DALSA
technology with vision

Advantages and Disadvantages of Various CCD Area Array Sensors

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Purpose

The purpose of this document is to:

1. Discuss the advantages and disadvantages of the Interline Transfer, Full Frame, and Frame Transfer sensor types:

2. Discuss the advantages of 100% fill factor on image quality, aliasing, and sub-pixel interpolation.

3. Explain how the exposure control feature can be used to achieve fast shutter speeds.

4. Explain how image quality can be improved on fast shutter speed images through the use of mechanical shutters or strobed light sources.

Overview

There are several different options when it comes to choosing an area array sensor technologies, but which one is the best? The answer depends on the application. For applications that do not require a 100% fill factor an Interline Transfer sensor may be the most cost effective and simplest choice. Interline Transfer sensors are found in pick and place machines, printed circuit board inspection or wire bonding applications. For applications that require higher performance and 100% fill factor there are two choices; Frame Transfer and Full Frame sensors. Typical applications that require 100% fill factor are found in medical imaging, semi-conductor wafer alignment, and light starved applications where photons are at a premium. This paper will help to decide which sensor technology is suitable for the application at hand and the tradeoffs associated with these technologies.

Interline, Full Frame, and Frame Transfer Sensors

A. Interline Transfer

The most common type of area array sensor architecture used in the industry is Interline Transfer (ILT). Interline transfer devices are suitable for most low-end applications and are primarily used in RS-170 cameras, which are mainly used for video applications such as those found in camcorders or CCTV systems. As a result, the resolutions of ILT sensors are generally tied to the RS-170 video format, which results in limited sensor resolutions and options.

How Interline Transfer Devices Work

Between columns of pixels on the sensor there is a storage column. The sensor integrates a frame of data and then quickly transfers it to the storage column where it is then shifted down one row at a time to the horizontal shift readout register (also known as an HCCD or CCD for short).

Advantages

The advantage of this type of architecture is that very short integration times can be achieved without the image smearing as a result of the very quick transfer of the signal charge to the light shielded storage column. Since ILT cameras account for approximately 90% of the vision industry they can take advantage of the economy of scale and are typically a much cheaper type of technology when compare to other types of sensors.

Disadvantages

The major disadvantage of ITL devices are that they suffer from poor fill factor (approximately 30%—See figure 1). Fill factor is the percentage of area of a pixel that is actually light sensitive. This 30% typical fill factor can be increased to up to around 60% through the use of a micro-lens. A micro-lens is a layer of miniature lenses placed on top of individual pixels that takes the light from the non-sensitive areas and focuses it onto the active area of the pixel.

ILT devices are not suitable for many high-end applications because details can literally fall between the cracks. In applications where sub pixel interpolation is being performed, 100% fill factor is critical since any aliased information will dramatically throw off the interpolated values being calculated. This is shown below in the aliasing example. Utilization of 100% of the incident photons is critical in photon-starved applications such as medical imaging, where each additional photon comes at a price of patient radiation exposure. DALSA progressive scan cameras do not use ILT sensors.

Figure 1: Interline transfer sensor architecture.
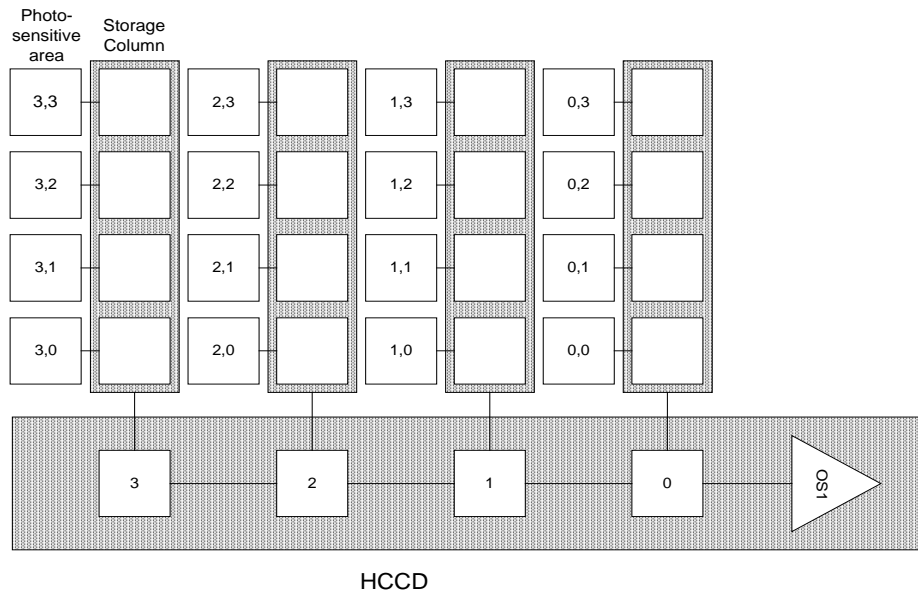
B. Full Frame

Full Frame sensors differ from the Interline transfer devices in that they do not have a storage column where the charge is transferred before readout from the HCCD.

