Dynamic Noise

Image Processing Basics: Sensitivity

What is the irradiance needed to produce a camera signal suitable for image processing? What are the maximum and minimum intensities in the brightest and darkest areas of an image, respectively, which will allow for stable algorithms? When tackling these questions, you will immediately realize that a short glance at a data sheet will not settle this case. The article describes some basic concepts which may be helpful for further reading [1] about this complex topic.

Sensitivity

The signal in CCD and CMOS sensors is generated by the internal photoelectric effect. Photons from the incoming flux of light release electrons within a detector pixel. The probability for this process is called quantum yield or quantum efficiency. The quantum yield depends upon the wavelength of the incoming radiation. Camera chips thus are not sensitive to the power or energy of the radiation, but to the number of single photons N_{ph}, which hit the detector during the integration time interval. The source signal is the number of photoelectrons N_e which are generated in a pixel during the shutter time and are stored at this detector site, hence a charge. This charge will be read out and results in a voltage, which in turn will be converted to a grey level by an analog-to-digital converter. The factor $K = g/N_e$ is called output conversion gain and is an important figure of merit for a camera. To aid the reader the pseudo-unit "DN/e$^-$" is added to the number, "digital numbers per electron," that is grey levels per electron. The value $K = 0.25$ DN/e$^-$, e.g., shows that four signal electrons are converted to one grey level step. A constant value for K in the full range of the camera signal means a very good performance of the electronic signal path. Cameras with significant deviations from this ideal, however, are out there. When, as a second quantity, the quantum yield is specified, the number of photons required to produce a certain grey level in the digital signal may be calculated. On the other hand, the grey level to be expected may be estimated from the radiation flux which hits the pixel and from the shutter time by calculating the number of incoming photons [2]. As a measure for sensitivity the ratio s between the grey level and the number of incoming photons may be specified, the unit being DN/photon. An alternative is the grey level related to the cumulative energy of the incoming photons during integration time, resulting in a sensitivity figure associated to the unit DN/J or, if

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more suitable, normalized to the unit cell size, DN/(J/m²). An application specialist who wants to estimate a grey level signal from the information given in a data sheet thus will be grateful to read a number for the unit cell size, for the absolute spectral sensitivity with one of the units DN/photon, DN/J or DN/(J/m²) and for the corresponding wavelength of the radiation used to determine these values. In addition, the wavelength dependence of the sensitivity or of the quantum yield must be given, at least in relative units. As an alternative, the two quantities quantum yield and output conversion gain K with the unit DN/e⁻ will be helpful.

Dark Signal and Full Well Capacity

Even in a capped camera, with no light shining on the detector array, electrons are released and stored in a pixel during the integration time. This dark signal is generated by thermal effects within the detector material and may only be reduced by cooling. There is no means to discriminate between signal electrons and dark electrons, they look perfectly alike. The total signal thus will be the sum of the dark signal and the photo signal, $N_{total} = N_e + N_{dark}$. A single detector pixel, however, has a limited capacity for signal electrons, the so-called "full well capacity" FW. In standard cameras, the maximum shutter time is determined by the frame rate, and the dark signal under these circumstances will be far below the saturation limit. In any case, however, the dark signal will reduce the signal range available for the photo signal. As an example, a dark signal of 4,000 electrons in a pixel with 16,000 electrons FW will reduce the range fort the photo signal to 12,000 electrons only. With K = 0.25 DN/e⁻, e.g., the full range of 4,000 grey levels, corresponding to a 12bit-signal, is reduced to 3,000 grey levels for the photo signal. As a consequence, low light intensity in a scene may not just be compensated by an increase of the shutter time up to a proper signal. The dark signal will also increase, and the net signal range will be reduced. A further problem is the non-linearity of most sensors in the vicinity of FW, resulting in a non-linear dependence of the signal as function of the irradiance. Many application specialists thus avoid this range.

