linearity

Linearity as it relates to digital image sensors refers to the relationship between incoming light and the output signal. This signal can be in analog or digital form after the primary light to charge conversion. High performance image sensors exhibit a high quality of linearity, whereas their predecessor video CCD based and other solid-state image sensors do not. Excellent linearity is particularly important in quantitative imaging for ratio calculations, flat field corrections and linear transformations that mandate these camera systems to be linear.

1 linearity – measurement

The following series of images were taken with a 12 bit camera system using exposure times of 1ms, 10ms, 100ms and 500ms. The left images illustrate individual images scaled to maximum (gray levels of 0-255 correspond to 0-4095 counts). The images below show each image individually scaled to minimum-maximum level (gray levels of 0-255 correspond to full-scale ranges).

Figure 1
Left image: scaled to full scale 0 - 4095 => 0 - 255
Right image: scaled to minimum - maximum 53 - 75 => 0 - 255
exposure time = 1ms, the white rectangle shows the position and size of the area, which was used to calculate the values for the graph in figure 5.

Figure 2
Left image: scaled to full scale 0 - 4095 => 0 - 255
Right image: scaled to minimum - maximum 62 - 190 => 0 - 255
exposure time = 10 ms (for white rectangle see legend figure1)

Figure 3
Left image: scaled to full scale 0 - 4095 => 0 - 255
Right image: scaled to minimum - maximum 167 - 1400 => 0 - 255
exposure time = 100 ms (for white rectangle see legend figure1)

Figure 4
Left image: scaled to full scale 0 - 4095 => 0 - 255
Right image: scaled to minimum - maximum 604 - 4095 => 0 - 255
exposure time = 500 ms (for white rectangle see legend figure1)

2 linearity – evaluation

There is the EMVA 1288 standard which defines how to measure the linearity values of a digital image sensor or a camera system.
The graph in figure 5 shows the average intensity vs. exposure time for the values from the image in the previous example. The resulting values are averaged over a 20x20 pixel area indicated by the small white frames in the images in figure 1 - 4. The solid line in figure 5 illustrates the regression fit whose values are given in the legend of figure 5.

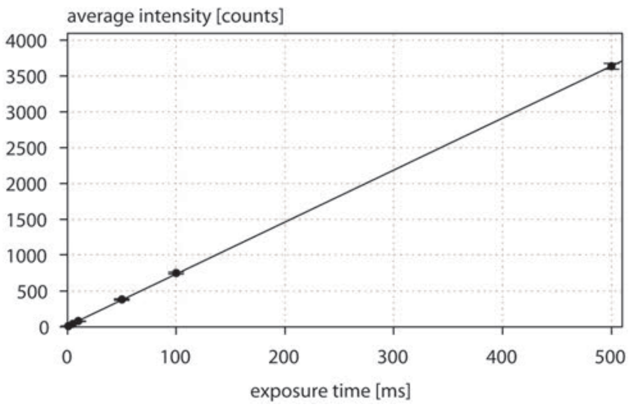

Figure 5
Values of the linearity measuring sequence of figure 1 - 4 and linear regression of these values:
Assuming the intensity is described by: intensity = m * t + n, m = 7.26, n = 6.77 and r^2 = 1.000

linearity

As shown in figure 5, one option to determine linearity is to compare the mean signal values and the exposure time over full dynamic range. Further data analysis using a linear least-square regression provides a measure for camera system non-linearity.

table 1: linearity results & regression fit

exposure time	signal [counts]	regression [counts]	deviation [counts]
1 ms	8.4	14.0	- 5.6
5 ms	38.2	43.1	- 4.9
10 ms	76.3	75.2	+ 1.2
50ms	375.3	369.7	+ 5.6
100 ms	745.0	732.7	+ 12.3
500 ms	3632.0	3636.3	- 4.3

The following equation evaluates the non-linearity of the camera system in the above examples, resulting in a non-linearity of 0.4%.

$$\text{non-linearity} = \frac{(|+\Delta_{max}| + |-\Delta_{max}|)}{\text{maximum}} \cdot 100\,\%$$

{ $+\Delta_{max}$ = maximum positive deviation, $-\Delta_{max}$ = maximum negative deviation, maximum = maximum signal}

Non-linearity has numerous origins, many of which are based on the camera system's settings and adjustments. As a major objective in camera system design is the use of the maximum possible dynamic, manufacturers strive to use the image sensor range of zero to full well capacity as the camera's performance range. However, as full well capacity is reached, the CCD image sensor starts to become non-linear because of saturation phenomena. There are also CCD image sensor control voltages that impact linear performance. The performance of the output amplifiers is as well critical for measurements above noise level. Therefore the optimization of a camera system is a complex process.

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