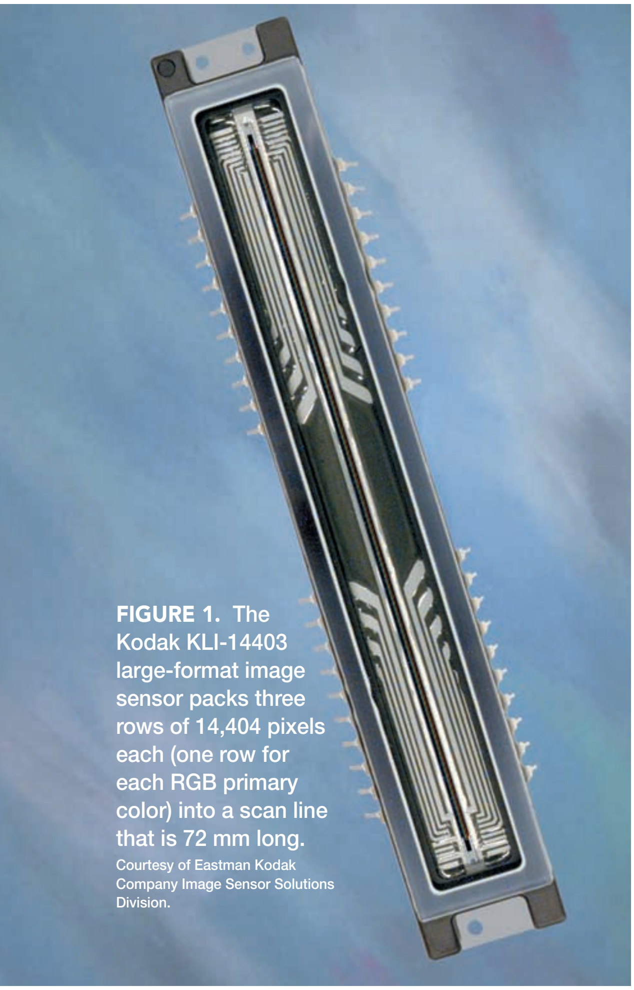

FIGURE 1. The Kodak KLI-14403 large-format image sensor packs three rows of 14,404 pixels each (one row for each RGB primary color) into a scan line that is 72 mm long.
Courtesy of Eastman Kodak Company Image Sensor Solutions Division.

THE BIG PICTURE

KNOWLEDGE OF MECHANICAL, OPTICAL, AND ILLUMINATION ISSUES CAN HELP YOU TAKE ADVANTAGE OF LARGE-FORMAT IMAGING SYSTEMS.

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Large-format imaging systems offer advantages in resolution, sensitivity, and ease of integration over their smaller format predecessors for online inspection, factory-floor automation, and high-end scientific applications. One key to successfully implementing a large-format system is to select the right large-format lens—a task that first requires an understanding of the complete setup, including sensors, illumination, and mounting options.

Availability of large-format area- and line-scan sensors (**Figure 1**) has increased over the past few years. Area-scan sensors have grown from a 1-in. format (12.8x9.6 mm) to 36x24 mm. Line-scan image sensors used to be limited to 10 mm, but now have a maximum size of 90 mm.

The consumer digital-imaging industry has largely driven these developments, with consumers demanding the convenience of digital photography combined with the image quality of film photography. This drive toward better image quality is driving advances in CCD-chip manufacturing and testing.

Although chip manufacturers have long been able to reduce CCD pixel sizes, they do so at the cost of decreased signal-to-noise ratio (SNR). All else being equal, the signal from a CCD pixel varies in proportion to its area. The electronic noise sources, however, do not. So, decreasing the pixel area reduces the signal level for the (more or less) same noise level, and SNR drops precipitously. Small changes in the unit under test (UUT) that cause small signal changes become more difficult to detect.

The question becomes: "How do you increase sensor resolution without sacrificing sensitivity (measured by SNR)?" One answer is to increase the number of pixels without reducing individual pixel size, which increases overall sensor size. Large-format area- and line-scan sensors both take advantage of this philosophy.

