Application Note

Line Scan Imaging Basics

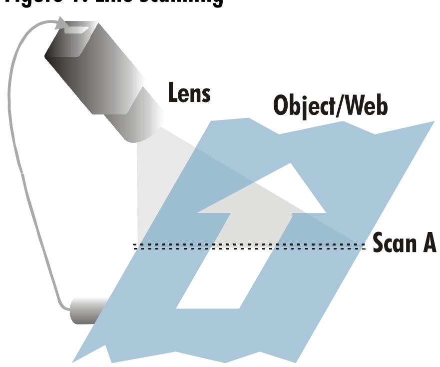
DALSA cameras are available in a variety of models, but all can be categorized as either area array or line scan array. This application note compares and contrasts area array, line scan, and high sensitivity line scan cameras. It is intended for readers who are familiar with area array cameras but would like to learn more about line scan technology and how it works. Detailed examples using line scan cameras are provided.

Sensor Architecture Comparison

Most people are familiar with area array sensors—sensors with two-dimensional arrays of pixels in varying resolutions (e.g. 640 horizontal by 480 vertical, 1024x1024, 1600x1200. See Figure 2). Consumer digital cameras use these types of sensors. They excel in imaging still or slow-moving objects. But using area arrays to image high-speed motion of objects or continuous webs is problematic. To “stop the action,” area arrays need short exposure times as well as shuttering, synchronization equipment, or powerful, strobed illumination, all of which add to system complexity and usually make it harder and more expensive to get good images.

In contrast line scan sensors lend themselves well to imaging high-speed objects or webs. With a single line of pixels (Figure 1, Figure 2), line scan sensors build continuous images not limited in their vertical resolution. Vertical resolution comes from the object’s own motion. Instead of 1024x1024, they can produce 1024 x N, where N keeps growing as long as the camera is running. Perhaps the most common example of line scan imaging is the fax machine.

Figure 1: Line Scanning



Line scan imagers such as fax machines use a single line of sensor pixels to build up a two-dimensional image.

High sensitivity line scan sensors, using TDI technology, are another form of line scanning. TDI is a method of scanning which provides greater sensitivity than that available from other line scanning methods. It permits much greater scanning speeds with normal lighting, or allows reduced lighting levels (and costs) at conventional speeds. Figure 2 compares the architecture of an area array and line scan sensor.

Figure 2: Comparison of Area Array and Line Scan Sensor Layout

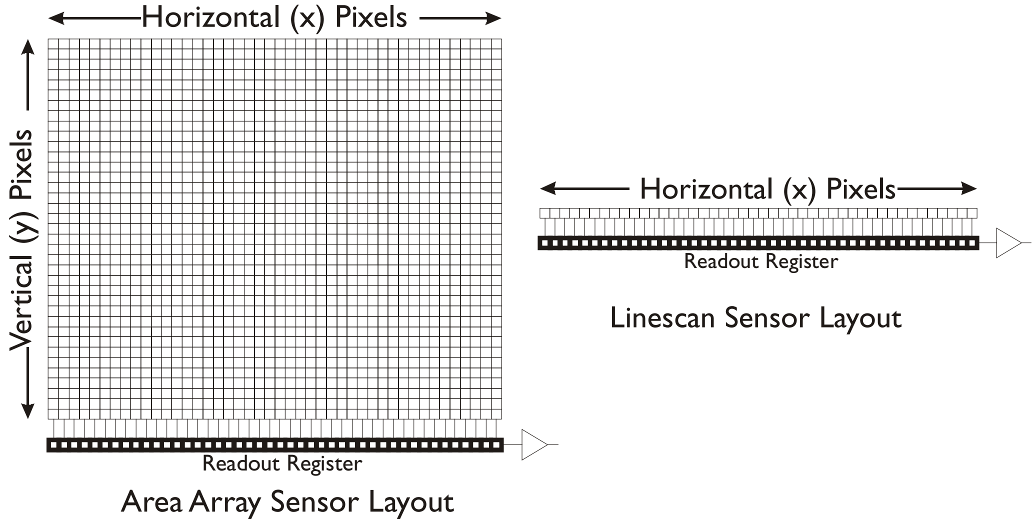
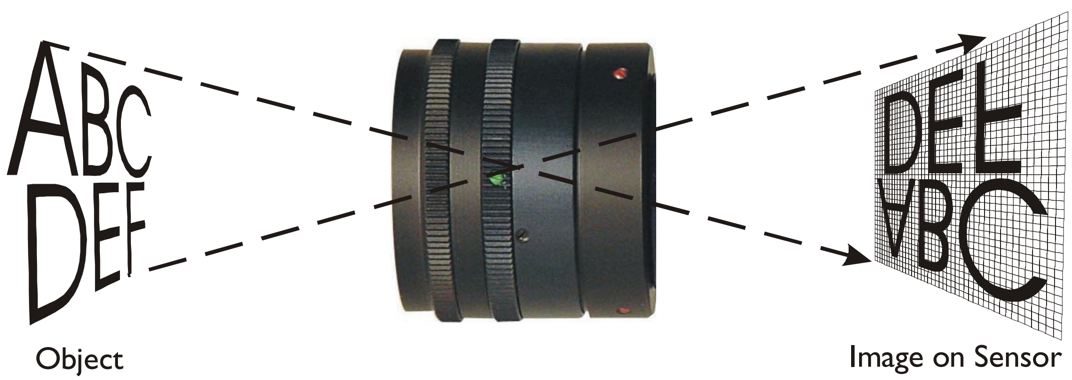


