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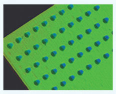
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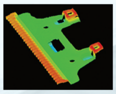
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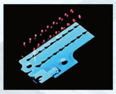
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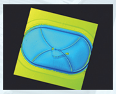
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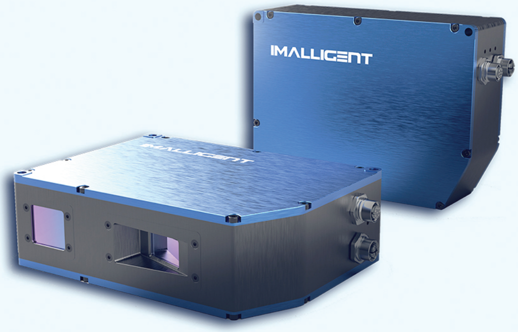

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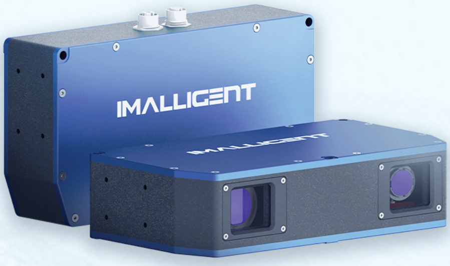

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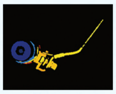
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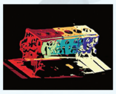
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Inspection dominates machine vision applications

THERE IS no doubt that machine vision is expanding beyond its roots in industrial inspection. It's a key enabler of autonomous driving and navigation, automated assembly, bin picking, and more.

Expansion into these newer types of applications bodes well for a robust industrial sector with plenty of opportunities for talented engineers. Indeed, Interact Analysis (Irthlingborough, UK), a research firm specializing in automation, expects machine vision revenues to grow by a CAGR of 6.4% between 2022 and 2028, increasing from $6.5 billion in 2022 to $9.3 billion in 2028.

Some of that growth will come from newer application areas; however, inspection will remain the prevailing source of use cases. Inspection accounted for more than 40% of revenues to machine vision vendors in 2022, and will represent nearly 42%, or $3.9 billion, in 2028, the firm predicts.

Why? Part of the reason is that engineers are applying machine vision to a wider variety of inspection tasks using AI and cameras.

We report on several inspection projects in this publication, and we will cover many more in future months—and years.

Linda Wilson
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Fundamentals of imaging lenses

Choosing the right lens is an important step in developing a machine vision system.

CHRISTOPHER RAZZE

Machine vision, or imaging, is a fast-growing field. Engineers in numerous disciplines—such as factory automation, autonomous systems, life sciences, aerospace, and logistics—are creating vision systems to help fulfill automation objectives.

Choosing the correct lens is an important step in system development. To help navigate this process, this article describes how to select an appropriate lens.

Defining requirements for a machine vision system

The first step in choosing a lens for a machine vision system is to define the requirements for your application. The two parameters that drive selection are the working distance and field of view. The specific definitions for these parameters are:

- Working distance (WD)—The distance from the front or first surface of the lens to the object under inspection.
- Field of view (FOV)— The viewable area of the object under inspection. This is the portion of the object that fills the camera's sensor. This area is commonly reduced to horizontal (HFOV) or vertical (VFOV) dimension for ease of calculation.


Photos/Edmund Optics

When specifying an entire FOV (Horizontal by vertical dimension or HxV), keep in mind that the typical machine vision sensor will have a 4:3 aspect ratio (ratio of width to height). That is why you should define the critical parameter of the FOV (either horizontal or vertical) and use that for the calculations described in this article.

After defining the WD and FOV, the next parameters to specify are the sensor size and required resolution.

Sensor size

The size of a camera sensor's active area is typically specified as a fractional inch or decimal such as 1/1.1 in, 2/3 in or 1.2 in.

It is worth noting that this nomenclature is in reference to the sensor equivalent of an analog tube; while this is no longer relevant, it is still the given specification for the vast majority of sensor manufacturers. The important parts of a sensor's active area are horizontal and vertical measurements (for determining FOV) and diagonal dimension of the sensor (for determining compatible lenses).

