Digital Photography: The Influence of CCD Pixel Size on Imaging Performance

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Abstract

As digital photography becomes increasingly competitive with traditional analog systems, questions of both comparative and ultimate performance become of great practical relevance. In particular the questions of camera speed and of the image sharpness and noise properties are of interest, especially from the possibility of an opening up of new desirable areas of photographic performance with new digital technologies. Clearly the camera format (array size, number of pixels) plays a prominent role in defining overall photographic performance, but it is less clear how the absolute pixel dimensions define individual photographic parameters. This present study uses a previously published end-to-end signal-to-noise ratio model to investigate the influence of pixel size on various aspects of imaging performance.

Introduction

An important topic of contemporary interest in the development of digital photography systems is that of the format and pixel size of the sensor array. In particular the question arises of the optimum choice of pixel size within a fixed physical array-size. There are of course practical technical constraints to this choice, but these aside, the implications to overall photographic performance are not necessarily as intuitively obvious as are the equivalent format considerations in analog photography. This is compounded by the fact that while some sensor-array properties are specified in terms of the array as a whole, others are often specified in terms of individual pixels, and the relationship between (local) pixel and (global) array performance parameters may be less than straightforward. However the analogy with conventional photography can provide strong guidance to this problem.

In silver-halide photography the sensor comes in the form of a piece of film to be exposed in a given format, typically 35mm or APS formats, for example. With this film comes a speed rating implying the efficiency of converting exposure light into a negative image, with associated parameters of tone-reproduction, resolution and noise. These performance parameters are seen as global parameters to the film as a whole, as opposed to being format-specific, although clearly the negative-to-print degree of enlargement will clearly influence the print resolution and noise properties, and this in turn may be a format issue. However here we are not concerned initially with the question of enlargement, since this is a well-known factor in both analog and digital photography, and can be dealt with in a separate, well-established manner.

The question here is the applicability of a similar global set of photographic performance parameters for any given digital sensor array, taking into account the complicating existence of a grid with a fixed pixel size. However to address this question we can take the silver-halide analogy further by considering the case where a conventional negative image is scanned as input to a digital system, which is in fact an increasingly commonplace activity. In doing so the scanning system implies placing over the film a virtual grid much akin to the physical grid of sensor arrays. The choice of the grid size is not seen as interfering with the global photographic exposure properties, though clearly it will impose its own resolution constraints on the information recorded in the negative, and if scanning is associated with the introduction of any spurious noise sources, will also modify the eventual image noise.

We now use this analogy to investigate the relationship between these local and global sensor properties associated with digital scene-acquisition, in an attempt to identify the fundamental principles which govern optimal pixel size for a fixed sensor array. But first we gain useful insight from a straightforward approach to the problem via information theory.

The Information Theory Approach

We adopt the well-known Shannon expression for information capacity (IC) in the form

$$IC = N \log_2 M \qquad (1)$$

where N denotes number of distinct pixels and M the number of distinguishable levels within a pixel. Thus the main problem is define the criterion for a distinguishable scene level as detected by an individual pixel. If the array size has area A, the pixels have side x, and the noise criterion for level separation is set at two-sigma, it follows that the array information capacity approximates to:

$$IC_A = A\, x^{-2} \log_2 \{\, x\, (\sqrt{(e_{sat})} - \sqrt{(e_{dk})}\,) + 1 \} \qquad (2)$$

Here e_{sat} denotes the electron saturation level and e_{dk} the dark count, assuming that e_{sat} and e_{dk} are both expressed per unit sensor area, and that both are inherent properties of sensor-detection, and are thus the respective equivalents in the silver-halide case of the inherent properties associated with the completely-developed grain population and the number of fog grains.