Image information is transferred out of the sensor through the readout register. Each type of sensor includes a readout register located just below the active pixel array. The readout register is positioned at the bottom of the array because the image of an object applied to the sensor is mirrored and flipped through the lens. Figure 3 illustrates this relationship.

Figure 3: Flip and Mirror Effect of a Lens



Area Array Frame Readout

Transferring image information out of a sensor takes time and is dependent on the camera resolution and internal timing signals. Figure 4 illustrates the readout procedure for an area array sensor.

Figure 4: Area Array Readout

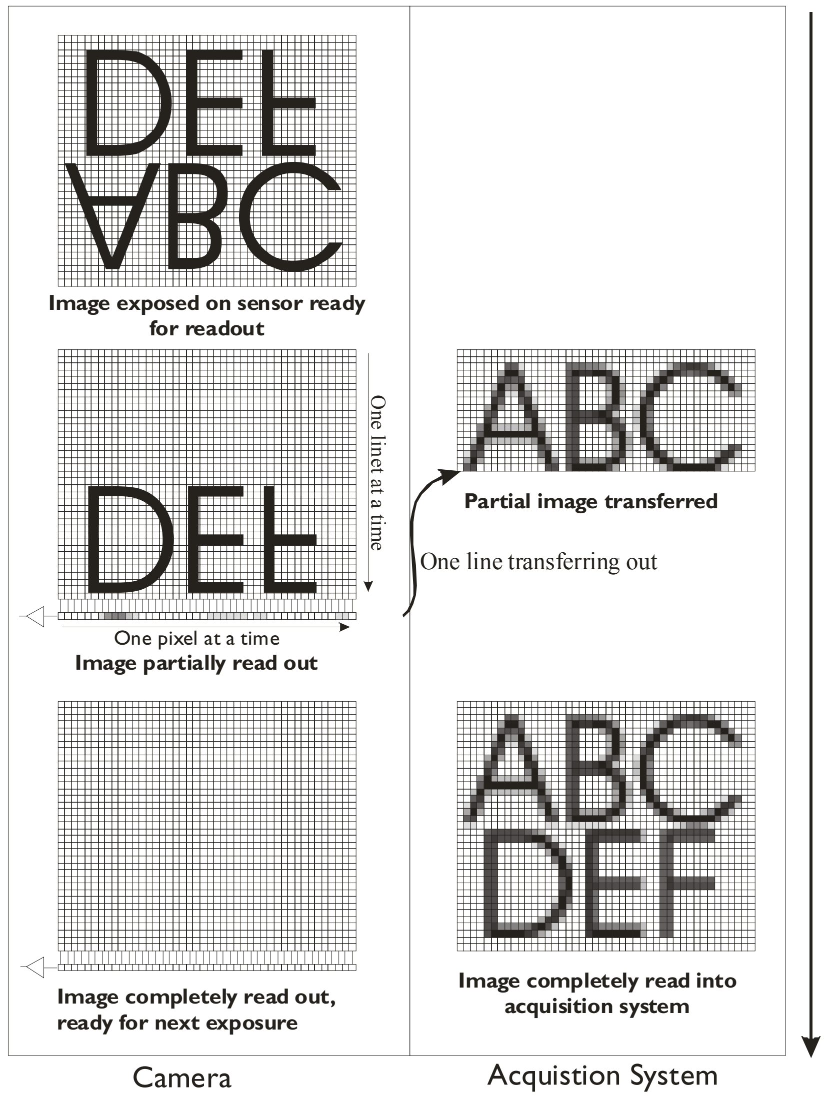
Readout Steps:

1. Transfer all of the image information down by one row in a parallel fashion, so that the lowest row is moved into the readout register.