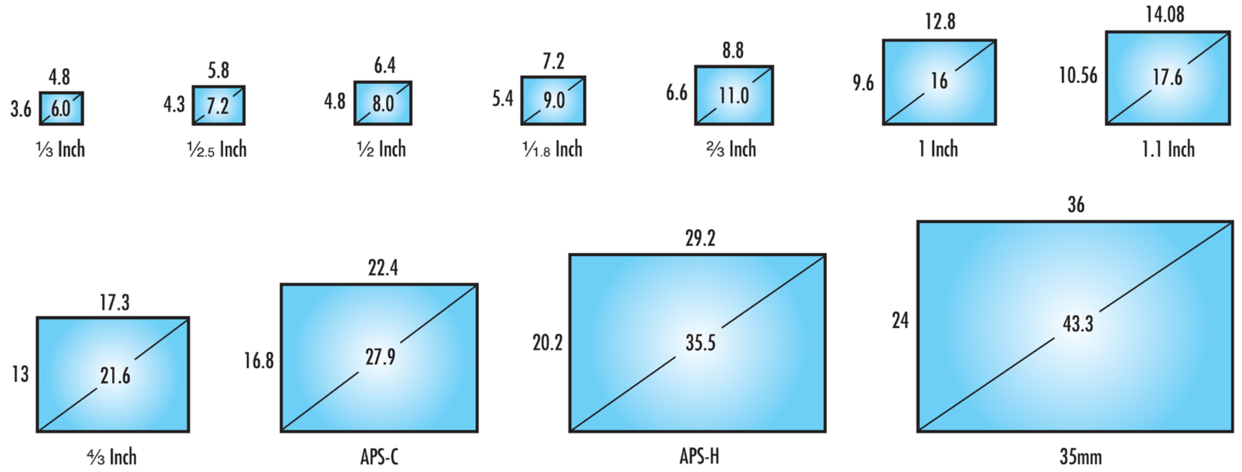

FIGURE 1.: Typical machine vision camera sensor formats. *(Courtesy of Edmund Optics)*

Resolution

The resolution is the minimum feature size of the object that can be distinguished by the imaging system. Resolution is more accurately described as spatial frequency, measured in line pairs per millimeter (LP/mm).

To determine the appropriate resolution, define the size of the minimum feature that is required to be resolved for the application and then define a pixel count for that feature, which will depend on the goal of your application. While there is no concrete definition for how to select pixels per feature and the only true way to know if your resolution is adequate would be to test it, you can find some general benchmarks below.

	Pixels per Feature
3	Detection
4	Orientation
10	Recognition
16	Identification

This can then be used to determine the minimum pixel size and convert it to LP/mm.

$$\frac{LP}{mm} = \frac{1}{2\ x\ Pixel\ Size}\ x\ 10000$$

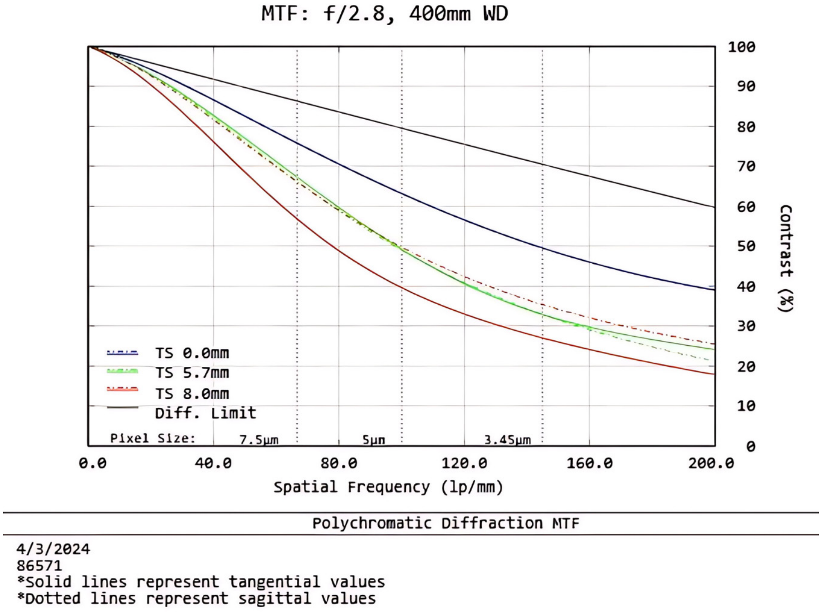

FIGURE 2. Example MTF curve for a lens, showing the contrast levels that can be achieved at different spatial frequencies, or feature sizes on an object being imaged. *(Courtesy of Edmund Optics)*

While this information is not required to determine the size of the lens, you will use it to determine the quality of the lens necessary for a particular application.