How Full Frame Sensors Work

The entire imaging region of a full frame sensor is photosensitive. This translates into a 100% fill factor. The charge gets transferred down to the HCCD one row at a time where the row is then read out serially until all of the rows have been read out (See figure 2.).
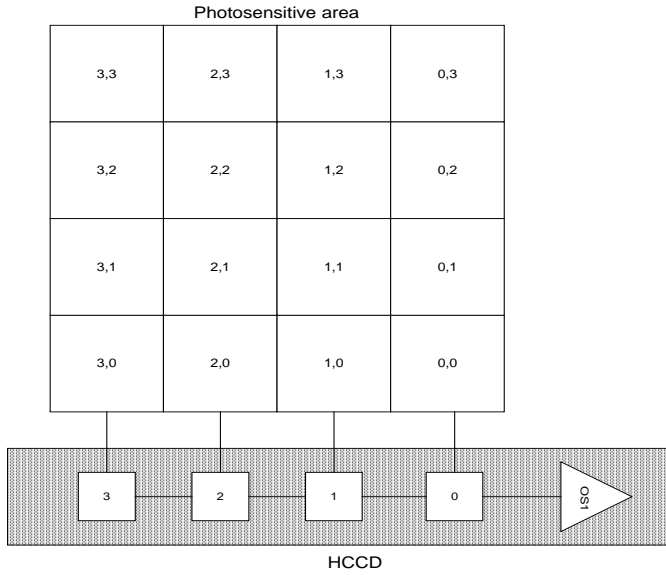
Advantages

As a result of the 100% fill factor full frame sensors provide greatly reduced aliasing and since 100% of the silicon is able to capture incident light it is an extremely effective use of the silicon. Because frame transfer devices utilize the silicon area so well they are typically used for sensors with larger pixel arrays (>1kx1k pixels). Full frame sensors and cameras are not tied to the RS-170 timing standard and are thus available in a wide array of resolutions (<64x64 pixels to >4k x 7k pixels) and output formats (anywhere from single output to four outputs and higher). The timing of the full frame sensors can be very flexible offering frame rates of less than 1 frame per second to integration times of less than a millionth of a second. This is called progressive scan.

Disadvantages

In general, the light to the sensor needs to be blocked during frame readout, either with a shutter (mechanical/LCD) or by strobing the light source. Some applications do not permit the use of a strobed light source (such as imaging of the Earth's surface, astronomy etc.). Additionally, some applications do not permit the use of shutters because of the limitations of the shutters. LCD shutters do not allow 100% of the light through when they are open and do not block 100% of the light when they are closed. Mechanical shutters can take milliseconds to open and close, which is fine when working with long integration times, but is unacceptable for the very short integration

times commonly used in machine vision. A shutter or strobed light source is not necessary with full frame sensors if the integration or frame time is sufficiently longer (>10x) than the frame readout time. Currently some DALSA products use full frame sensors to take advantage of the large array sizes.

Figure 2: Full Frame sensor architecture.

Photosensitive area

3,3	2,3	1,3	0,3
3,2	2,2	1,2	0,2
3,1	2,1	1,1	0,1
3,0	2,0	1,0	0,0

| 3 | 2 | 1 | 0 | OS1 |

HCCD

C. Frame Transfer

The technology that is currently used in the majority of DALSA pogressive scan cameras is Frame Transfer.

