Line Scan Imaging in Machine Vision: Fundamentals and Sensor Types

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Following an overview of line scan and area scan imaging principles in machine vision, this white paper highlights synchronization requirements in high-speed line scan camera systems, compares color line scan sensor technologies, and provides hands-on guidance for robust industrial inspection system design. It is intended to support engineers and system integrators in selecting the appropriate technology for demanding inspection applications and making informed system-level decisions.

Introduction to Line Scan Imaging

Successful machine vision system design begins with a clear understanding of all available tools that can be used to solve a given problem. One such tool is the line scan camera. With line scan cameras, high-resolution images can be captured at high speeds without requiring the bandwidth typically associated with area scan systems of comparable resolution. Line scan cameras require continuous relative motion between the object and the imaging sensor and are commonly deployed in textile inspection, battery winding and various agricultural inspection systems. Before exploring line scan camera technology in detail, a brief overview of area scan cameras provides helpful context and introduces the necessary fundamentals.

Area Scan Fundamentals

Area scan cameras are the most commonly encountered sensor technology in day-to-day life; cell phone cameras, television broadcasts, films, car parking assist cameras, and security cameras are included in this category. Since area scan images are captured in a manner similar to the human eye, this type of camera is more easily comprehensible.

The output of these sensors is an image of horizontal and vertical dimensions determined by the system magnification and the size of the imaging sensor, resulting in a two-dimensional (X, Y) image (see Figure 1).

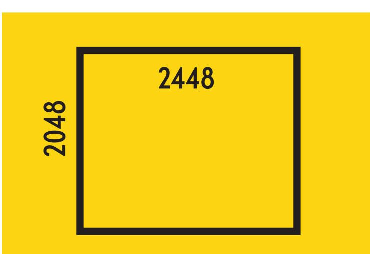

Figure 1 – A standard 5MP area scan sensor comprised of an array of 2448 x 2048 pixels

The pixel size determines the overall sensor format and image size. For example, a standard 5MP 2/3" format sensor with 3.45μm pixels coupled with a 1X magnification telecentric lens will yield an image of 8.4 x 7.0mm (2448 x 3.45μm by 2048 x 3.45μm). An area scan sensor will expose all the pixels on the sensor array before displaying the complete image.

How Line Scan Imaging Works

A monochrome line scan camera, in its most basic form, is composed of a single row of pixels whose length is typically 2k (2048), 4k (4096), 8k (8192), or 16k (16384) pixels (see Figure 2).

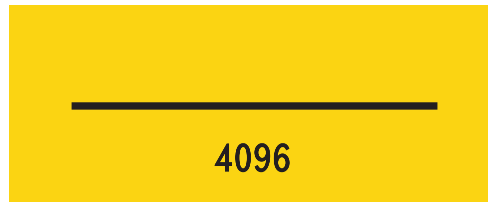

Figure 2 – A standard 4k line scan sensor comprised of an array of 4096 pixels each 7μm

When paired with a lens of a given magnification, an extremely small section of the object is captured, and this line is continuously stacked with subsequent lines. Continuous motion of the object is required; otherwise, identical lines would be combined, producing an incomprehensible image.

For example, when a standard 4k monochrome line scan camera with 4096 pixels and 7μm pixel size (producing a sensor size of 28.7mm x 7μm) is paired with a 50mm lens at a 250mm working distance, a magnification of 0.2X is obtained. This results in a 35μm object-space pixel size, meaning that each captured line represents only a 35μm slice of the object. If the object were stationary, the same 35μm portion would be repeatedly reproduced. When the object is in motion, however, these lines can be stacked to form a complete image. Examples of images taken with a stationary and moving object are shown in Figure 3.

Figure 3 – A stationary object (left) and the same object in motion (right) captured with a line scan sensor

Importance of Synchronization in Line Scan Applications

Since only a 35μm sliver of the object is captured at any given moment, one of the greatest challenges in building a line scan system is image synchronization. During setup, a line rate must be selected. This functions similarly to the frame rate of an area scan camera, though it describes the rate at which individual lines are captured, typically expressed in hertz (Hz).

Manual synchronization of the line rate with the object's speed is possible, but it presents a significant difficulty. Since line sizes exist on the scale of microns and capture rates are often on the scale of kilohertz (kHz), manual adjustments are challenging, and any change in object speed would necessitate repeating the process.

If synchronization is incorrect, two scenarios may occur. If the object moves too slowly relative to the line rate, over-triggering occurs, meaning the same portion of the object is captured multiple times, causing the image to appear elongated. Conversely, if the object moves too quickly relative to the line rate, under-triggering occurs, causing portions of the object to be missed and the image to appear compressed. Figure 4 shows examples of over- and under-triggering.

