

Superresolution Cameras Empower Line-Scan Imaging



▲ The processing of PCBs is one of the many applications of modern optical inspection and line-scan technology.



Integrating software algorithms with both single-row and time delay integration arrays produces two images with half-pixel offsets that enable high-speed automatic optical inspection.

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Machine vision requires increasingly higher performance and better detectability, but also lower system-level costs, for successful deployment in industrial environments. Line-scan imaging has the capability to meet the requirements of today's vision systems that integrate various technologies such as multispectral and multifield high-speed imaging¹⁻⁴. However, hardware-based solutions alone are not sufficiently adaptable to meet these rapidly changing requirements.

Superresolution technology

Superresolution (SR) emerged in the 1980s as a technique for multiframe signal reconstruction and found early practical application in airborne imaging, where platform motion naturally provides subpixel diversity. During the 1990s, spatial domain methods enabled operational resolution enhancement in airborne imaging systems, improving performance without requir-

ing more expensive optics. Although detector advancements have reduced dependence on SR, its system-level value has ensured its continued use in inspection applications, with many of today's approaches still rooted in those early foundations.

SR technology, including versions patented by Teledyne Digital Imaging, leverages dual linear sensor arrays positioned with precise half-pixel offsets to achieve image quality beyond the native sensor capabilities (Figure 1)⁵. This approach doubles the effective pixel density, transforming input images into higher-resolution output images using unique algorithms. The technology supports both single-row and time delay integration (TDI) arrays, enabling deployment across a wide range of line-scan applications, from mid-market web inspection to high-end precision semiconductor metrology, for detecting pinhole and particle defects.

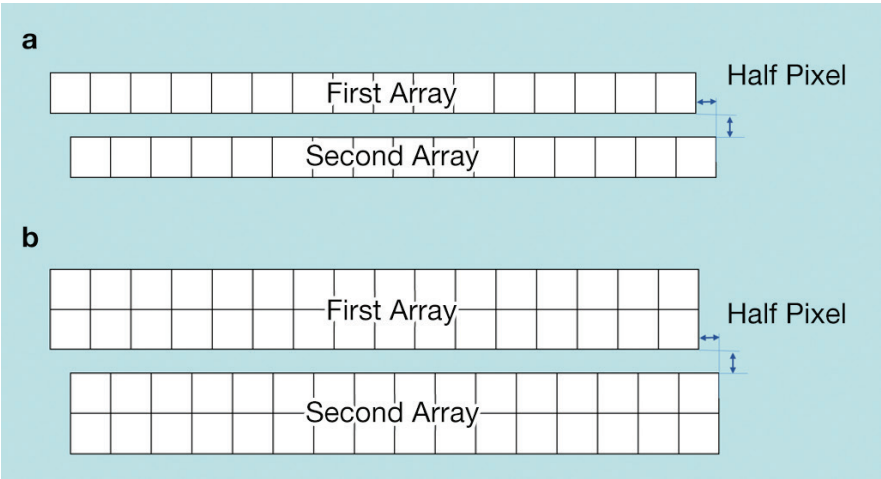
And superresolution doesn't just mean a target is "scaled up" digitally. Systems using this approach actually

take multiple images of an object and use the extra data to create a higher-definition output image.

SR imaging in a machine vision context consists of three primary stages: capture, reconstruction, and output. During image capture, dual sensor arrays simultaneously acquire offset images at native resolution. During the reconstruction stage, algorithms integrate the offset images, interleaving pixel data to generate the SR output. Data reconstruction can be executed in a host driver using control software, providing flexibility for systems with available CPU resources, or on a frame grabber for high-throughput processing.

From line scan to TDI

Two primary camera model types use SR technology, each with distinct performance profiles optimized for different applications. The first iteration delivers 8K SR output through dual 4K/7- μm arrays, utilizing a standard 2.5/10 Gigabit Ethernet interface for cost-sensitive applications with a maximum line rate of 75/82 kHz. This camera model performs well for general industrial inspection, packaging verification, and document scanning, where 8K resolution is sufficient.



Teledyne Digital Imaging

▲ **Figure 1.** Superresolution sensor architecture using two linear arrays with half-pixel offsets horizontally and vertically. The sensor array can be either a single-row array (a) or a multistage time delay integration (TDI) array (b). Images from both arrays are read out independently.

For demanding subpixel and metrology applications, another camera achieves 32K/2.5- μm output resolution from dual 16K/5- μm TDI arrays, employing a Camera Link HS interface to support the substantial 13 GB/s data throughput with maximum 400-kHz line rates. This camera effectively targets semiconductor wafer, flat-panel display, and PCB inspection applications that require maximum spatial resolution (see Table below).