Noise

The signal in a single pixel is not constant when tracked over several integration periods. There is always noise on the signal. Even under perfectly identical circumstances a series of images will show stochastic variation for the dark signal as well as for the photo signal around their mean values. A good measure for this scatter is the square root of the mean squared deviation from the mean value, rms. For a particle detector like a CCD or CMOS sensor, noise is equal to the square root of the number of particles. A mean signal of 16,000 electrons, e.g., will be associated with a fluctuation within an rms range of about 125 electrons. When mapping this signal to 12 bit, which means to represent 16,000 electrons by a grey level of about 4,000, the rms noise corresponds to about 32 grey levels. Subtracting the dark signal does not provide a solution. Unfortunately, rms values add as squared values under the square root, and the noise of the difference of two signals will be larger than any of the two single noise levels. The larger the dark signal, the larger will be the noise on the total signal and, if so, also on the difference signal, and the signal will eventually be completely obscured by noise. As a consequence, there may be cases where the grey level resolution provided by the ADC will not be the ultimate criterion for the number of grey levels which can reliably be detected in an image. The limiting factor is noise.

Dynamic Range

The situation for signals just below the saturation limit has been described above. When dealing with very low signals, read-out noise has to be taken into account. Even with truly identical numbers of signal electrons the grey value for subsequent read-out of a detector array shows fluctuations around the mean value. The rms value of this scatter is the read-out noise. Read-out noise may be larger than a grey level step produced by the ADC. As an example, five electrons rms are not uncommon for a good CCD array. As a figure of merit, the ratio between FW and read-out noise is given, the so-called dynamic range DR. In our example, DR would amount to 16,000/5 = 3,200 or 70 dB, which would be quite an impressive figure for an industrial camera. This value, however, does not mean that 3,200 grey levels can be reliably detected, since signal noise near saturation will amount to about 125 electrons, outnumbering read-out noise by a factor of 25. For this reason the dynamic range (DR) must not be confused with the signal-to-noise ratio (SNR) as can unfortunately be found in some data sheets. In our example, SNR near saturation is only about 125, and it will by no means become better at any other signal level. Even this number is an optimum figure, since the electronics downstream can and usually will add further noise to the signal. In order to discriminate a signal against the noise floor, a SNR of at least 10 is usually requested. In our example, a signal of 120 electrons would be associated with a total noise of about 12 electrons, where we have omitted the dark signal. The grey level 30 would thus pick up a noise of about three grey levels. There are probably several application specialists around who dare to tackle such a signal with their image processing algorithms. Grey levels larger than 400 would provide SNR = 40 and higher, and a noise of about 10 at a grey level of 400 may well be called a fine signal. This simple reasoning, however, already shows that the considerations concerning the influence of signal quality upon the stability of algorithms are not yet finished at this point. Whenever differences of grey levels are to be detected, which is at the heart of most image processing algorithms, the absolute noise is the key parameter rather than the SNR, resulting in different criteria for dark and bright areas of the image.

Summary

When grey levels in an image are to be estimated, the brightest and the darkest spots in the scene should be examined and the light energy or the number of photons be measured or calculated which will fall upon a pixel within the integration time period. The spectral distribution of the radiation has to be taken into account for these calculations. Quantum yield and output conversion gain or an alternative measure of the sensitivity of the detector will then provide the grey levels. When the signal is too low in dark areas, a larger aperture of the optics or more light on the scene may solve the problem. On the other hand, the bright zones of the image must not be saturated. Longer integration time will also yield higher signals, but the dark signal will increase along with the photo signal. Choosing a higher gain results in a higher output signal, but the noise floor of the source signal will also be amplified. If the bright spots are saturated, the signal may be attenuated by equivalent means. The next step will be to calculate the signal-to-noise ratio for the bright areas as well as for the dark regions of the image. This provides the data base for the decision whether a certain algorithm may work properly on this image or not. If not, have a look for a camera with higher quantum yield, tune the lighting to the spectral range where the camera has the maximum quantum efficiency, reduce the dark signal (choose a shorter shutter time and a strobe light, e.g.) or get a model with higher FW and smaller read-out noise, hence better dynamic range. Finally, a brief look at the EMVA 1288 standard [3] is recommended, which provides material on several interesting topics such as fixed-pattern noise or, in forthcoming version 3.0, features of cameras with non-linear characteristics.

References

[1] G. C. Holst, CCD Arrays, Cameras and Displays, 2nd ed., SPIE 1998

[2] INSPECT 2/2010, p. 18, Radiant Presence, Optical Metrology Basics: Radiometry

[3] www.emva.org/standard1288

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