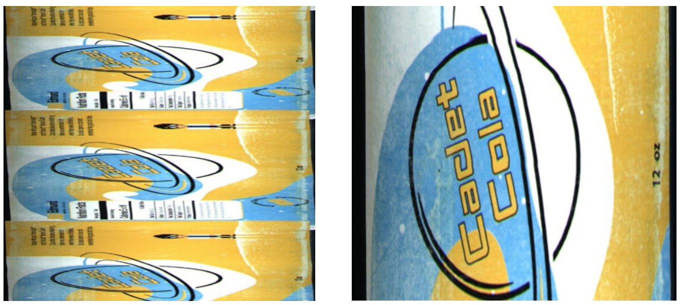

Figure 4 – Example of under- (left) and over-triggering (right)

Synchronization is typically achieved using an encoder, which converts motion into electrical signals. When the encoder is attached to the motion source and connected to a camera I/O port, these signals allow communication between the motion system and the camera. A multiply/divide ratio in the SDK (Software Development Kit) is then used to translate the encoder's resolution to match the object-space pixel size.

Color Line Scan Technologies

Color imaging on a typical area scan sensor is produced by a Bayer pattern that is applied to the surface of the imaging sensor. One red, one blue, and two green pixels are included in each quadrant of the checkerboard-style pattern, and this pattern is repeated across the entire sensor (see Figure 5).

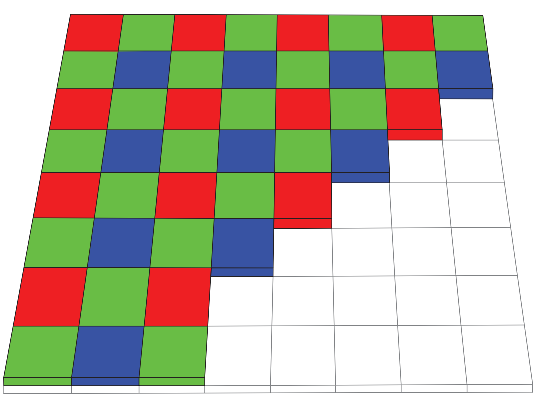

Figure 5 – Area scan Bayer pattern

Though a finished color image needs information about all three color channels per pixel, each pixel only measures color information for a single channel. Interpolation (debayering) of the remaining color channels is performed using information gathered from neighboring pixels. Through this arrangement and processing, color sensitivity approximating that of the human eye is achieved. However, because two of the three color channels are interpolated rather than directly measured, a degree of inaccuracy is introduced when a color area scan camera is used.

For a line scan sensor, a 2D checkerboard pattern cannot be applied to a single line of pixels. As a result, it is not possible to implement a conventional Bayer pattern in the same way as in area scan cameras. A different method must be used, and several techniques have been developed for color line scan imaging, notably bi-linear, tri-linear, multispectral, and prism-based approaches, with each subsequent technique generally representing a more expensive solution.

Bi-Linear Color Line Scan Imaging

In a bi-linear sensor, two lines of pixels are used—one line with pixels all dedicated to the green channel, and the other line with pixels alternating between red and blue (see Figure 6). These lines are synchronized in their acquisition so that the same portion of the object is captured before the line is displayed. Since all three color channels cannot be directly measured for each displayed pixel (each pixel provides either green/red or green/blue), a debayering process is still required, and performance is similar to that of a color area scan sensor.

Figure 6 - Bi-linear color line scan sensor

Tri-Linear Color Line Scan Imaging

In a tri-linear line scan sensor, a third line is added to separate the red and blue channels, allowing full color information for each displayed pixel to be directly measured (see Figure 7). This eliminates the need for debayering, and a true color image is produced without degradation of image quality.

Figure 7 – Tri-linear color line scan sensor

Multispectral Color Line Scan Imaging

In a multispectral line scan sensor, a fourth line of pixels dedicated to the NIR channel is integrated (see Figure 8). NIR sensitivity is thereby increased, and this approach is typically used only when an application requires the collection of NIR light.

Figure 8 – Multispectral color line scan sensor

Prism-Based Color Line Scan Imaging

A prism-based camera operates similarly to a tri-linear design, but instead of a synchronized delay between the acquisitions of the three color channels, the incoming light is split by a prism into three separate spectral bands, which are then projected onto three separate sensors—one each for blue, green, and red (see Figure 9). A true color image is produced as a result, though the use of specially designed imaging lenses is required to accommodate the prism within the optical path. Although highly effective, prism cameras can be cost-prohibitive.