One camera vs. many

Rather than using a large-format camera, you could assemble a high-resolution image from multiple lower-resolution images acquired with multiple small-format CCD cameras. But this strategy, which engineers have been forced to use in the past, raises issues of image registration and mechanical alignment.

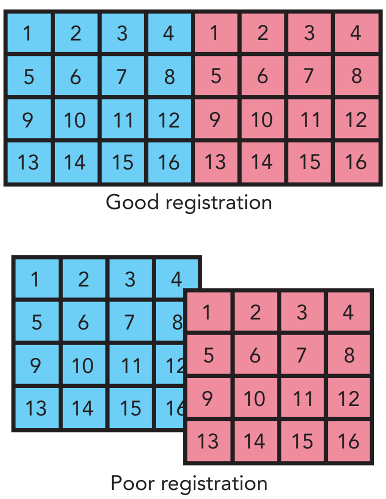

FIGURE 2. Registration can be a serious issue for multiple-camera systems.

Registration relates pixels in an image acquired with one camera to adjacent pixels acquired with another (**Figure 2**). Image registration needs to be completed before other analysis can occur. The goal is to create a coordinate system that spans the images so image-processing algorithms can seamlessly operate on the combined data set as if it were one image. There are many image-registration methods offering tradeoffs between speed and accuracy.

Mechanical alignment makes registration possible. Before image-processing software can stitch together images acquired with multiple cameras, the cameras must be rigidly mounted so the pixels of one line up with the pixels of the next one and then stay aligned to better than 1-pixel resolution from frame to frame.

Consider a setup in which three cameras are directed toward the same part from slightly different positions. Each camera would need to be mounted rigidly and have up to six mechanical degrees of freedom to allow initial alignment. In addition, each camera would need a separate lens with its own focus adjustment and iris control. The image-processing software for such a setup would have to account for both angular differences between the cameras as well as small variations in the lens settings—neither of which is easy for software to do.

You can eliminate these image-registration concerns and simplify system setup by replacing three cameras with just one large-format camera. The test-software developer can then focus on fundamental image-processing issues, saving development time as well as test time on a per-piece basis. An added benefit is that processing becomes simplified, with only one video signal to process rather than three.

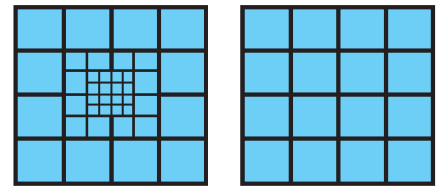

FIGURE 3. Human eyes emphasize optical performance near the field center (left), whereas machine-vision systems demand consistent resolution across the entire field of view.

Large-format challenges

Of course, as many economists have pointed out, "there is no such thing as a free lunch." Engineers wanting to partake of large-format cameras' advantages have to pay for them by heeding considerations that users of small-format systems may take for granted.

For example, the ability of a large-format camera to capture large amounts of data can create a bottleneck when the information is transferred to a computer. The rate at which the camera transfers image information depends on the number of pixels and the operating frame rate.

The buses used to transfer data from analog cameras can accommodate 640x480 pixels at 30 frames/s. Digital buses move data more quickly, but as sensors acquire more pixels, the information content of each image can overwhelm even these digital data-transfer techniques. When image transfer becomes a bottleneck, the frame rate must go down. The result can be less than what one would perceive as a "live feed." One way to alleviate the bottleneck is to employ line-scan cameras, if your application permits (see "Frame and scan rates," p. 40).

