications such as crop spraying. The company, founded in 2021 by Hector Xu, a former MIT scientist who led the development and successful flight of the first ion-propelled airplane, specializes in large drone technology.

This drone, known as Sprayhawk, is in the final stages of development before going on the market. Indeed, Sprayhawk has flown successfully several times, including a demonstration flight at the National Agricultural Aviation Association's Ag Aviation Expo in Fort Worth, Texas, in November 2024.

"We were flying, we were spraying; it works," says Nicholas Coates, vice president of partnerships with Rotor. "We are now fine tuning all these systems."

Sprayhawk is not a fully autonomous vehicle but integrates

FIGURE 1. Rendering of a Sprayhawk drone helicopter in action. *(Photo Credits: Rotor Technologies)*

FIGURE 2. A Sprayhawk can land and take off from small platforms, such as the top of a truck used to transport it to the area where it will perform its mission.

autonomy and autopilot systems and is flown remotely by a pilot on the ground. It is built on the airframe of a Robinson R44 four-passenger helicopter. Instead of seats, however, Sprayhawk is outfitted with the equipment it needs to function. This includes four 2.9 to 5 MPixel industrial cameras from Allied Vision (Exton, PA, USA) equipped with Sony (Tokyo, Japan) Pregius global shutter sensors, LiDAR, and GPS. It also has an onboard computer system that utilizes Nvidia (Santa Clara, CA, USA) GPUs that allows the pilot to control the craft and all its functions, from flying and navigation to spraying crops.

Vision components, multisource data stream helps pilot fly drone

Underpinning Sprayhawk's functionality are numerous elements working in synchronization to provide the pilot with the most detailed and useful information possible, in as close to real time as possible. The drone has four cameras, three in front facing left, right and center and another mounted at the tail facing the rear. Simultaneously, the LiDAR and GPS gather and transmit topographical information of the area in which the drone is flying.

> Sprayhawk is not a fully autonomous vehicle but integrates autonomy and autopilot systems and is flown remotely by a pilot on the ground.

"Somebody might call that a 'digital twin,' where we're loading 3D maps of the environment that we're flying in, and we're using that to create sort of a backdrop for our pilot," explains Alex Lesman, Rotor's Director of Software Development. "Then, we're taking the images and we've calibrated our cameras to the aircraft. And so we're able to overlay the video stream onto this digital environment, to present the pilot with a cohesive view of the world. And it also gives us some kind of fallback."

"You can imagine if something happens to a camera physically or if our bandwidth is severely degraded or something else is obstructing visibility, you have this digital twin backdrop."

While the digital twin currently does not show dynamic obstacles in the area, it does give the pilot a general sense of the area, he says.

Communicating useful flight data to a remote pilot

Data is collected via cameras, LiDAR, and GPS and transmitted to a small commodity computer equipped with Nvidia GPUs that is installed aboard the aircraft. The information is then streamed to the pilot over multiple mediums, Lesman says.

"Broadly speaking, we use the Nvidia GPUs and some other libraries, and code we've written in as low latency a way as possible, process the video streams, and then stream them over to the pilot over mixed links—those links could be LTE, satellite, radio, or whatever we have available. We split up the video stream, send it across those multiple links, reassemble it on the far side, do some error correction, put it back together, and play it to the pilot—and try to do that while introducing as little latency as possible."

They use multiple streams so as not to be dependent on one medium; if a satellite link goes down, for example, the pilot can still receive the information over another link, such as radio.

"We can support multiple communications links," Lesman says. "We can support communications by running a communications relay. Our focus has been delivering reliable low latency video to the pilot. And so that means no single wireless link is perfectly reliable but if you put enough of them together it's reliable enough."

Challenges and next steps for the drone

The team has conducted flights from different distances, from areas within sight line and/or radio range of the drone and from remote locations several miles away from where the drone is flying. The imaging/communications systems have worked as intended, Lesman and Coates say.

There were some challenges along the way, they say. When they first started building the system, they used GigE cameras. However, this added latency to the video stream and was expensive at higher levels. USB3 is significantly more cost effective and works efficiently for their purposes, but they are working on further ruggedization, they say.

And, while their basic system works as intended, they are fine-tuning and improving the communication system for optimal operational ability for the pilot.

"I think the idea over time would be to do more and more fusion, to try to fuse our virtual map of the world with our real time data," Lesman says.

Another goal is to eventually increase the autonomy of the aircraft by automating some routine functions to free up the pilot for other tasks that require attention. For example, the aircraft must constantly maintain precise altitude and speed while it's spraying a field. To be able to automate that aspect of the flight would be beneficial for the pilot, who can then handle additional tasks associated with the mission.