2. Transfer each pixel horizontally out of the readout register one by one until all of the pixel information for the row has been moved out.

3. Transfer all of the remaining rows of information in the sensor down by one row again so that the next lowest row is moved into the readout register.

4. Repeat steps 2 and 3 until all rows of image data have been transferred.



This shows that the time required to move a complete image out of an area array camera is non-trivial. Also note that the sensor should not be exposed during the image transfer. In most cases, if the sensor continues exposing an image while transferring the current image, the image will be smeared—sometimes beyond usefulness. To eliminate image smear, you will need to make use of strobed lighting, shutters, and system timing.

Example

A camera with a sensor resolution of 1024 x 1024 and a pixel clocking set at 20 MHz would take approximately 52 milliseconds to read out an image. To calculate the time it takes to read out an image:

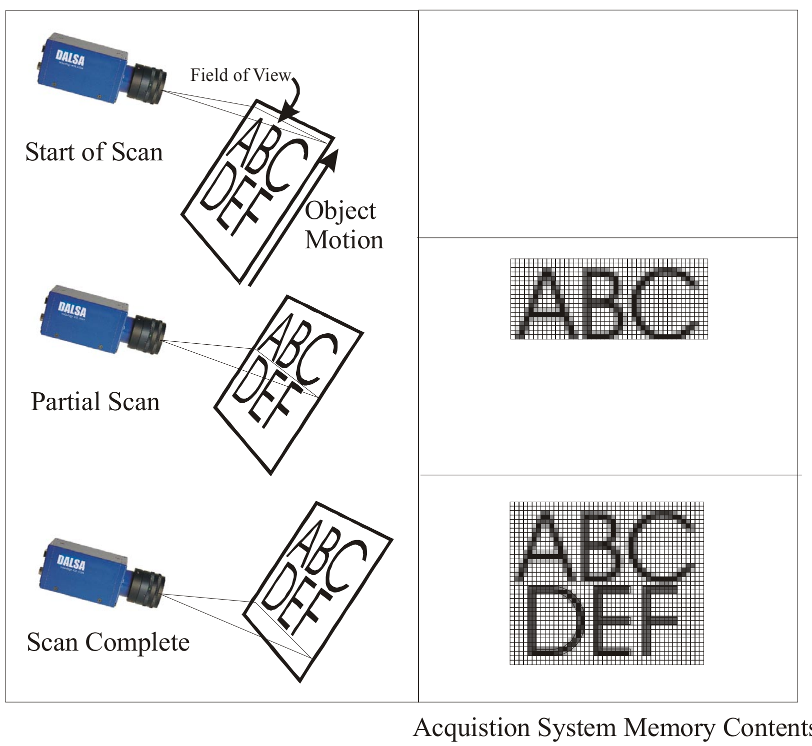
1. Take the horizontal resolution and divide by the pixel clock to get the time required to read out a single line. For this example, $1024/20x10^6$ = 51 microseconds.
2. Next, multiply this number by the vertical resolution (1024 in this case) to get the approximate time for the entire frame to be read out of the camera.

Generally, there will be some small amount of additional time required because of other camera timing constraints, but this method will give an approximate indication of the frame readout time. To calculate the frame rate, take the reciprocal of the frame readout time. For this example, the reciprocal of 52 milliseconds works out to be approximately 19 frames per second.