Additional parameters that should be considered are depth of field (DOF) and environmental requirements, such as IP rating, vibration tolerance, or athermalization. The Depth of Field is the maximum object depth that can be maintained entirely in acceptable focus, which is typically expressed as +/- X.X mm.

How lens parameters relate to those requirements

Now that you have all the required specifications for a lens, calculate the required focal length (FL). This can be approximated using the following expression:

FL= (H x WD) / HFOV

Where H is the horizontal measurement of the sensor, WD is the working distance and HFOV is the horizontal measurement of the field of view. If using the vertical dimension as the critical measurement, simply replace the horizontal measurements with the vertical measurements.

This will output the approximate FL required for your HFOV and WD. Keep in mind that FLs are relatively standardized across different manufacturers. For instance, if your approximate FL is 19.7 mm, you would be unlikely to find a direct match, so this number will either need to be increased or decreased depending on the flexibility of the system.

As illustrated in the expression above, FL and FOV are inversely proportional to one another. For example, if you assume the HFOV used in the equation above is the minimum requirement for your vision system, you want to select a FL one step below the approximate value to increase your FOV—in this case moving from 19.7 mm to a more standard 16 mm lens.

f/#	Diffraction Limited Resolution	Depth of Field	Light Throughput	Numerical Aperture
∧	v	∧	v	v
v	∧	v	∧	∧

From here, you can select a lens with the required FL to cover the sensor that you will use in the application. Be mindful of how large of a sensor the lens covers. If you select one too large, you may spend more money than necessary. But if you select one that is too small, it will not cover the sensor and vignette (defined below).

- Vignette—When light rays do not make it through the entire lens system to the sensor because they are blocked by the edges of individual lens elements or mechanical stops.

From here, you can analyze the specification sheet to determine whether the lens will handle the parameters defined in the previous step. If you cannot find the relevant information for your WD/FOV requirements in the generated specification, reach out to the manufacturer to get those curves, or if you have access to optics software, request the prescription.

Key lens parameters

Now that you've selected a lens, read its performance curves to insure it meets the needs of the application.

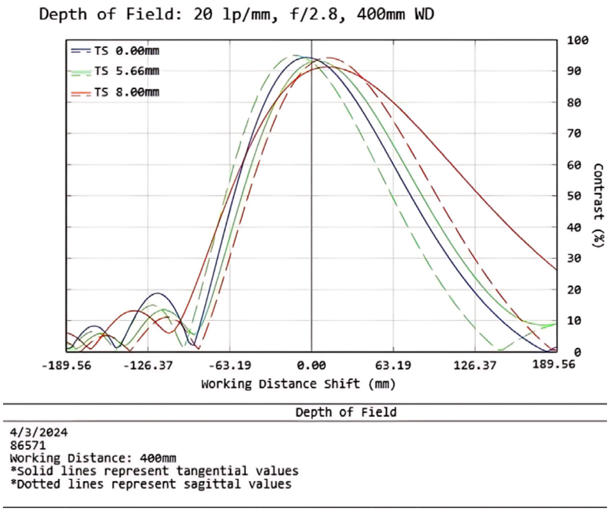

FIGURE 3. Depth of field curve for a lens, showing how shifting the working distance of the lens affects the focus of the image, described by the percent contrast. *(Courtesy of Edmund Optics)*

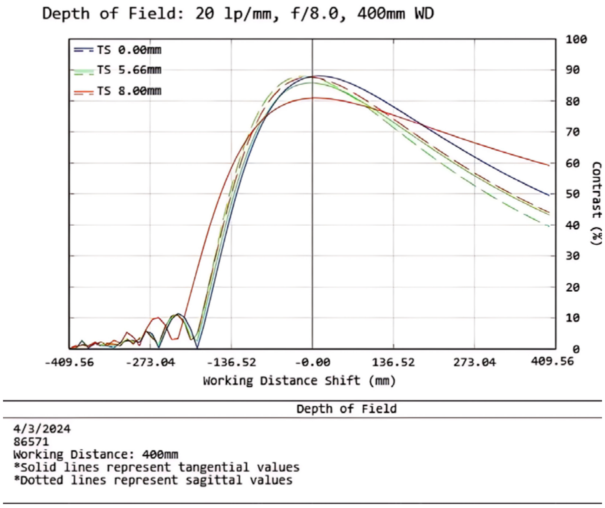

FIGURE 4. Depth of field curve for the same lens used in Figures 2 and 3, but running at *f*/8.0 instead of *f*/2.8. *(Courtesy of Edmund Optics)*

The first and most important curve is the modulation transfer function curve (MTF), which is defined below.