Also, the aircraft is usually transported to the work site on a truck, from and upon which it takes off and lands. If a pilot is performing crop spraying tasks, then that pilot will be taking off and landing very frequently. This is not mundane, but it is routine and can be ultimately very tiring to the pilot.

"You go out, you spray, and you come back to reload the chemicals," Coates says. "You're landing on that truck and you're taking off from that truck, over and over and over again. It's incredible to see the pilots do it—they land on a truck that's smaller than the helicopter and they come in hot while they're doing it."

Coates and Lesman do note that the autonomy would be related to pilot and flight safety before anything else.

"There are ways we can have kind of—maybe you would call it collaborative autonomy—where the aircraft would assist, rather than take over," Coates says. "You could think about it as lane keeping in a modern car—it's not driving for you, but it helps you stay on course and safely in your lane. I think we'll figure out where the sweet spot is between assistive autonomy and full autonomy."◎

> Data is collected via cameras, LiDAR, and GPS and transmitted to a small commodity computer equipped with Nvidia GPUs that is installed aboard the aircraft.

Using MWIR hyperspectral imaging to battle black plastic pollution

Currently, the recycling rate for black plastic is very low because traditional sorting technologies used in recycling facilities to sort plastics cannot "see" the black color.

MINNA TÖRMÄLÄ

Plastics are an essential part of everyday life, with worldwide production surpassing 380 million metric tons each year. Among the different types of plastics, black plastic represents a significant portion of this output due to its functionality and visual appeal, making it popular in consumer products. Black plastics are widely used in high-demand industries like automotive manufacturing for their durability and wear resistance. In electronics, they protect delicate components, such as casings and parts, and preserve freshness by blocking light and oxygen in food packaging.

Studies suggest that black plastic accounts for approximately 15% of the plastic waste stream. However, the current recycling rate for black plastic is low. Why? The traditional plastic-sorting technologies used in recycling facilities cannot distinguish the black color. Consequently, black plastics are often misidentified, leading to low recycling rates, which poses a growing environmental problem.

Stricter regulations are being implemented across various regions, requiring manufacturers to include a specific percentage of recycled plastics in their new products. For instance, the European Union's End-of-Life Vehicle (ELV) Directive mandates that when a vehicle is no longer in use, at least 85% of its weight should be reused or recycled. This means that materials can be reprocessed into new products or parts can be reused. Additionally, at least 95% of the vehicle must be reused or recovered, which includes processes like generating energy from materials that cannot be recycled. Additionally, the EU's Packaging and Packaging Waste Directive requires that 50% of plastic packaging be recycled by 2025 and 55% by 2030. Effective methods for sorting black plastics are needed to meet the targets.

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FIGURE 1. MWIR hyperspectral imaging overcomes the previously difficult challenge of sorting black plastics, enabling effective recycling.

How the plastic recycling process works

Plastic recycling is a multi-step process. It typically begins with collecting and separating plastics from general waste streams. Once separated, the plastics are sent through shredding machines that break them into smaller flakes, making them easier to process. These flakes are then washed to remove dirt, labels, and other contaminants. After that, optical sorting systems sort plastic flakes by polymer type to ensure that each batch is composed of a uniform plastic resin, which is crucial for producing high-quality recycled materials.

Optical sorters typically rely on near-infrared (NIR) imaging spectroscopy to identify plastic types based on their unique spectral signatures. For most plastics, this system works seamlessly. However, black plastics, which are typically colored with carbon black pigments, absorb almost all light in the visible and infrared spectrum instead of reflecting it, rendering them effectively invisible to NIR sensors. As a result, black plastic flakes are often misclassified or discarded as waste, reducing recycling rates, and sending valuable material to landfills or incinerators.

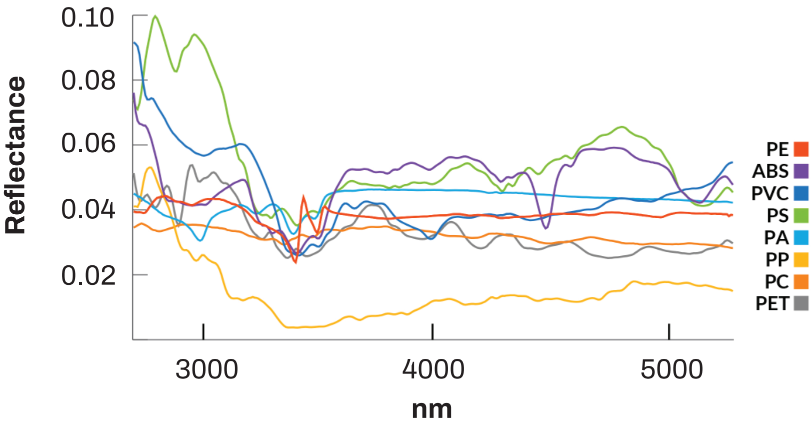

FIGURE 3. MWIR hyperspectral imaging can identify the unique spectral characteristics of different plastics, regardless of their color. *(Credit: Specim)*

Alternatively, gravity sorting—where materials are separated based on density in water or other fluids—has been used as a fallback option. While it can help separate black plastics, the process is resource-intensive, requiring significant amounts of water and chemicals. Additionally, gravity sorting is less precise, resulting in lower purity levels in the recycled plastics.