Line Scan Readout

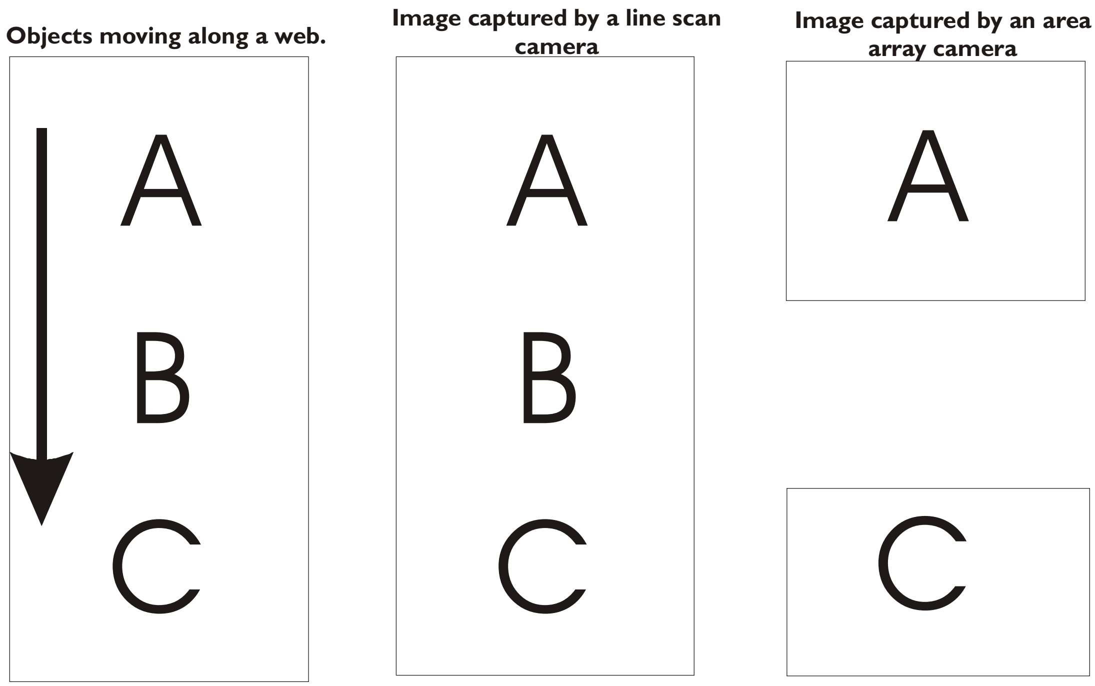
Line scan cameras output only a single line of pixels per exposure and therefore require much less time to transfer the sensor image information into the readout register than area array cameras. This is initiated by the application of a trigger pulse to the camera. The trigger pulse signals the end of the exposure period and the start of the readout period for the current line. The readout register is not responsive to light and the pixel information is then moved out of the camera a single pixel at a time. This completes the image output phase. While the readout occurs, the next exposure period occurs in parallel.

Figure 5: Line Scan Readout



A line scan camera holds an important advantage over full frame area array cameras. Unlike these area array cameras, a line scan camera can expose a new image while the previous image is still reading out its data. Once the pixel information from an exposure has been transferred to the readout register, the active pixels are available for the next exposure.

Figure 6: Area Array vs Line Scan Image Capture



The entire image is captured using a line scan camera because pixel readout is fast enough to allow the camera to continuously expose the image.

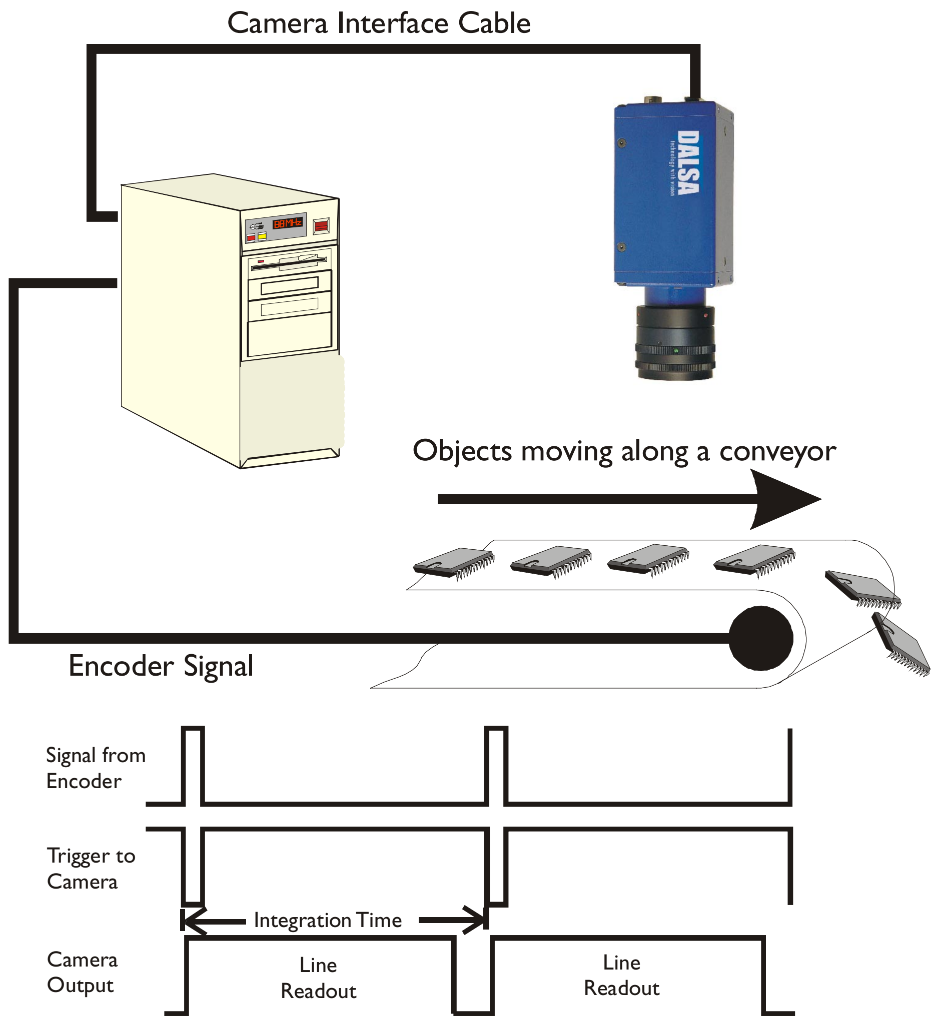
Full frame area array cameras cannot efficiently capture moving images because they are "blind" during readout. Notice above how the middle object has not been imaged. The camera was unable to capture this object because it could not expose another image until readout had finished. In this case, the missing object moved in front of the lens while the camera was still reading out the previous frame.