Modulation transfer function. Modulation transfer function (MTF) is an information-dense metric that reflects how a lens reproduces contrast as a function of spatial frequency (resolution).

This figure provides the percentage contrast vs. the spatial frequency at a given point on the sensor chip. The general rule of thumb for the minimum required contrast for machine vision purposes is 20%. This leads us to generally define lens performance as the spatial frequency at 20% contrast. From this graph, we can

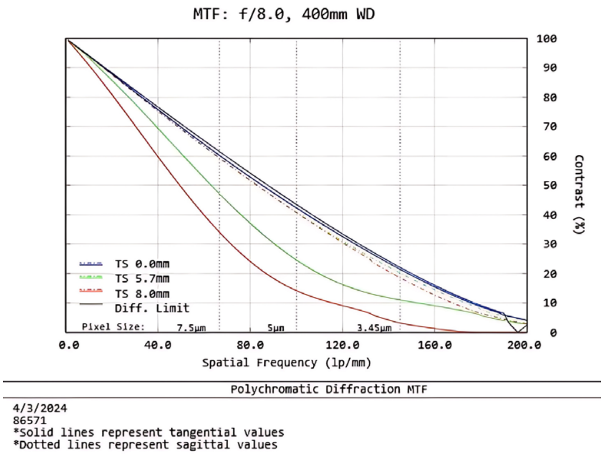

FIGURE 5. MTF curve for the same lens used in Figures 2 and 3, but running at *f*/8.0 instead of *f*/2.8. *(Courtesy of Edmund Optics)*

extrapolate that our worst field (in this case the 8 mm corner of our chip) has approximately 175 lp/mm at 20% contrast in image space, meaning on our image sensor. To convert this to object space, we would simply multiply this by the magnification of our lens.

Depth of field. Depending on the needs of your application, you may also be interested in the DOF of the lens at your given WD and *f*/#. Below is an example curve for a lenses DOF:

Much like the MTF curve, our *y* axis is contrast. However, the *x* axis of a DOF curve is instead the working distance shift. The 0.0 point on this curve is the point of best focus, moving +/- along the *x* axis is the depth at which your image will remain in focus. This is defined at a specific resolution requirement—in this example 20 lp/mm—and typically defined at 20% contrast.

> The first step in choosing a lens for a machine vision system is to define the requirements for your application.

If the given DOF is not sufficient, it can be increased by increasing the lens' *f*/# (pronounced "F-number"). The definition for this parameter can be found below:

- *f*/#—Setting on a lens that controls overall light throughput, depth of field (DOF), and the ability to produce contrast at a given resolution.

The effects of altering the *f*/# is summarized in the table on p. 46, where the top row shows if that parameter increases / improves (Λ) or gets worse / decreases (V) as *f*/# either increases (Λ) or decreases (V).

Lenses with lower *f*/#s are considered fast and allow more light to pass through the system, while lenses of higher *f*/#s are considered slow and feature reduced light throughput. Here is an example of the same lens used previously running at *f*/8.0 instead of *f*/2.8:

> Choosing a lens can be a daunting task if you do not have somewhere to start.

As you can see, the simulated working distance shift is significantly larger when compared to the previous figure (2–3X more DOF). However, the resolution is slightly lower.

As the *f*/# is progressively increased, you will see the same thing occur. Finding the appropriate balance between resolution and DOF should be determined on an application-by-application basis.

Common pitfalls

One of the most common pitfalls in designing a vision system occurs when you do not save enough space for the lens and camera. Typically, most lenses have a minimum working distance of 100 mm for moderate focal lengths (8–25 mm) and up to 750–1000 mm for longer focal lengths. The general rule of thumb is to save a 4:1 ratio of WD:FOV. This is not a catch-all solution but using it as a benchmark can help avoid headaches down the road. A good machine vision lens can be expensive but not as expensive as a fully custom solution.