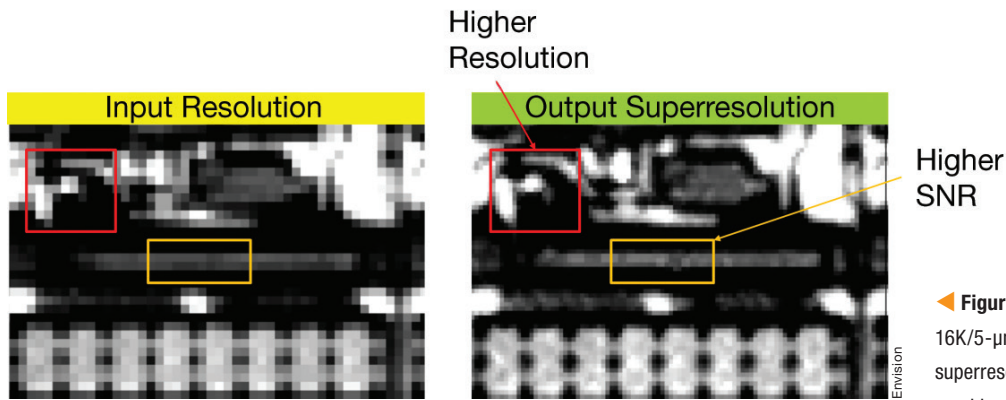
Both models feature the core dual-array architecture with half-pixel offsets but differ in resolution, interface bandwidth, and target application cases.

An SR line-scan system is easy to use since the gap between the two arrays is only $\sim 10\ \mu\text{m}$. For TDI systems, however, the gap between the two TDI arrays is larger, at hundreds of micrometers. The larger gap requires tighter tolerances in mechanical movement design to ensure alignment between the camera and sample.

Differences exist between area-

Comparison of Line Scan vs. TDI

Specification	Line Scan	TDI
Native Input Resolution	2× 4K/7- μm pixel	2× 16K/5- μm pixel
Architecture	2× single array with half-pixel offset	2× 64-stage TDI array with half-pixel offset
Superresolution Output	8K/3.5- μm pixel	32K/2.5- μm pixel
Interface Type	nGigE	Camera Link HS
Data Throughput	1.2 GB/s	13 GB/s
Target Applications	General industrial inspection, packaging verification, document scanning	Semicon wafer, flat-panel display inspection, PCB verification
Differentiation	Cost-effective and small-form-factor 8K line scan	High-speed and high-resolution 32K TDI
Application	Easy to use	Tighter tolerance in mechanical movement



▶ **Figure 2.** A comparison of the original input 16K/5- μm image and the output 32K/2.5- μm superresolution image. The superresolution image provides higher resolution and a better signal-to-noise (SNR) ratio.

camera SR and line-scan SR. With area-scan systems, the sensor is often shifted by microscale distances, which may affect the modulation transfer function (MTF) of the image due to blurring that can result from the movement. Line-scan and TDI systems do not move the sensor dynamically. It is possible to use up to four images to create a complete superresolution image, but generally, just two suffice if the image is shifted both horizontally and vertically.

Resolution, SNR, and MTF

As shown in Figure 2, SR technology delivers measurable improvements in both spatial resolution and signal-to-noise ratio (SNR) compared with the native sensor resolution. Direct comparison of 16K/5- μm input versus 32K/2.5- μm superresolution output demonstrates visibly enhanced edge definition, finer feature reproduction, and reduced noise characteristics. The doubled pixel density enables detection of features at half the original pixel pitch, significantly improving the system's spatial resolving power.

Beyond pure resolution gains, the dual-array averaging inherent in data

reconstruction provides a significant improvement in signal-to-noise ratio, depending on defect characteristics such as contrast. This SNR enhancement is particularly valuable for subpixel defect detection, where subtle gray-level variations must be distinguished from sensor noise.

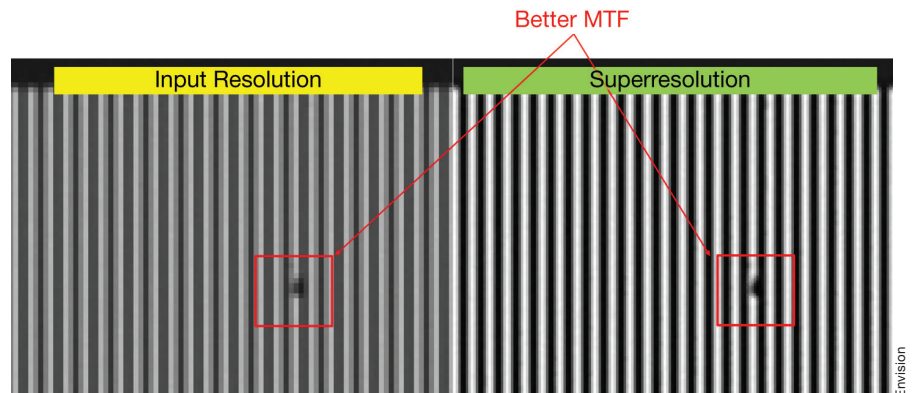
Existing applications in semiconductor inspection, flat-panel display verification, and precision PCB examination benefit substantially from the combined resolution and SNR improvements, enabling detection of defects previously masked by noise or below the native pixel size.