How Frame Transfer Works

In a 1k x 1k sensor there are 1024 x 1024 pixels where the charge is accumulated during the integration period. The charge that gets accumulated in the imaging region is then transferred at high speed to the storage region which is an additional 1024x1024 region that is not light-sensitive. From there the frame gets read out one row at a time (similar to full frame sensors) while the next frame is being integrated.
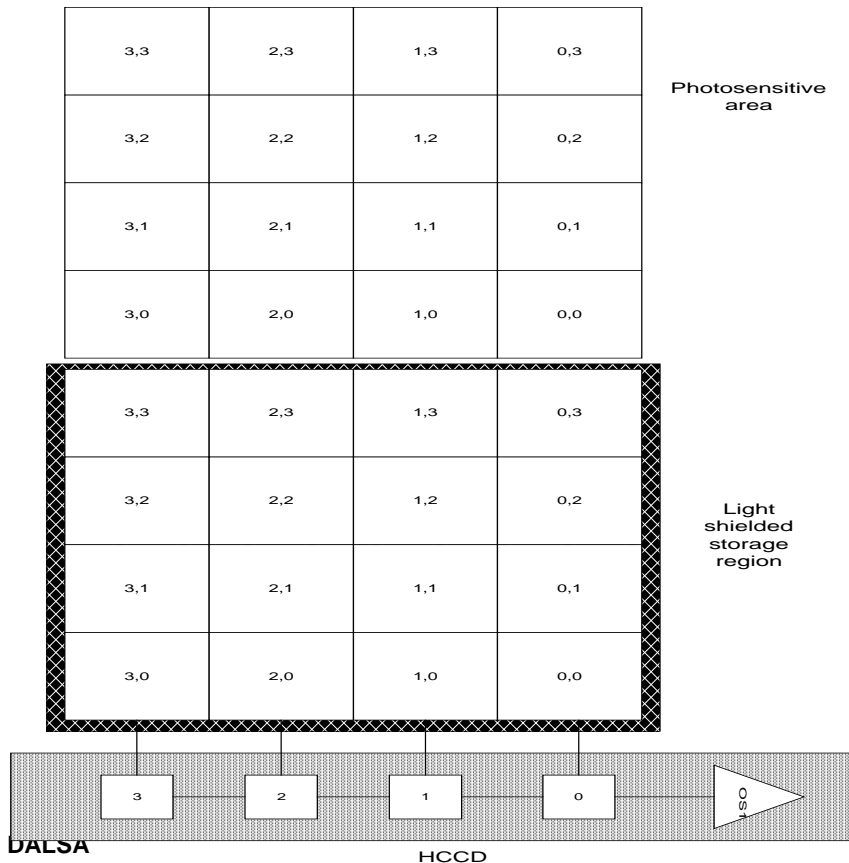
Advantages

Frame transfer cameras have all of the advantages of Full Frame cameras plus they have the additional benefit of not requiring shuttering or strobing of the incident light. Frame Transfer provides a 100% fill factor that utilizes 100% of the incident light, and provides reduced aliasing (see the aliasing example in Appendix C).

Disadvantages

The major disadvantages to this technology is that twice as much silicon is needed as full frame sensors, and the image smear that can be associated with the frame transfer.

Frame transfer technology is normally not used for very large array sizes. The amount of silicon required is double that of a Full frame device leads to higher cost and lower yields since there would be a greater chance of having a defect with a larger area.

Figure 3: Frame transfer sensor architecture.

3,3	2,3	1,3	0,3
3,2	2,2	1,2	0,2
3,1	2,1	1,1	0,1
3,0	2,0	1,0	0,0

Photosensitive area

3,3	2,3	1,3	0,3
3,2	2,2	1,2	0,2
3,1	2,1	1,1	0,1
3,0	2,0	1,0	0,0

Light shielded storage region

| 3 | 2 | 1 | 0 | OS |

HCCD

Effect of 100% Fill Factor on Image Quality, Aliasing, and Sub-pixel Interpolation

A sensor with less than 100% fill factor will not have the same quality image as one with 100% fill factor. The reason for this is that some of the photons that hit the sensor will fall onto the non-photosensitive region of the sensor and some of the photons will hit the photosensitive region of the sensor. The photons that hit the non-sensitive region can be thought of as lost pieces of the image. At lower spatial frequencies all of the information necessary to reproduce the image will be present, but as the spatial frequency increases (finer details) the lost piece of information might mean missing critical information altogether. This is known as aliasing and will affect the camera's ability to image small defects in a material. The resulting image could be unacceptable in certain applications such as medical imaging. To overcome this deficit more pixels are needed in the field of view so that information is not lost. For an example of aliasing see Appendix C.

When a great deal of positional accuracy is required a technique known as sub-pixel interpolation is often used. Sub-pixel interpolation is when a pixel or a group of pixels is used to very accurately determine position. When an object is imaged and it's edge occurs on the boundary between 2 pixels one will be dark and the next one will be bright and thus it will be very easy to determine exactly where the edge of the object is. If the edge of the object moves and its boundary occurs in the middle of the pixel you could expect that pixel to be around 1/2 saturation. The exact position of the edge of the object can still be determined by looking at the level of this pixel which will tell you how much of the pixel is covered by the edge of the object and thus where this edge occurs. By using a group of pixels the accuracy of the interpolated value can be greatly improved. If a sensor did not have a 100% fill factor the interpolated value would be thrown off considerably making it virtually impossible to do sub-pixel interpolation.