Line scan cameras require a moving subject in order to obtain an image. Synchronization of the movement between the object and camera is required to ensure a constant aspect ratio. The next section discusses synchronization in detail and provides an example application.

Line Scan Imaging

Most applications using line scan imaging will require synchronization between the moving object and the camera. Synchronization is often achieved with the use of an encoder.

Figure 7: Line Scan Camera with Encoder



Example Application using an Encoder

Determine the Smallest Feature Size

A system scanning 8.5 x 11 inch documents with a minimum resolution of 200 dots per inch, would require a pixel with a horizontal distance of 1/200 or .005 inches. This would be the smallest feature size of the object. In order to calculate the required camera resolution for this application, you take the field of view and divide by the smallest feature size (which in this case is 8.5 inches). The resulting calculation would be 8.5/.005 = 1700. Therefore, this application would need a camera with a resolution of at least 1700 pixels.

Choose Appropriate Camera Resolution and Recalculate Smallest Feature Size

Cameras are available with a variety of fixed sensor resolutions (none of which are 1700), so the best choice would be a camera with 2048 pixels. The 8.5 inches field of view will be applied across the 1700 pixels of the array and a minimum feature size of .005 inches will be maintained. Since the camera has an array of 2048 pixels there will be pixels on either side of the image which will extend beyond the field of view. This can be helpful in multiple camera systems where some degree of overlap may be necessary for alignment purposes.

Determine the Aspect Ratio

Since one pixel will represent .005 inches of horizontal object distance, it is necessary that one pixel also represents .005 inches of vertical object distance. This will ensure that the image is vertically and horizontally proportional to the object and that it will have the same aspect ratio. To achieve this, a synchronization signal must be sent to the camera for every .005 inches of vertical motion of the object. This is usually accomplished by incorporating an encoder into the system, which is connected to the drive system that forces the object to move through the field of view of the camera. Typical encoders are shaft mounted devices that rotate and provide a fixed amount of pulses per revolution.

Set up the Encoder

For this example, an encoder which provides 1024 pulses per revolution can be used. The encoder needs to be mounted somewhere in the system so that it can mechanically couple the encoder shaft directly to a part of the drive system. Through a system of gears/adapters/rollers/etc., the encoder has to produce a pulse for each .005 inches of object travel. One mounting possibility is to simply put a wheel on the shaft of the encoder. The wheel will ride on the surface of the conveyor that moves the documents through the camera field of view. To retain the aspect ratio of .005 x .005, the circumference of the encoder wheel would have to be 5.12 inches. This is calculated by multiplying the number of encoder pulses (1024) by the vertical object distance (.005).

Configure the Hardware and Software

The system now requires software and hardware to recognize when an object of interest has come into the camera field of view and also to determine when the object of interest has been completely scanned. Once an image of an object has been completely scanned, the system will then do some further image processing and also look for the next object of interest.

Camera Speed

System speed also needs to be considered. A standard DALSA SP-14-02k40 camera will operate at a maximum line rate of 18.7 KHz, or at a maximum of 18,700 lines per second. If you were to use this camera with this example application, where one line represents .005 inches, the system could run at a maximum object speed of 93.5 inches per second. The minimum line rate of the camera is 300 Hz, so the minimum system speed would be 1.5 inches per second.