The MTF quantifies an imaging system's ability to reproduce contrast at varying spatial frequencies, serving as the definitive metric for optical resolution performance. SR technology demonstrates substantial MTF improvements across the spatial frequency spectrum compared with native sensor resolution (Figure 3). This MTF advan-

tage translates directly to improved edge acuity, enhanced fine feature definition, and more reliable detectability. For line-scan flat-panel display inspection applications requiring 1- to 5- μm feature resolution at high line rates, the MTF improvement enables systems to operate at higher speeds while maintaining detection confidence.

A 32K/2.5- μm SR image significantly improves MTF compared with the input images from 16K/5- μm sensors. However, when compared with the image captured using a true 32K/2.5- μm pixel size, the SR resolution image has an inferior MTF (assuming a suitable lens has been selected for both cases). A simulation study carried out by the authors and colleagues indicated that SR technology provides an effective pixel size of $\sim 3.5\ \mu\text{m}$ with equivalent MTF performance (Figure 4). In other words, the output image's MTF performance

▶ **Figure 3.** Superresolution significantly improves the modulation transfer function (MTF). This is particularly important not only for defect detection but also for metrology, where contrast is paramount.

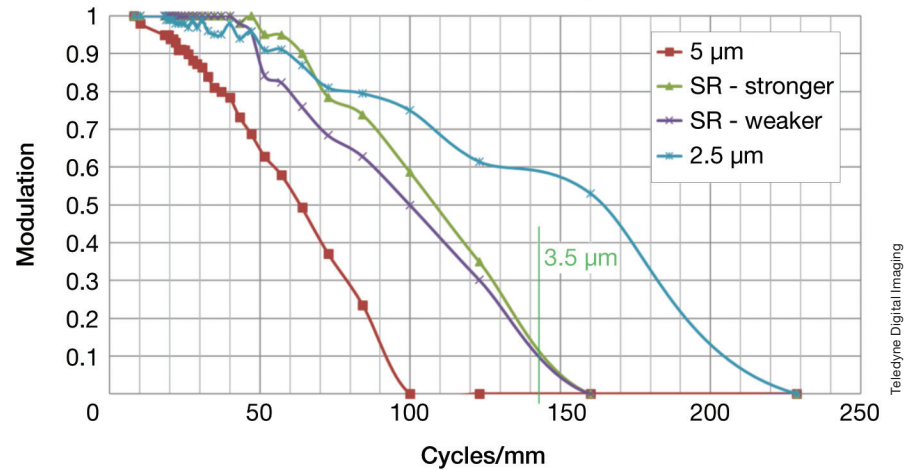


falls between that of an image with the native pixel size and that of an image with the output pixel size.

Subpixel defect detection

One of the challenges of optical inspection is subpixel defect detection. SR technology excels at detecting defects smaller than the native pixel pitch through combined resolution enhancement and noise reduction. Traditional single-array sensors struggle with subpixel defects (such as a subpixel pinhole) because the faint defect signal may be distributed across several pixels and easily obscured by sensor read noise. The dual-array architecture with half-pixel offsets enables defect energy to be sampled at intermediate positions, effectively quadrupling the spatial sampling density. Simultaneously, the reconstruction algorithm's inherent averaging reduces random noise, improving the SNR by a factor of four to five, depending on defect type and contrast characteristics.

In Figure 5, four regions of interest demonstrate this effect: ROI 1, ROI 2, and ROI 3 show subtle defects clearly resolved in the superresolution output but barely visible above the noise floor in conventional imaging, while ROI 4 represents the baseline noise floor for comparison. This performance advantage makes superresolution particu-



▲ **Figure 4.** The effective MTF of a superresolution camera falls between that of a camera with the native pixel size and that of a camera with the output pixel size. SR: superresolution.

larly valuable for semiconductor wafer inspection, flat-panel display defect detection, and PCB trace verification, where defects ranging from 1 to 5 μm must be reliably identified at production line speeds.

There are several ways to use the subpixel information, specifically through algorithms designed to combine the data into a composite image. For example, the algorithms can be used to reduce noise or for edge enhancement. Each of these approaches may be more or less beneficial to the end application, and the end user can select the exact parameters.