Conclusion

Choosing a lens can be a daunting task if you do not have somewhere to start. This can be a nuanced decision and sometimes requires trial and error in a lab environment. If you are ever faced with trouble in making the correct lens solution, reach out to your imaging lens supplier for guidance and recommendations.

Christopher Razze is a machine vision sales engineer at Edmund Optics (Barrington, NJ, USA).

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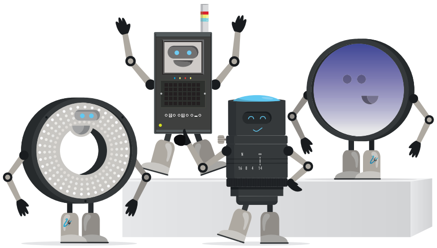

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Norfolk Southern's machine vision system inspects moving rail cars

The railroad company worked with Georgia Tech Research Institute to develop the vision system by combining AI and high-resolution, high-speed cameras.

LINDA WILSON

To spot defects on moving trains, Norfolk Southern Railway (Atlanta, GA, USA) is building train inspection portals on tracks in the United States.

The Georgia Tech Research Institute (Atlanta, GA, USA) is collaborating with the railroad on the inspection project.

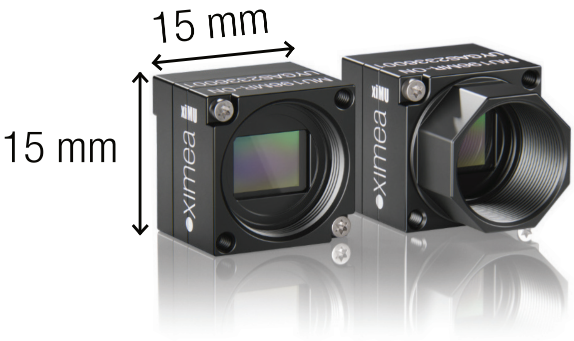
The portals combine high-resolution cameras, stadium lights, and AI algorithms to capture and then analyze images of trains moving at up to 60 mph. All components are installed trackside inside tunnel-type steel structures.

Two inspection portals were deployed in 2023 on adjacent tracks in Leetonia, Ohio—not far from where a train derailed in February 2023, spilling hazardous chemicals. Trains pass through the new inspection portals about once per hour.

Norfolk Southern plans to deploy a dozen automated portals by the end of 2024 to augment, not replace, human inspectors.

"Human inspections consist of experts walking the length of the

FIGURE 1. Train inspection portals combine high-resolution cameras, stadium lights and AI algorithms to capture and then analyze images of trains moving at up to 60 mph. *(Courtesy of Norfolk Southern)*


15 mm
15 mm

train at various points along the rail network, monitoring for defects. As you can imagine, this process can be time-consuming and subject to uncontrollable conditions—like weather," says Mabby Amouie, chief data scientist at Norfolk Southern.

In addition to weather resistance, the automated system provides the railway with information about potential problems that may be difficult for humans to uncover. "One advantage of the automated inspection portal is that the trains can be inspected in motion, under forces that can expose faults that are not obvious when the train is sitting still," says Colin Usher, senior research scientist, Georgia Tech Research Institute (GTRI).

There are a variety of defects that Norfolk Southern wants to detect. "As big as trains are, surprisingly, it comes down to relatively small bolts and cotter pins located in various locations to keep everything working properly. In addition, safety equipment, such as ladders, is going to be inspected for damage. Finally, items such as open hatches or open doors are also going to be inspected," explains Usher.

Norfolk Southern plans to deploy a dozen automated portals by the end of 2024 so trains can be inspected in motion, under forces that can expose faults not obvious when the train is sitting still.

Machine vision and AI

Engineers at GTRI designed the hardware setup for the new inspection portals, and Norfolk Southern's employees created the AI-enabled inspection algorithms.

The system includes 38 cameras, which are installed strategically at various angles, including some at track level pointing up, to capture specific points on each rail car.

The cameras include both area and line scan models, and the combination produces approximately 1,000 images per rail car, producing a 360° view of each rail car.

The cameras and lenses are installed inside protective enclosures and mounted on arms that are attached to the sides of the tunnel structure.

Stadium lights are mounted inside the tunnel enclosure along the sides and top. "To capture clear images of trains traveling at up to 60

FIGURE 2. Cameras are installed strategically at various angles, including some at track level pointing up. *(Courtesy of Norfolk Southern)*

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vision.vieworks.com | sales@vieworks.com mph requires extremely fast shutter speeds, which dictates that we provide lots of light to illuminate the trains," Usher says.