Using Exposure Control to Achieve Fast Shutter Speeds

Frame Transfer sensors do not require shuttering because the amount of time it takes to transfer the charge to the storage region is typically less than 10% of the frame period and therefore the image smearing will be less than 10% (see Appendix A). There are of course some exceptions to this that should be taken into consideration. If the Pixel Reset Input (PRIN) signal is used to shorten the integration time (also known as exposure control mode) then the amount of smearing increases. For example, if the time it takes to move the charge from the imaging region to the storage region is 1ms and PRIN is used so that the integration time is only 1ms, then a 100% smearing would occur and the image would be useless (see Appendix B). In this case it is necessary to use a strobed light source to turn off the light while the image is transferred to the storage region. The following formula can be used to help decide when a shutter or strobed light source is required.

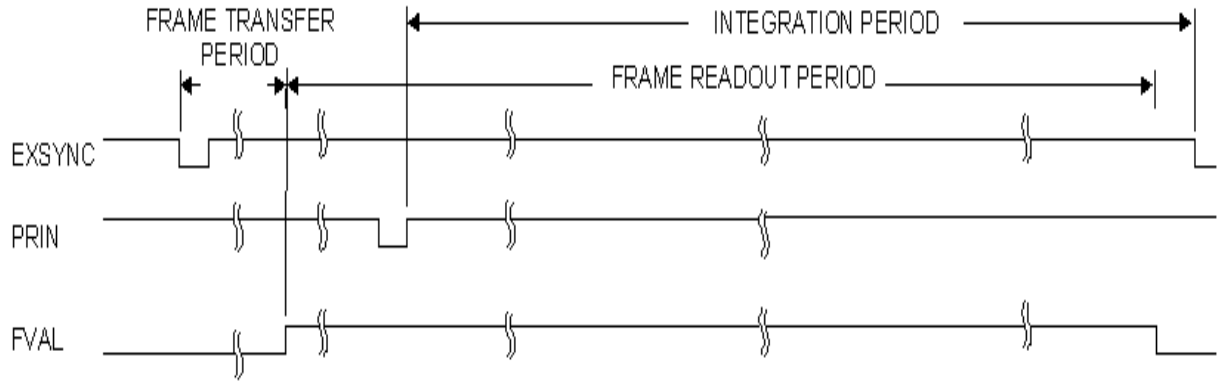Percentage of image smear = (frame transfer time/Integration time) *100%.

Figure 4: Exposure control mode timing diagram

Why would you want to use the PRIN signal when you know it will increase the percentage of smear in the image?

The PRIN signal is useful when using an area camera in an application used to image an object in motion, or to image an event of very short duration. If the object being imaged moves during the integration of the frame then the image will be blurred. Reducing the integration time will proportionately reduce the amount of blurring in the image. This can be accomplished in two ways. The first is to run the camera at a faster frame rate and the second is to use the PRIN signal. The camera will only integrate charge when the PRIN signal is high, therefore by changing the duty cycle of the PRIN signal the integration of the camera can be controlled independent of the camera's frame rate.

If the duration of the event being captured is much shorter than the frame readout time then the ambient lighting will contaminate the image. In this case the PRIN signal can be used to shutter the ambient light to the camera and thus give a clearer image.

Summary

The choice as to which type of sensor technology to use for an application is strictly dependent upon the application at hand. Though one thing is clear, 100% fill factor is critical for getting the best possible images required by most high end imaging applications.

Recommended Exposure Times for Area Scan Cameras

Based on the frame transfer times of various DALSA area scan cameras, it is recommended that the minimum integration time be not less than 10 times the frame transfer time.