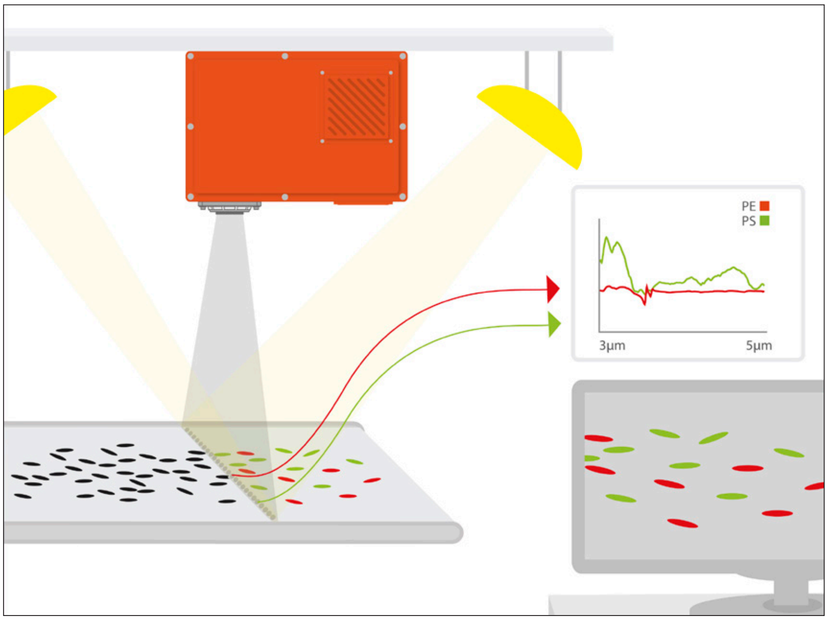

FIGURE 2. Hyperspectral cameras specifically developed for industrial applications and operating in the MWIR range can detect plastic and rubber at high speeds. *(Credit: Specim)*

Plastics that are not pure are often downcycled or converted into alternative products like oil, while higher-purity recycled plastics are more suitable for creating new, high-quality materials.

Mid-wave infrared (MWIR) hyperspectral imaging (HSI) enables precise identification and sorting of black plastics, providing a solution to address the limitations of the traditional NIR and gravity-based systems.

Advantages of and challenges of hyperspectral imaging in sorting plastic

Hyperspectral imaging is an advanced technology that merges spectroscopy with imaging capabilities. Hyperspectral cameras capture and analyze the unique spectral signatures of different materials, allowing for accurate identification and separation based on their chemical composition rather than visual characteristics such as size, shape, or color.

HSI enables precise differentiation of materials that may appear similar to the naked eye, such as different types of plastic. Additionally, HSI supports real-time processing, allowing for rapid, accurate, and automated sorting. This makes it a powerful and widely adopted solution for industrial waste management, particularly in sorting plastics.

Hyperspectral cameras scan materials on conveyor belts at high speed, analyze their spectral data, and classify them using advanced algorithms. Sorting systems then automatically separate identified plastics through mechanisms such as air nozzles.

Hyperspectral imaging is an advanced technology that merges spectroscopy with imaging capabilities.

Overcoming black plastic sorting with MWIR hyperspectral imaging

Mid-wave infrared (MWIR) hyperspectral imaging is proving to be a highly effective solution for the challenge of sorting black plastics, a task that NIR imaging has long struggled with. While NIR hyperspectral imaging operates in the spectral range of approximately 900 to 2500 nanometers (nm), MWIR HSI expands the scope by capturing highly detailed spectral data across the 3 to 5 micrometer (μm) range.

In the MWIR range, different plastic types exhibit distinct spectral features due to their molecular composition (See Figure 3). Consequently, when using hyperspectral imaging in the MWIR range, it's possible to differentiate between different types of plastic, regardless of their color, including the most challenging black plastic.

Real-world applications and industry benefits

Industries relying heavily on black plastic polymers, such as automotive, electronics, and packaging, benefit significantly from this advanced technology. For example, black plastic is widely used in dashboards, bumpers, and trim components in the automotive sector. By effectively sorting these materials, MWIR HSI technology can help automotive manufacturers achieve their recycling goals and reduce the environmental impact of vehicle production.