Benefits of superresolution

SR technology offers many benefits for real-world applications. First, it overcomes technical challenges

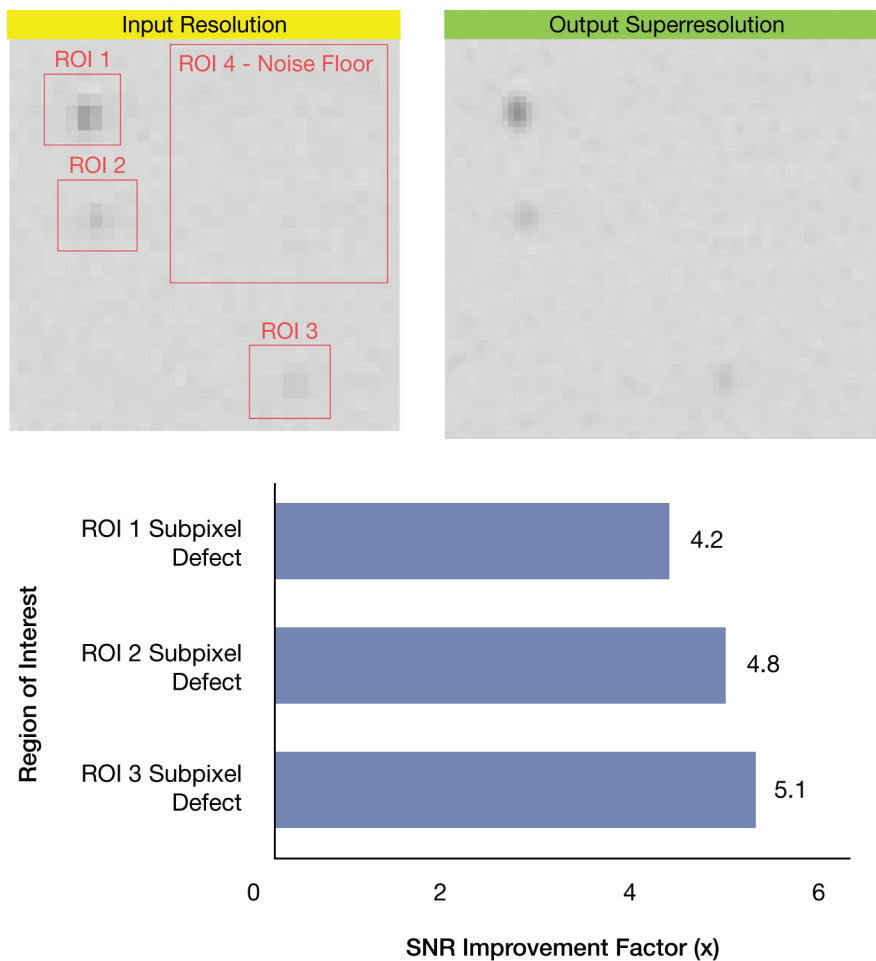
in designing a small physical pixel in a CMOS sensor. A small pixel often comes with disadvantages, including low responsivity, small full-well capacity, and worse MTF than larger pixels. In particular, for TDI devices, a pixel smaller than 2.5 μm is technically challenging.

Second, a sensor with a small pixel requires an expensive optical lens. The high cost of the lens becomes prohibitive for many cost-sensitive applications in machine vision, such as PCB inspection.

Third, a sensor with a small pixel size also requires high-brightness lighting, which can generate significant heat and result in high maintenance costs. In addition, the degradation of high-brightness LEDs over time also requires regular, costly replacement and maintenance.

Finally, SR technology reduces the data transmission bandwidth requirement for a cable. After the pixel data is transferred from the camera through the cable, it doubles in the host or the frame grabber, reducing the amount

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◀ **Figure 5.** Superresolution technology offers the best performance for detecting subpixel defects due to an improved SNR. Depending on the type of defect, the SNR can be improved by a factor of four to five using superresolution. ROI: region of interest.

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of data going through the camera interface and the cable. The data reduction is significant because, in many applications, the data interface is the bottleneck in today's high-performance vision systems.

Software meets hardware

Unlike conventional image upscalers, which use only software to expand a lower-resolution image, the physical pixel offsets used in SR technology capture real physical information in the pixel data. This feature preserves true image quality for machine vision applications.

Tuning the SR algorithm to achieve the best results requires knowledge of the application requirements and al-

gorithm design. Furthermore, because camera resources are required to run these algorithms, highly efficient code and memory management are necessary to achieve the best results in real time. The capabilities of the CPU and PC memory are important considerations.

The previously described SR technology uses a software-defined pixel size based on a unique hardware pixel-offset sensor architecture, rather than software implementation alone. Solutions based on hardware combined with software innovation represent the future direction for meeting the demanding and rapidly changing image quality requirements of machine vision.