Camera	Resolution	Data Rate	Frame Transfer Time	Frame Readout Time (no pretrigger)	Minimum Exposure Time	Notes
CA-D1 STD A	64	16 MHz	20 µsec	320 µsec	200 µsec	
	128	16 MHz	40 µsec	1.15 msec	400 µsec	
	256	16 MHz	80 µsec	4.35 msec	800 µsec	
CA-D1 STD T	64	8 MHz	40 µsec	640 µsec	400 µsec	
	128	8 MHz	80 µsec	2.3 msec	800 µsec	
	256	8 MHz	160 µsec	8.7 msec	1.6 msec	
CA-D1 R01 A	128	15 MHz	44 µsec	1.31 msec	440 µsec	no binning
	256	15 MHz	87 µsec	4.81 msec	870 µsec	no binning
	128	15 MHz	44 µsec	657 µsec	440 µsec	2x2 binning
	256	15 MHz	87 µsec	2.41 msec	870 µsec	2x2 binning
CA-D1 R01 T	128	10 MHz	66.9 µsec	1.97 msec	669 µsec	no binning
	256	10 MHz	131 µsec	7.22 msec	1.31 msec	no binning
	128	10 MHz	66.9 µsec	985 µsec	669 µsec	2x2 binning
	256	10 MHz	131 µsec	3.61 msec	1.31 msec	2x2 binning
CA-D4 A	1024	25 MHz	1.021 msec	46.1 msec	10.21 msec	1 channel, no binning
	1024	25 MHz	1.021 msec	23.5 msec	10.21 msec	1 channel, 2x2 binning
	1024	25 MHz	1.021 msec	23.8 msec	10.21 msec	2 channels, no binning
	1024	25 MHz	1.021 msec	12.4 msec	10.21 msec	2 channels, 2x2 binning
	1024	20 MHz	1.265 msec	57.6 msec	12.65 msec	1 channel, no binning
	1024	20 MHz	1.265 msec	29.4 msec	12.65 msec	1 channel, 2x2 binning
	1024	20 MHz	1.265 msec	29.8 msec	12.65 msec	2 channel, no binning
	1024	20 MHz	1.265 msec	15.5 msec	12.65 msec	2 channel, 2x2 binning

CA-D7 T	1024	10 MHz	2.531 msec	115 msec	25.31 msec	no binning
	1024	10 MHz	2.531 msec	58.8 msec	25.31 msec	2x2 binning
CA-D6 W	256	25 MHz	61.7 μsec	961 μsec	617 μsec	
	512	25 MHz	285 μsec	3.48 msec	2.85 msec	
CA-D8 W	512	25 MHz	419 μsec	12.4 msec	4.19 msec	
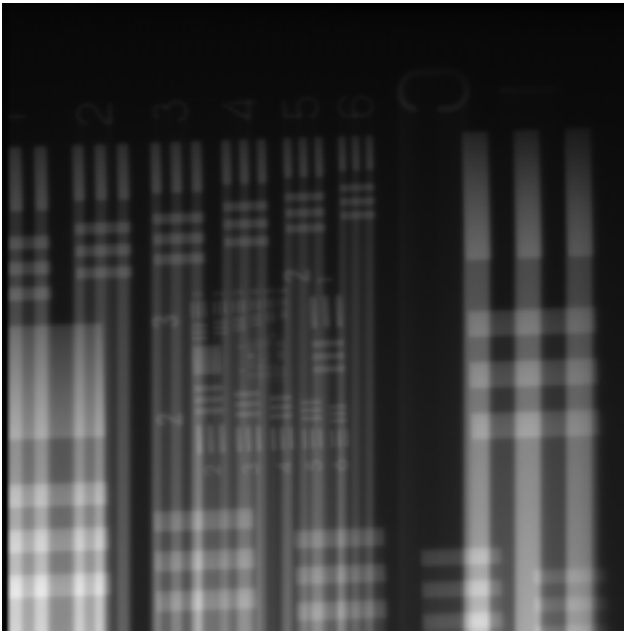
Figure 5.

Figure 5. is an image of a test pattern taken from a CA-D4-1024A camera with a 1.0 millisecond integration time. The frame transfer time is 1.021milliseconds which represents a 102.1% smeared image (1.021/1.0*100%). In this example a strobed light source must be used to get a useful image.

Figure 6.