The minimum line rate of a DALSA camera should not be less than specified. If a situation occurs where the system rate varies below the minimum speeds, then you need to ensure that the camera does not run at less than the specified minimum line rate. When a camera operates below the minimum line rate, a great degree of overexposure can occur in the sensor leading to oversaturation of the image. The sensor will need to read out several lines at a rate greater than the minimum in order for it to recover to normal operation. If the system is stopped for a period of time and then re-started, the initial lines from the camera will be useless, and it could take 10 to 20 lines before useful information is available from the camera.

In contrast, if the system is operating at a speed where the maximum line rate of the camera is exceeded then it will miss lines. The maximum line rate of the camera is determined by the amount of time it takes for the camera to send one line. If a trigger pulse is sent to the camera before it has finished sending the current line, then that trigger pulse is ignored. Once that camera has finished sending a line, it waits for a trigger pulse to initiate the transmission of the next line.

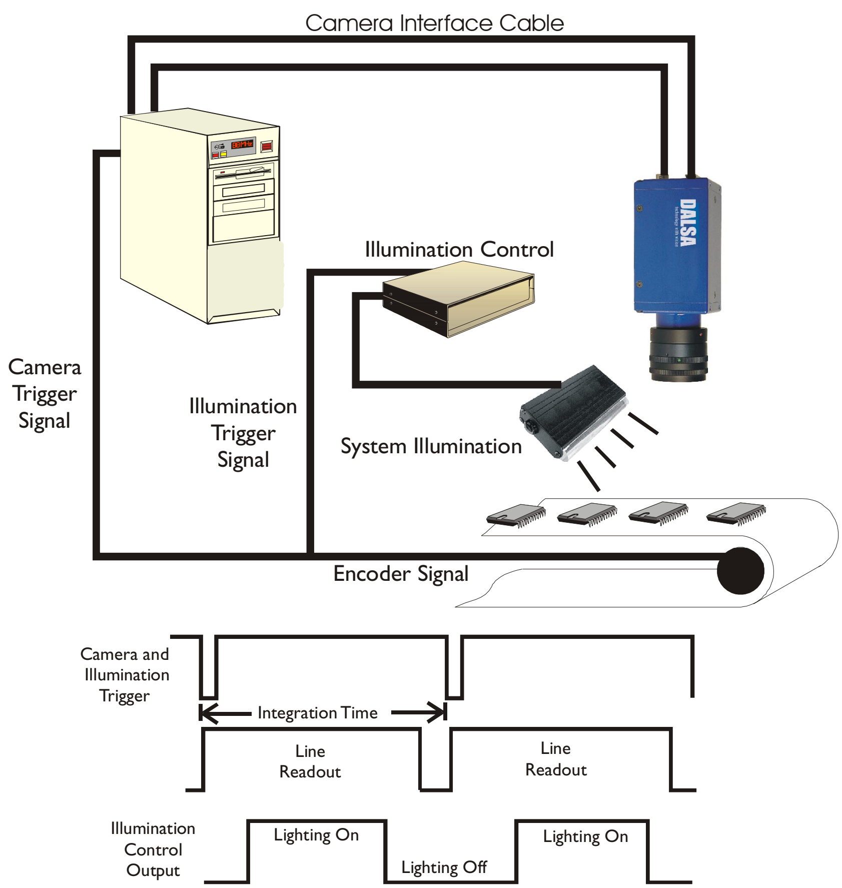
Exposure Control

Exposure is dependent on the time between individual encoder pulses. If the system is operating at a speed where the encoder is providing pulses at a rate of 1 kHz, then the camera exposure is operating at an integration time of 1 millisecond. Increasing the speed so that the encoder is operating at a rate of 10 kHz will reduce the exposure time to 0.1 milliseconds. When the system lighting remains at a constant level for all speeds, the images produced at 10 kHz will be 1/10 of the brightness that would be obtained when operating at 1 kHz.

You can also control camera exposure independently of the speed of the system. If a camera has exposure control, then it can be used to maintain a constant exposure time period for each line of the camera integration period. How the exposure control works is dependent on the camera model. Using this method, the system illumination would remain on and at a constant level.

You can also control exposure with illumination systems. This could involve a simple manual adjustment of the illumination intensity used in the system as the line rate changes, or it could incorporate some method of feedback to detect any speed change and automatically adjust the illumination intensity accordingly. Strobed illumination is another method of exposure control. This method requires sending a trigger pulse to an illumination system so that objects are illuminated during the exposure period of the camera and the illumination is on for a predetermined amount of time.