Sensors that detect the presence of an oncoming train and its speed, trigger the entire process. Based on the speed, software developed at GTRI calculates when each camera should take images and lights should turn on. Cameras are synched to a microsecond. "Only images of critical components are taken and the other areas of the train that are inconsequential to identifying defects are not captured. That optimizes the image capture and saves space in the computer system," Usher says.

AI-enabled algorithms analyze image data on-site to determine if defects are present.

To further save space, image data is compressed.

AI-enabled algorithms analyze image data on-site to determine if defects are present. Within minutes, results are then transmitted to Norfolk Southern's network operations center, where subject-matter experts review the data. Critical defects are flagged by the AI software for an immediate response, such as scheduling the train for service at the next train yard or stopping immediately if the problem is severe.

Norfolk Southern's inspection algorithms "have very high detection rates, while also having very low false alarms," adds Amouie.

Machine vision design challenges

Usher says the team overcame numerous obstacles in the design of the system.

"We encountered challenges with data throughput, processing times, and storage. Each train results in an average of 300 gigabytes of data and this is after significant image compression," Usher says.

To solve the problem, Usher continues, "we use enterprise systems similar to those in data centers to manage the data and processing requirements." Multiple enterprise-level computers are located inside the power supply cabinet at each inspection portal.

Another challenge was protecting the components—such as cameras, lenses, and lights—from outdoor weather as well as vibration caused by the passing trains.

For example, the enclosures are made of steel, which not only protects the components from inclement weather but also blocks direct sunlight from the imaging sensors "so as not to cause bloom on the images," Usher says.

FIGURE 3. The cameras and lenses are installed inside protective enclosures and mounted on swing arms. *(Courtesy of Norfolk Southern)*

Similarly, stadium-type lighting is designed to withstand outdoor environments.

When asked what is unique about the train inspection system, compared with others in use in the railroad industry, Usher says, "This system adds numerous additional camera angles and views of the train cars and components that we are unaware of in other systems. We also use higher resolution and high-speed cameras and a combination of area and line scan cameras to generate comprehensive views of components for looking at specific types of defects."


RADIANT
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Titan Cement adds inspection system to production facility

An AI-assisted vision system detects defects in bags of cement mix.

JIM TATUM

Titan Cement (Athens, Greece), a global company that produces cement and building materials for the construction industry, has deployed an automated inspection system at its Patras, Greece, cement manufacturing plant.

Traditionally, at the Patras facility, inspections of these cement sacks were performed by human inspectors working eight hour shifts, 24 hours a day, in harsh conditions, doing manual, in-person inspections. If inspectors found a defect, they had to manually shut down the production line to remove the defective sack(s).

This is an expensive way to solve the problem. An interruption on a cement production line causes delays and reduces efficiency; a few defective cement sacks can spoil entire product pallets, leading to significant extra costs in time and money.

There also were other issues with the manual process. Humans become fatigued or may need to periodically leave the line during the production process. While they are experienced and competent at their jobs, human inspectors have their limits; often, they just cannot see minute/obscure defects on the bags. And, because the process is labor intensive and generally performed in challenging conditions, inspections performed by humans are error prone, which makes it difficult to capture meaningful QA data.

In late 2021, Titan partnered with Irida Labs (Patras, Greece) to develop and implement an automated inspection system that can inspect cement sacks on a production line. Titan executives wanted a system that identifies defects such as cracks, spills, dents, cuts, damaged edges, and printing errors, as well as sends alerts and takes corrective actions—and do it all 24 hours a day, seven days a week, 365 days a year, under such challenging conditions as variable ambient light, excessive dust, moisture, and vibration.

"The vision system should provide always-on defect detection on continuously running conveyor belts while providing real-time alerts when a defective product is detected," says Irida Labs' Thomas Charisis, Product Growth Director, PERCV.ai.

Photos/Irida Labs

FIGURE 1. Three cameras are mounted above the production line to inspect the cement sacks. Two color cameras scan for defects such as splits, holes, cracks, and spills. A third monochrome camera (above) scans for printing errors. A DC LED light is also placed above the line to overcome ambient light issues.