The problem of choice of pixel-dimension for optimization of information capacity was addressed over thirty-five years ago by Altman and Zweig[1] in the context of the optimum storage of information in microfilm. In summary, binary as opposed to multilevel recording will always yield maximum information capacity if the resolution capabilities allow the appropriate limiting pixel size, defined approximately in this case by

$$x\left(\sqrt{(e_{sat})} - \sqrt{(e_{dk})}\right) = 1 \qquad (3)$$

Inserting typical practical values for e_{sat} and e_{dk} yields values of x much less than 1micron. But this low value does not take into account the read-noise, which following the analogy with scanned film is not an inherent property of the detection process itself, but noise introduced in the subsequent digitization stage. Assuming the read-noise is significantly higher than the dark current, equation (3) is then replaced by an approximate definition of pixel size for binary recording, according to

$$x = \sigma_{read}\left(\sqrt{(e_{sat})}\right)^{-1} \qquad (4)$$

where σ_{read} denotes the read noise in rms electrons. Using typical values still results in the conclusion that a pixel size of the order of 1 micron will yield optimum sensor information capacity.

These above approximations indicate pixel sizes significantly smaller than those used in practical camera areas for digital photography, so we now investigate the corresponding photographic implications.

Imaging Parameters of Sensor Arrays

For the purpose of practical illustration a set of parameters have been chosen to describe a digital photography system based on CCD detection and TIJ printing (it is necessary to include a standard set of print parameters since the photographic properties of resolution and noise will of course depend on the system as a whole). These parameters are similar to ones used recently for a related system simulation.[3]

CCD

A 1024×1280 array has 8 micron pixels (ie an overall format of approximately 8×10mm, or about one-quarter the area of the standard silver-halide APS format) with primary quantum efficiency of 10%, dark current of 6 electrons per square-microns per sec at 25°C (with assumed exposure of one-sixtieth of a second at this temperature), and well depth of 500 electrons per square-microns (ie, 32000 electrons for this 8-microns pixel size).

Digitization

The separation between read levels is assumed at a two-sigma total-noise separation criterion. The read-noise will be introduced as a variable contribution to this total noise.

Print

The image on the sensor array is mapped to a 3.5×4.4" print, implying a linear magnification of around eleven, with digital levels mapped linearly to print reflectance. It is assumed that the printing technology is capable of reproducing all the detected digital levels.

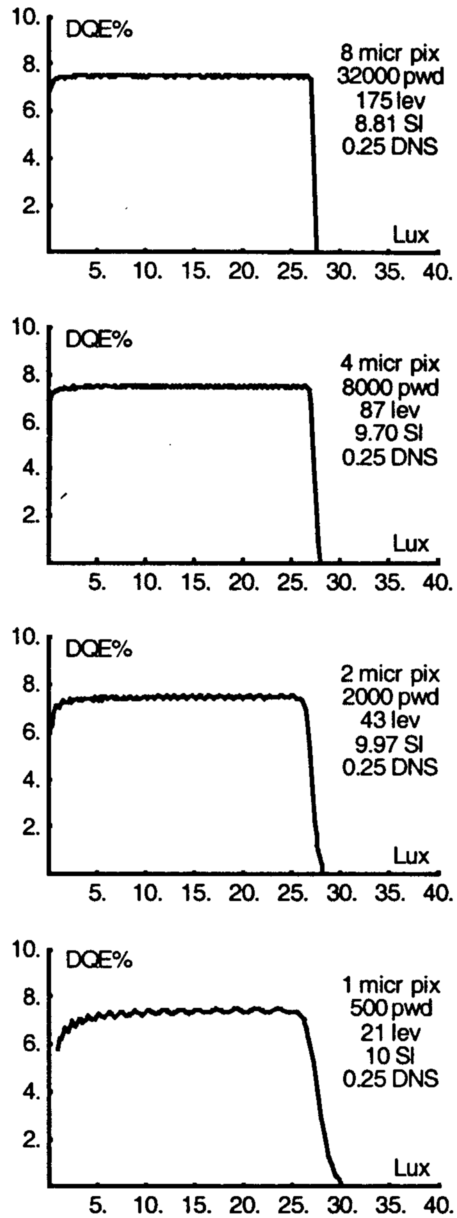

Figure 1. DQE-exposure curves for various pixel sizes

Imaging Parameters of Sensor Arrays

The above values are now used as the basis for an end-to-end signal-to-noise ratio model used previously by the author for similar studies,[2] along with separate indicators for photographic resolution and noise. The latter are in terms of a sharpness index[3] and a digital noise scale.[4]

Figure 1 shows the calculated DQE-exposure curves assuming pixel sizes of 1, 2, 4 and 8 microns. It is seen that these are virtually independent of pixel size, in spite of quite different pixel detection parameters - with well-depths varying from 500 to 32,00, and the associated capability of detecting from 21 to 175 distinguishable scene levels.