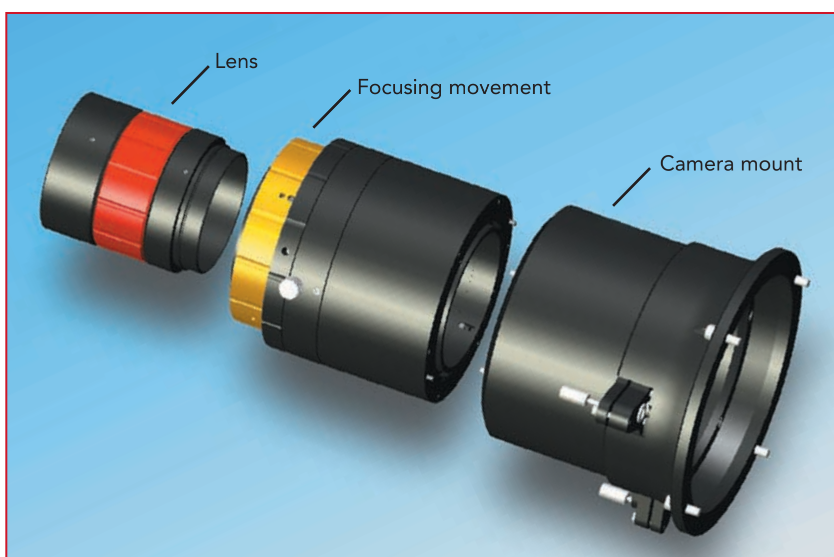

FIGURE 4. A modular lens-mounting scheme separates the lens system into three subassemblies: the lens optics, the mechanical focusing system, and an interface for the camera mount.

Another challenge facing engineers who want to use large-format cameras is obtaining compatible lenses that meet machine-vision performance specifications. Companies that manufacture large-format, high-speed cameras generally do not make the compatible lenses, so you need to turn to third-party suppliers.

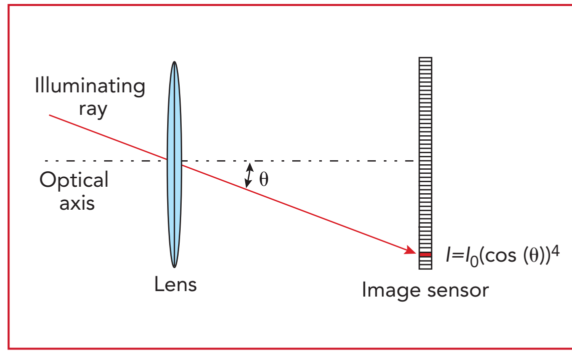

FIGURE 5. Image brightness naturally falls off toward a frame's edge.

Many photographic lenses can cover large film frames, but they are not the ideal choice for machine-vision applications. The resolution of a photographic lens, even one intended for use with large-format CCD cameras used by professional photographers, is optimized for the center of the image. The resolution at the edges may differ significantly. Human eyes emphasize the center of a scene and accept considerably poorer performance toward the edges (**Figure 3**). Imaging applications are not as forgiving.

Unlike human eyes, which have an area of enhanced visual acuity (the fovea) at their centers, the pixel size of a machine-vision camera is constant over the entire chip. Engineers studying the resulting images want to reliably detect the smallest features they can, independent of where they fall in the field of view (FOV). Meeting this demand for good optical performance over the entire field requires a lens whose resolution is uniform over the entire sensor area.

Engineers looking to integrate large-format cameras into their production-control systems have had only a few off-the-shelf machine-vision lenses to choose from as components. If none of them met the system requirements, the engineers were forced into paying for the

Frame and scan rates

In some large-format imaging applications, the use of a monochrome or color line-scan camera, in which the sensor consists of just a single row of pixels, can break data-transfer bottlenecks. The camera views parts moving by, such as on a conveyor belt. The sensor captures one row of pixels at a time at a scan rate adjusted to match the production-line speed. The display then shows an accurate view of each UUT without the need to stop the line to take images.

The amount of data a single line of pixels generates is significantly less than what an area-scan sensor would generate in the same time. Engineers who use large-format line-scan cameras can keep production rates high without compromising inspection resolution.

Not all inspection applications can use line-scan cameras, however. When parts don't move past the inspection station at a constant speed, you may need to image each part individually with an area-scan camera, whose frame rate depends on the signal format. Engineers should expect to trade processing speed for higher resolution. The maximum frame rate will depend on the signal format chosen and on the resolution of the camera being used. If the field of view (FOV) is flexible, it may be possible to control the resolution by lens selection. Tightening the FOV by increasing magnification permits the use of a lower-resolution camera and increases the system frame rate.—*Andrea Tollison* costly (and time-consuming) design of a custom lens. Fortunately, machine-vision lens developers are starting to develop off-the-shelf large-format lenses.