Building a solution: The vision system

The inspection system utilizes three Basler (Ahrensburg, Germany) cameras equipped with Basler premium lenses. Housed in IP67-rated custom built housings to protect them from the harsh conditions at the plant, the cameras are mounted on brackets over the production line and synchronized with photocell triggering to perform defect detection on the cement sacks as they come down the line. Two Basler ace 2 USB 3.0 color cameras are deployed for the sole purpose of inspecting the sacks for any physical defects. The third camera, a Basler ace 2 GigE monochrome camera, inspects the sacks for printing failures. More specifically, says Charisis, the monochrome camera uses optical character recognition to verify that the data label is positioned correctly within the frame in which it should be printed and to verify that the date on the label is correct.

DC LED lighting is installed on the line near the cameras to overcome challenges presented by the changing ambient light, Charisis says.

Adding AI to the solution

The cameras are hardwired to an ADLink (San Jose, CA, USA) DLAP-211-JNX edge computer, which is deployed along the line in close proximity to the cameras. The computer analyzes the image data in real time using Vision AI quality inspection modules developed by Irida Labs. These modules are built on Irida Labs' platform PerCV.ai, which is used to develop specific AI algorithms and manage the deployment of them.

"Image processing is performed at the edge; each camera sensor is paired with an on-site processing device that operates as near as possible to the sensor, making the system an edge AI vision solution," Charisis says. "The impact of edge processing is instrumental in achieving low latency, real-time defect detection, and alert triggering, as well as being privacy-preserving."

If the system detects a defect, there are several response options, he says. "Initially, there was an alarm going off and the conveyor belt would automatically stop, while a worker would take the defective cement bag off the belt and then restart the process," Charisis says.

FIGURE 3. Image data from the cameras are transmitted to this edge computer, also mounted near the line, which identifies, analyzes, and takes necessary corrective action to remove defective bags from the line.

FIGURE 2. Two color cameras mounted above the production line inspect cement sacks for defects such as splits, cracks, and spills.

Later, the team provided the real-time events via MQTT API, a messaging protocol often used in industrial settings for machine-to-machine communication, to a programmable logic controller that triggers a deviation system, which automatically removes the defective sack without stopping the production line, Charisis says.

Challenges, solutions, future plans

The team overcame challenges during implementation. In fact, one primary technical challenge turned out to be acquiring sufficient training data for the AI modules to recognize all the possible types of defects that could occur with the cement sacks.

“It would have taken an impractical amount of time to physically encounter and capture all potential defect cases in an operational production line,” Charisis says.

To overcome this challenge, the team came up with a solution that leveraged AI-generated synthetic data through the AI platform, which expedited the data acquisition process, Charisis says.

> The impact of edge processing is instrumental in achieving low latency, real-time defect detection, and alert triggering, as well as being privacy-preserving.

The inspection system, which has now been in operation at the plant for more than two years, has been successful, says Maravas Grigorios, supervisor of grinding, mixing, port & raw materials at Titan’s Patras facility. The system has significantly reduced the number of defective sacks that end up on pallets, Grigorios says.

“As a consequence, customer complaints about defective sacks have significantly decreased,” he notes. And, since human inspectors are no longer needed, the system has provided significant savings in labor costs.

The company plans to deploy the system in more plants in the second half of 2024, however, the exact dates and locations have not yet been finalized, according to Titan and Irida Labs officials.

Autonomous excavator builds retaining wall

Designed by researchers at ETH Zurich, the excavator is equipped with a LiDAR scanner, LiDAR sensors, and RGB camera.

LINDA WILSON

A park in Switzerland includes an unusual element: a stone retaining wall built by an autonomous excavator.

The robotic excavator used in the project is the HEAP (Hydraulic Excavator for an Autonomous Purpose), a customized Menzi Muck (Ruthi, Switzerland) M545 12t walking excavator. HEAP was developed by the Robotic Systems Lab, Eidgenössische Technische Hochschule Zürich, or ETH Zurich, (Zurich, Switzerland), a polytechnic university. The team worked with the chair of the landscape architecture department at ETH Zurich.

"As the building industry is a major contributor to global greenhouse emissions, it is critical to leverage new technologies toward more sustainable building practices. One such avenue is to rethink and reshape the embodied energy of material systems that are used in construction. In particular, developments in on-site robotic building methods offer the opportunity to leverage context-specific, locally sourced or upcycled materials that are inexpensive, abundant, and low in embodied energy," the researchers from ETH Zurich explain.