Figure 8: Controlling Exposure with Strobed Illumination

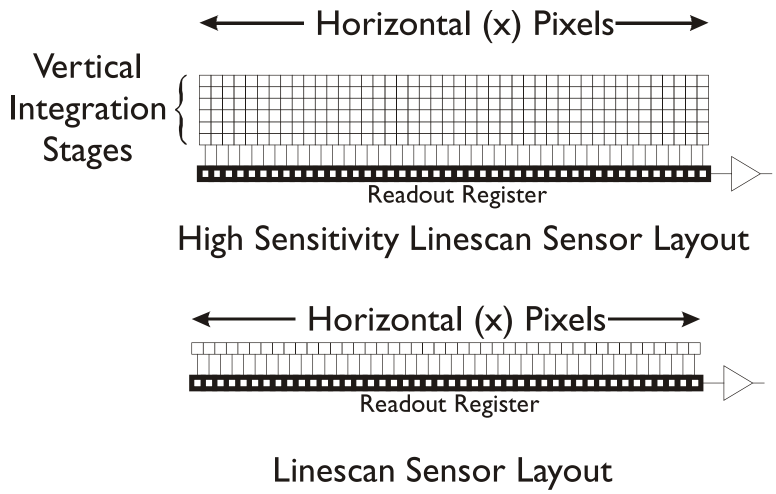


High Sensitivity Line Scan

A variation of line scan cameras available from DALSA are high sensitivity line scan cameras, which are also referred to as TDI (Time Delay and Integration). In operation, they are virtually identical to standard line scan cameras; however, they are much more responsive to light.

This increased sensitivity results from the sensor structure and timing method used to acquire images. With a standard line scan camera, a single line of an object is integrated and then sent from the camera to the acquisition system. When the next line of the object comes into the field of view of the camera, it is integrated and likewise sent out of the camera. Each line of the object is integrated once. Using high sensitivity line scan, each line of an object is integrated multiple times and the result is a summation of all line integrations. The amount of increased sensitivity is dependent on the number of vertical rows over which a line is integrated. The quantity of rows is normally termed as the number of integration stages of the camera, which come in a variety of resolutions, such as 96, 48, 24, etc. stages. Some cameras, such as the DALSA EC-11-xxx40 are fixed to 96 stages of integration, where others such as the CT-E4 camera are stage selectable to various numbers of stages.

Figure 9: Comparison of High Sensitivy and Line Scan Sensor Structure



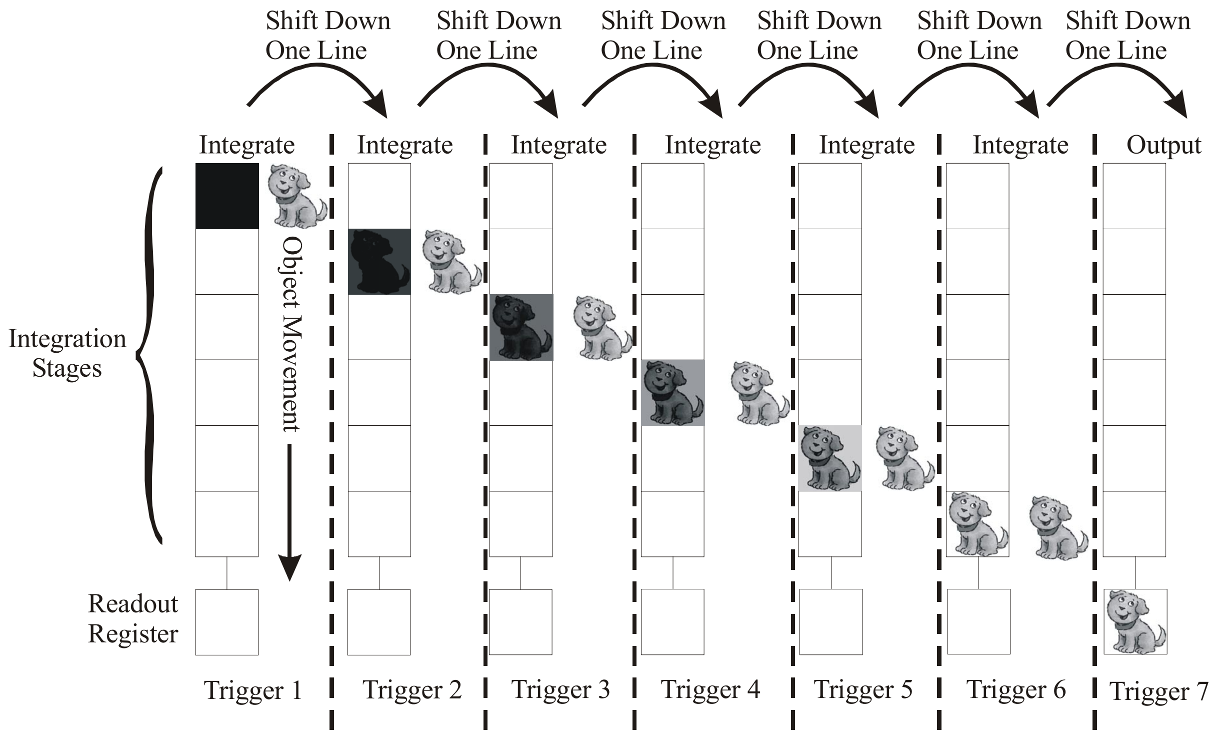
When a standard line scan camera is triggered to send a line, the first thing that happens is that all of the pixels are moved into the readout register. Following that, the contents of the readout register are moved out of the sensor one pixel at a time. During this readout phase the active pixels are integrating the next line of the image. Once the pixel information has been read out of the sensor, that line of information is gone. The next time the camera is triggered, the next line is moved into the readout register and then read out.