Along with identical overall signal-to-noise ratio properties, the absolute print noise is also independent of pixel size (at a level of 0.25, or micro-fine on the digital noise scale, but note that this assumes printer capability of faithfully reproducing all these scene-detected levels - reproducing a lesser number would increase the image noise in proportional manner[4]). Not surprisingly the important imaging variable is that of resolution, measured according to the sharpness index and again assuming printer capability of reproducing the pixel as mapped onto the print.

Figure 1 confirms the above analogy with conventional film, ie, the existence of global signal-to-noise (speed/grain/exposure) parameters, and indicate that in this sense the pixel size is as 'invisible' in the detection sense as is the virtual grid of the scanned-film analogy invoked above. Also, as in this comparison, the important variable with pixel size is the intuitive one of resolution. Note that Figure 1 also confirms an important potential advantage associated with (multilevel) CCD detection, namely the constancy of the efficiency of detection over the dynamic exposure latitude, implying linear transfer of signal-to-noise ratio. Conventional film is non-linear in this respect.

The global nature of DQE and noise values for the detector array, and their independence of exposure as pixel size is varied, are in keeping with the above information-theoretic analysis, with increased resolution providing the key to increased information capacity. However these conclusions must be modified in the presence of read-noise.

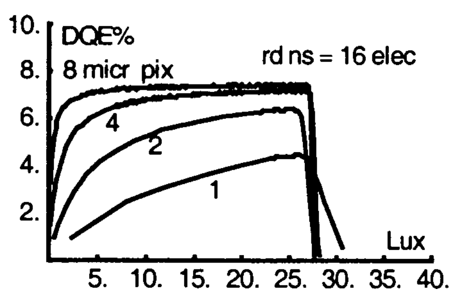

Figure 2. DQE-exposure curves: 16 electrons rms read-noise.

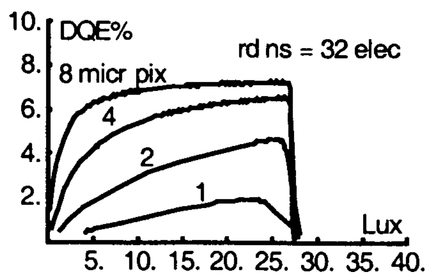

Figure 3. DQE-exposure curves: 32 electrons rms read-noise.

Figures 2 and 3 (assuming rms read noise of 16 and 32 electrons respectively) show the deterioration in imaging efficiency with decreasing pixel size, which as might be anticipated is more pronounced the higher the read-noise. In both cases the characteristics associated with the 8-micron pixel are scarcely influenced, but a 1-micron pixel shows not only significant reduction of DQE but variation of DQE with exposure on a par with conventional film. This implies that although there is no inherent loss of speed or exposure latitude, at low exposure levels this would be associated with lower gain and higher noise. This is of course follows intuitively from the direct effect of read-noise in the low-exposure region, as illustrated in Figure 4.

Figure 4 shows the number of distinguishable scene levels per pixel detected by the sensor as a function of pixel size. The linear relationship between the two is maintained down to low pixel sizes in the absence of read-noise. However with increasing read-noise the reduction in the corresponding number of distinguishable levels becomes predominant at low pixel size.