Figure 6. is an image of a test pattern from a CA-D4 camera with a 50mS integration time. The frame transfer time is 1.68mS, which represents a 3.36% smear and is not noticeable in this image.
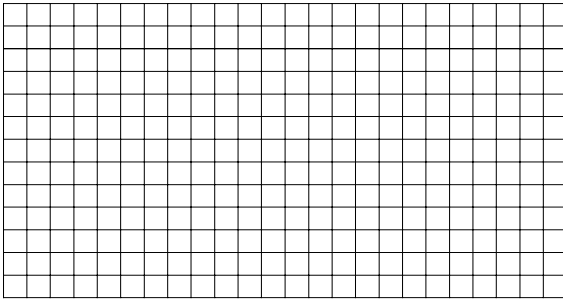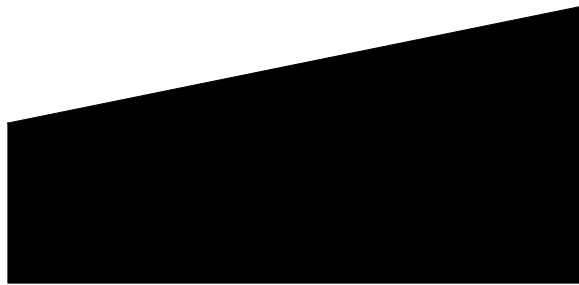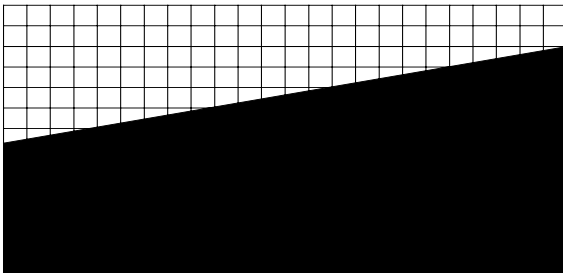
1. 100% Fill Factor Pixels
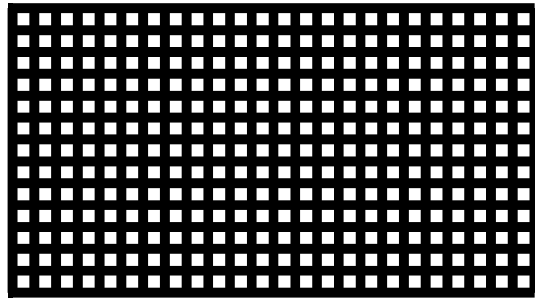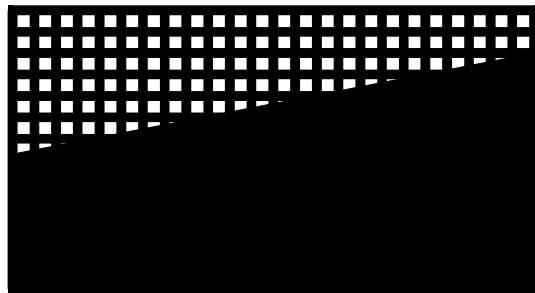

2. 30% Fill Factor Pixels
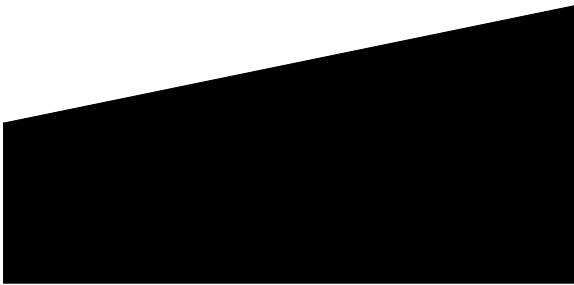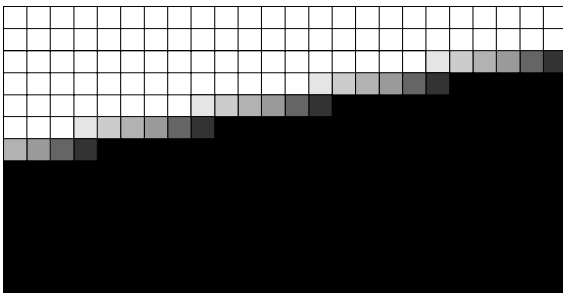

3. Object you want to image
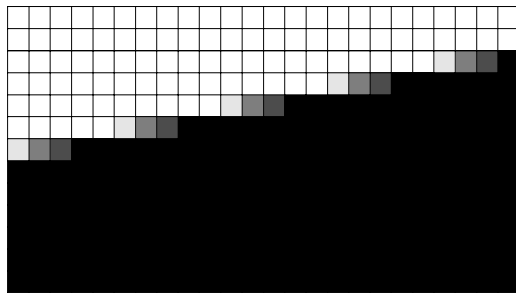

4. Object you want to image

5. Image projected on 100% fill factor sensor

6. Image on 30% fill factor sensor

7. Image from the sensor

8. Image from the sensor

As can be seen from image 7 and 8 the diagonal edge is clearly better defined with the 100% fill factor sensor. Image 8 shows a much courser stair step pattern. If sub pixel interpolation were being done which relies on the gray scale level of individual pixels then image 8 would provide an inaccurate measurement.