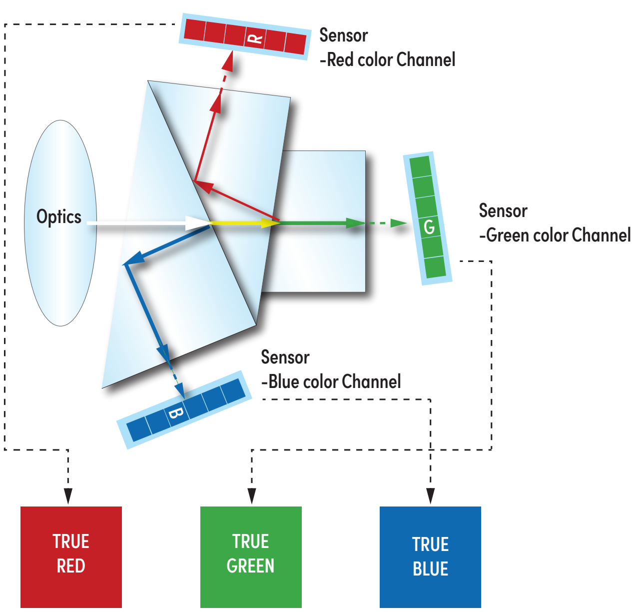

Figure 9 – Prism color line scan sensor

Considerations for System Building

Determining Required Pixel Count

The size of the required sensor is determined in a manner similar to that used for an area scan system. The object size, the number of pixels needed across the feature under observation, and the necessary horizontal field of view (hFOV) are first defined.

The minimum array size is then calculated as:

$$\text{Min Array} = \frac{\text{hFOV x Pixels per Feature}}{\text{Feature Size}} \tag{1}$$

Required Line Rate

The required line rate is determined as a function of the object speed divided by the object-space pixel size:

$$\text{Line Rate} = \frac{\text{Object Speed}}{\text{Object Space Pixel Size}} \tag{2}$$

Imaging Lenses for Line Scan Systems

Imaging lens selection for a line scan system is approximated in the same way as for an area scan system. The primary distinction is that the horizontal length of the line scan camera is used instead of the diagonal of the area scan sensor.

Example Calculation for a Line Scan System

An OCR (Optical Character Recognition) application is to be designed, and feature sizes of approximately 0.5mm are expected. An 100mm field of view is required, and the working distance must fall between 300–500mm.

hFOV: 100mm

WD: 300-500mm

Feature size: 0.5mm

Required n° pixels per feature: 10 Pixels

Object Speed: 500mm/s

The minimum array size is calculated as:

$$\text{Min Array} = \frac{\text{hFOV x Pixels per Feature}}{\text{Feature Size}}$$

$$\text{Min Array} = \frac{\text{100mm x 10 Pixels}}{\text{0.5mm}}$$

$$\text{Min Array} = \text{2000 Pixels}$$

Based on earlier calculations, the object is known to move at 500mm/s, and the required object-space pixel size based on the required number of pixels per feature is 0.05mm. The line rate is therefore computed as:

$$\text{Line Rate} = \frac{\text{Object Speed}}{\text{Object Space Pixel Size}}$$

$$\text{Line Rate} = \frac{500\text{mm/s}}{0.05\text{mm}}$$

$$\text{Line Rate} = 10{,}000\ \text{s}^{-1}\,(\text{or Hz})$$

$$\text{Line Rate} = 10\text{kHz}$$

From this information, a 2k Linea camera from Teledyne Dalsa (Edmund Optics® stock number 71-779) can be selected. Using an imaging calculator, it can be determined that a 50mm focal length lens like the Edmund Optics® 50mm CA series lens (Edmund Optics® stock number 11-320) is well suited for this application. It will yield a 100mm field of view at a working distance of 350mm.

Summary and Key Takeaways

When designing an imaging system, it is important to understand the available sensor technologies and key system features and to make a choice on whether to employ an area or line scan sensor. Line scan systems are preferred for continuous processes involving moving objects, such as web inspection, battery electrode manufacturing, or other roll-to-roll applications. In contrast, area scan cameras are typically used for stationary or indexed objects, where a complete two-dimensional image can be captured in a single exposure. Using line scan cameras in a machine vision setup enables high-speed, high-resolution imaging without requiring extremely high-bandwidth data interfaces. Understanding the importance of system synchronization using an encoder and being able to perform basic system calculations to select the appropriate lens and camera is critical for achieving accurate results. With the right system design, line scan technology provides a reliable and scalable solution for demanding industrial inspection applications.