When a high sensitivity line scan camera is triggered, the pixel information of all the rows is transferred down by one row. This places the contents of the lower most row into the readout register. The readout register contents are read out one pixel at a time and integration of the above rows takes place. Once the readout register has been completely read out, another trigger to the camera again shifts the contents of all the rows down by one row and then readout is initiated. This shifting of rows down by one with subsequent integration and then shift again followed by integration, etc. is the method used to accomplish very high camera sensitivity.

Synchronization of the object movement to the camera is mandatory for imaging with a high sensitivity line scan camera. The reason is that as the object moves through the field of view of the camera, the line which is being imaged must be coincident with each stage of the sensor array for each application of the camera trigger. In this way, the camera obtains multiple exposures of the same point in the object until that exposure is transferred into the readout register.

The diagram in Figure 8 describes the effect of time delay and integration as it applies to high sensitivity line scan cameras. The figure shows that as the object moves through each stage, the sensor is synchronized so that integration occurs when the stage is aligned with the object. Once a stage of integration is complete, the contents of the pixel are transferred down by one row where they again coincide with the location of the object where further integration occurs. The sequence continues until the image of the object reaches the readout register.

Figure 10: Time Delay and Integration Effect



Special Considerations for High Sensitivity Line Scan

High sensitivity line scan cameras require some additional consideration when used in an imaging system. It is very important that the sensor is aligned perpendicular to the direction of motion of the object. The portion of an object which is imaged in a pixel at the first stage of integration must also be imaged in the same column at the last stage of integration, otherwise blurring of the image will occur.

The direction of an object with respect to the direction of stage integration within the camera is also important. You need to take into account the flip and mirror effect of the lens to ensure that as an object is moving through the field of view of the camera that the direction is the same as the sensor integration direction. High sensitivity line scan cameras are available with selectable forward/reverse integration direction or single direction integration.

The type of lens and working distance from the camera to the object also require special consideration as it is necessary to have the vertical object resolution equal to the horizontal resolution in order to obtain an accurate image. In other words, if a system is required to image objects where one pixel represents a certain amount of inches horizontally, then the system must also ensure that each line acquired from the system represents the same amount of inches vertically.

One of the disadvantages of high sensitivity line scan cameras is that there is no method of exposure control enabled within the camera. If a system design dictates that constant exposure is required where line speed variations or fluctuating illumination occurs, then some method of controlled exposure must be incorporated. This can generally be achieved with some type of strobed illumination, and because of the high sensitivity of the camera, LED illumination systems can be reliably used. For further information on using strobed LED illumination with high sensitivity line scan cameras, refer to DALSA document 03-32-00540.

Summary

When choosing a camera for your application, it is important to understand which type of camera most effectively meets your imaging requirements. As this application note has explained, area array cameras are a good choice for capturing still or slow moving objects, while line scan cameras are a good choice for capturing smear-free images of fast moving objects. DALSA has a long history of industry-leading line scan products. We offer standard resolutions from 512 to 8192 pixels, single or multiple outputs, color products, antiblooming, exposure control, 100% fill factor, and a host of other features that high-performance line scan applications demand.