In the electronics industry, black plastic casings are common in everything from smartphones to home appliances. Using MWIR hyperspectral imaging, recyclers can effectively sort black plastic from discarded electronics, assisting manufacturers in meeting increasingly strict e-waste regulations.

The food packaging industry also stands to benefit. Black plastic trays are commonly used for ready-to-eat meals and other food products. By enabling more effective sorting of these trays, MWIR HSI helps reduce the amount of food packaging waste that ends up in landfills.

Environmental and economic benefits of recycling black plastics

The ability to sort and recycle black plastic brings significant environmental and economic benefits. Recycling prevents black plastics from being sent to landfills or incinerators, reducing environmental pollution and conserving valuable

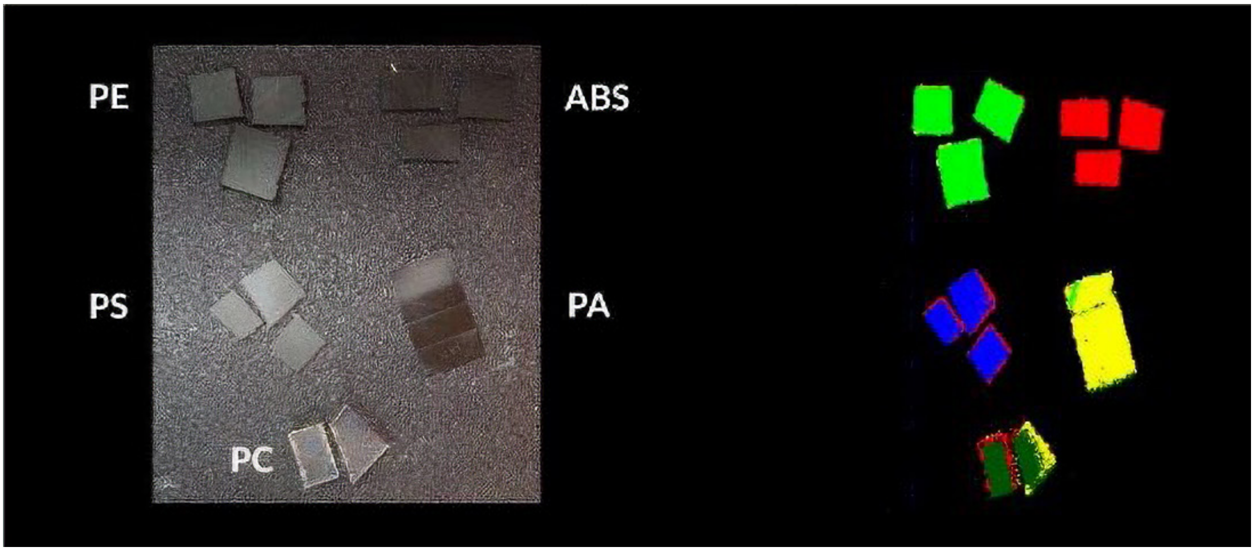

FIGURE 4. Example of the image-sorting process for black plastic, rubber and non-black plastic and rubber using MWIR hyperspectral imaging. *(Credit: Specim)*

resources. It also helps to close the loop on plastic waste, supporting the transition to a circular economy where materials are reused rather than discarded.

Economically, recycling black plastic offers cost savings for manufacturers. The ability to reuse black plastic in new products reduces the need for virgin materials, lowering production costs. Additionally, companies can avoid penalties for failing to comply with recycling regulations, making MWIR HSI a financially viable option for those aiming to remain competitive in an increasingly environmentally conscious market.

> The introduction of MWIR hyperspectral imaging technology represents a significant advancement in recycling black plastic.

Alignment with global sustainability goals

Integrating MWIR HSI into recycling processes benefits industries and aligns with broader global sustainability goals. The United Nations' Sustainable Development Goals (SDGs) emphasize reducing waste and increasing resource efficiency. MWIR HSI helps industries comply with these goals and regulations by enabling the efficient recycling of black plastics.

As more countries implement extended producer responsibility (EPR) regulations, which require manufacturers to manage their products' entire lifecycle, including disposal and recycling, MWIR HSI technology will become an essential tool for meeting regulatory requirements. Adopting this technology can provide companies with a competitive advantage in regions such as Europe, where these regulations are already established.

A new era for black plastic recycling using MWIR hyperspectral imaging

The introduction of MWIR hyperspectral imaging technology represents a significant advancement in recycling black plastic. This innovative technology overcomes the limitations of traditional NIR systems and non-optical sorting methods. It enables efficient sorting of black plastic, contributing to reduced landfill waste, supporting circular economy initiatives, and aligning with global sustainability goals. ◎

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