Once you have an appropriate lens, the next challenge is mounting the lens to the camera. There are perhaps as many different mounting standards for large-format area- and line-scan cameras as there are manufacturers. One way to address this problem is to have a modular mounting system (**Figure 4**), which separates the lens system into three subassemblies: the lens optics, the mechanical focusing system, and an interface for the camera mount. This system accommodates different mounting standards with the simple change of the relatively inexpensive camera-mount module.

Lens selection starts after you've selected a large-format camera for your inspection system.

A final challenge to the system developer is to provide even illumination. Photographic lenses, again, fail to meet the machine-vision performance criterion. The human eyes that view photographic images (being logarithmic detectors) suppress illumination variations as well as concentrating on image centers, so they readily forgive illumination variations between the center and the edge.

For machine-vision systems, good lighting can make the difference between success and failure. Unfortunately, the laws of radiometry work against lens designers trying to obtain even illumination across the field. Even a perfect lens design will have some fall off of illumination levels at the edges of the FOV. Image brightness varies with $\cos^4\theta$, where θ is the angle between the optical axis and a ray passing through the lens center to reach the off-axis image point (**Figure 5**). A 120-mm focal-length lens used with a line-scan camera having a 90-mm sensor will suffer an image-brightness falloff by 20% between the center and ends of the pixel line.

Photographic lenses do even worse, however. Their designers generally trade brightness variations for improved resolution near the edges via a technique called vignetting. By adding baffles in the light path, the lens designers selectively block off-axis rays that enter through the lens' edge, which contribute the most to spherical aberration. Vignetting, however, can reduce the light level by another 50% to 60% below the center brightness.

Finding the right lens

Lens selection starts after you've selected a large-format camera for your inspection system, because the camera's physical parameters determine the lens specifications. When choosing a lens, here are some questions you should ask:

- **What are the sensor's physical dimensions?** For a line-scan camera, the important value is the sensor length. For an area-scan camera, the horizontal and vertical dimensions are important. Camera vendors will often quote these as the "sensing area" HxV (horizontal size x vertical size). If the vendor does not specify the sensing area, you can calculate it by multiplying the number of pixels by the pixel size. Note that the number of pixels as well as the pixel dimension may differ between horizontal and vertical directions.
- **What is the pixel size?** Usually specified in microns (µm), the pixel size will determine the best image-space resolution (that is, the resolution at the image plane) that the lens-and-sensor combination can achieve. Make sure the lens can at least achieve pixel-level resolution.
- **What type of mount does the camera have?** Typical camera-to-lens interfaces are C-mount (cine-mount) or CS-mount (cine-short-mount) lenses, although others are also available. In addition to knowing what type of lens mount a camera has, you also need to know the camera's flange distance (the distance from the camera's mounting-flange surface to the CCD's active surface). This information allows you to specify a camera-mount adapter module to make connecting the lens to the camera much easier and to save adjustment and alignment time.

You will also want to know the requirements and limitations of the imaging system:

- **What is the allowed working distance range?** Working distance for a machine-vision camera is the distance between the front of the lens to the camera-mounting flange. Any constraints on working distance are important because mounting adapters for large-format lenses can be quite long.
- **What is the desired FOV?** Or, what is the desired resolution? For a given camera, the system's FOV and resolution depend upon one another. Determine whether the size of the image on a display screen or the smallest distinguishable feature size is more important, then use that value to choose the correct system magnification.

The benefits available to engineers who integrate large-format cameras into their inspection systems outweigh potential concerns. It is important, though, to understand the effects that frame rate and illumination falloff can have on a system. As new electronic signal formats are developed and as new large-format lenses are released, these considerations will become more familiar, and the advantages to making the switch to large-format systems will become even more convincing then they are today. T&MW

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