For example, autonomous construction systems can use boulders found on-site as well as concrete remnants from other projects to build retaining walls.

As an initial demonstration project, the researchers from ETH Zurich built a 10 × 1.7 × 4 m-long freestanding stone wall out of 109 boulders and concrete pieces. The structure was built over a two-week period at a rate of 17.4 minutes per stone, which is nearly as fast as would be possible with human operators.

Using the hands-on experience gained building the first wall, the researchers then built a permanent retaining wall with dimensions of 65.5 × 1.8 × 4 m out of 938 elements, which they integrated into a four-level terraced landscape with two pedestrian access ramps at Circularity Park in Oberglatt, Switzerland. The wall-and-terrace structure allows people to traverse differences in the park's natural elevation. The structure also helps control water runoff and soil erosion.

Because the freestanding wall was built on a concrete slab inside a facility, it was constructed without a human inside the cab of the excavator.

On the other hand, the permanent retaining wall was built on-site in the park, so a person, sitting in the cabin, managed unexpected situations such as a falling stone or one that didn't settle into place as expected. And, while the excavator picked, placed, and scanned stones autonomously, the human drove the excavator.

FIGURE 1. The Menzi Muck picked up and scanned each boulder as it built the wall. *(Circularity Park in Oberglatt, Eberhard AG, 2021-2022 © Gramazio Kohler Research, ETH Zurich, Eberhard AG. Photo: Marc Schneider)*

Autonomous process to build the wall

Reporting on their work in *Science Robotics* (bit.ly/3Jv0Hhb) the researchers write, "Our comprehensive pipeline allows for the construction of arbitrarily curved and explicitly defined wall shapes from highly heterogeneous stones, using light detection and ranging (LiDAR) mapping, learned image segmentation, grasp heuristics, and classification to isolate, digitize, and manipulate stone instances in unstructured environments."

The wall-building process began by creating a point-cloud representation of available boulders and concrete pieces. To accomplish this, the excavator picked up individual stones in its gripper, scanned them using LiDAR sensors mounted on its cabin and boom, and then returned them to the ground.

This allowed the researchers to develop a limited inventory of stones represented by the point cloud, which geometric planning software used to develop an initial plan for the wall.

The excavator then picked up each stone again to place it in the wall, reorienting it as necessary. After HEAP placed the stone, the vision system scanned the stone again and then updated the geometric planning software.

These steps happened dynamically as the excavator completed its work.

In a separate but related project, HEAP also worked on terraced landscaping. Specifically, the autonomous excavator dug up the soil at the site and dumped it nearby, so the soil could be reused to form the terraces.

Components of the machine vision system

The AI-enabled machine-vision building system was comprised of numerous components.

Specifically, a Velodyne (San Jose, CA, USA) Puck VLP-16 LiDAR scanner and a Livox (Shenzhen, China) MID-70 LiDAR sensor were mounted at the front edge of the cabin's roof. A second Livox Mid-70, mounted on the excavator's arm, provided an overhead view. A RGB Blackfly from Teledyne FLIR (Wilsonville, OR, USA) was mounted at the base of the cabin and a second RGB camera was mounted on the roof.

A machine controller solution—iCON iXE3 3D from Leica Geosystems (St. Gallen, Switzerland)—automated the functioning of the boom and bucket on the excavator. It created a 3D map during the swing motion of the boom. As the boom swung to the side, the map was updated with information from the LiDAR sensors.

FIGURE 2. Aerial view of the retaining wall at Circularity Park. *(© Gramazio Kohler Research, ETH Zurich, Eberhard AG. Photo: Marc Schneider)*

FIGURE 3. Computational planning and stone placement using the autonomous HEAP. *(© Gramazio Kohler Research, ETH Zurich, Eberhard AG. Photo: Ryan Luke Johns)*

Draw wire encoders were used to measure the position and velocity of the hydraulic arm and grapple cylinders.

All software is written in C++, and the robot operating system (ROS) is used to transfer data over the network between the different software nodes, which were distributed on several computers. The ROS master, managing the connection between processes, is located on the on-board computer of HEAP.

"The process provides a fully reversible alternative to concrete that can be applied, for example, to the construction of retaining walls, load-bearing structures, and revetments for civil infrastructure and landscaping," the researchers conclude on a website (https://gramaziokohler.arch.ethz.ch/web/d/forschung/382.html) created for the project.

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