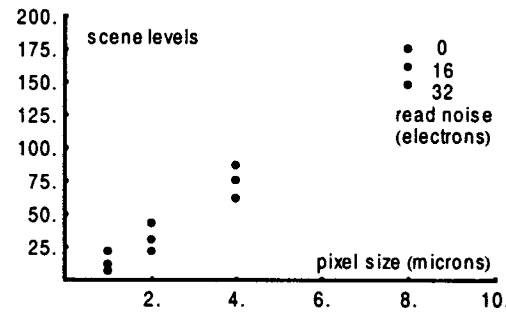

Figure 4. Scene-levels as function of pixel size and read-noise

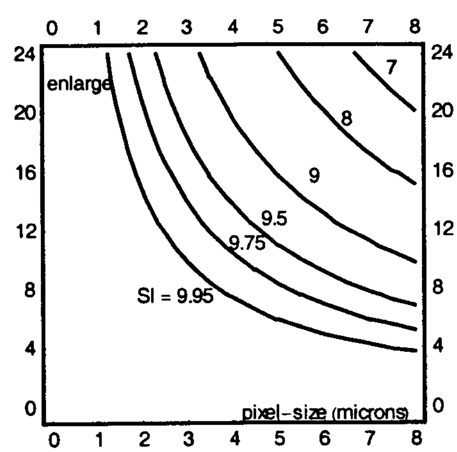

Figure 5. Sharpness as function of pixel-size and enlargement .

It is recalled that these conclusions apply to the specific set of assumed sensor-detection parameters, such as those of saturation and dark-currents, but other values can readily be substituted in the model for similar practical calculations. Similarly, other sensor formats and print sizes may be introduced into the model, although these will not change these fundamental conclusions of the role of pixel size and read-noise, or the global nature of the sensor-array imaging-properties.

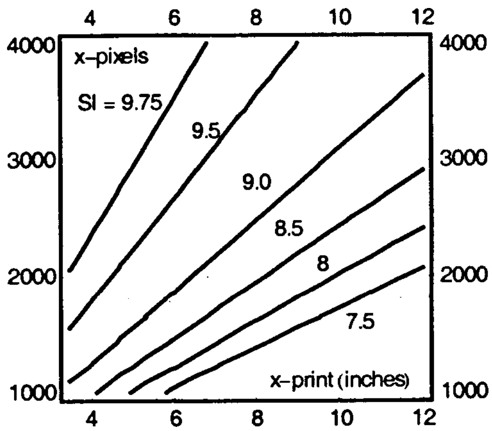

Figure 6. Sharpness as function of print-size and pixel-number.

Image Resolution Relationships

In view of the direct relationship between pixel size and image resolution, we now look specifically at the factors influencing image sharpness, as expressed in terms of the sharpness index (SI) on a scale of 1 to 10. The values previously ascribed to SI were for an implicit sensor-pixel-to-print-enlargement of approximately 11. Since degree of enlargement will clearly play as direct a role in determining SI as does pixel size, the trade-off between the two can be expressed as in Figure 5.

Since the product of the sensor pixel size and linear enlargement is merely the pixel dimension in the print, which in turn is defined by the ratio of the print size (say in the x-dimension) to the number of sensor pixels in this same dimension, it follows that an alternative form of expressing the sharpness relationship is as in Figure 6. This shows the necessary number of sensor pixels in order to meet various sharpness criteria in a print of prescribed size. If for example a sharpness in the print is required according to SI=9, a 10-inch print calls for around 3000 x-pixels, or approximately 300 pixels-per-inch printing capability. A sensor-format equivalent to that of APS, would then imply pixels of approximately 5 microns, while the (8mm) sensor-format assumed in the earlier calculations would imply pixels about half this size.

Summary and Conclusions

Due to the first-order nature of the properties of individual pixels, a CCD imaging array may be ascribed global speed, latitude and noise properties at the detection stage in the same way that these are ascribed to conventional silver-halide film. These properties include linear signal-to-noise transfer over a wide dynamic exposure latitude. Read-noise during digitization modifies these properties in a similar manner to the introduction of noise during the scanning process used in the digitization of analog film.

The primary role of the physical dimension of the pixels is to define the resolution of the detection process and hence influence the final sharpness level in the print. Sharpness will also be directly influenced by the ratio of the print and sensor formats, and examples have been given of these factors in terms of a simple sharpness index. Smaller pixels sizes than those currently used in consumer digital photography may be necessary to match the highest levels of traditional print sharpness.

References

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