An Inherently Calibrated Exposure Control Method for Digital Cameras

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Abstract

Digital Camera Exposure Control

Digital imaging systems have less exposure latitude than traditional film imaging systems. Thus it is very important to minimize exposure error in digital cameras.

This paper presents a method for efficiently determining exposure parameters utilizing the camera's image sensor as the data source. Eliminating light meter circuitry and the associated manufacturing calibration steps for both light meter and image sensor photoresponse reduces cost and exposure error. Further, this approach enables the exposure control module to optimize image SNR.

First, an introduction to exposure control will be presented. Next, the key design issues for exposure control in digital cameras will be discussed. Finally, a digital camera system exposure control method that overcomes the practical problems will be described.

There are two key aspects to this exposure control method. The first is a run time characterization of the noise in the imaging pathway. The second is an efficient technique for the image sensor to self-select a correct exposure utilizing that noise behavior information.

Introduction

The simplest conventional film cameras with built-in exposure metering use the lower center weighted exposure metering technique. In this method, the average brightness of the lower center portion of the scene is used to determine the shutter speed and F/#.[1] The well-known relationship linking scene brightness to exposure control parameters is

$$B = kA^2/TS \tag{1}$$

where B is the scene brightness, k is constant, A is the F/# of the taking lens, and S is the photosystem ISO speed.[2] The relationship is grounded in the methods for assessing the ISO speed of photosensitive materials and the general observation that on average, reflectance of scenes is equivalent to an 18% gray.

This simple exposure control approach is successful for the majority of scenes. The lower center weighted meter fails in scenes where

- the sun is directly imaged or reflected off a highly reflecting surface such as a water, snow, and sand,
- scenes where the subject is atypically illuminated such as backlight and
- other scenes that do not fall into the average 18% reflectance category.

Exposure control algorithms in advanced SLR film cameras evaluate scenes by regions to do a better job of detecting the atypical scenes. They may categorize a scene based on its dynamic range, the brightness distribution pattern in upper and lower regions, the overall average brightness level, etc. For example, if a central region is a few stops dimmer than the remainder of the scene, it is likely that the subject is backlit. The exposure control can choose to add flash to illuminate the subject or to purposefully leave the backlit effect.

Digital cameras have the opportunity to perform similar evaluative analyses on the scene, as they have a wealth of regions to utilize. Simple exposure schemes can map the digital image's mean intensity to 18% of the A/D output range. More complex evaluative schemes can apply a large rule set to categorize the scene and determine an appropriate exposure.

Problem Definition

The practical difficulties in designing in-situ evaluative exposure control for a digital camera include:

1) The integrative nature of electronic image sensors compared to instantaneous light meter circuits.
2) The image sensor's limited dynamic range compared to the tonal range in real scenes.
3) Mapping the most important scene tones onto the imaging system capture range.
4) The requirement to choose an exposure that accommodates both signal and noise charge accumulation in pixels.

The first problem above relates to the difference in exposure data acquisition. Whereas a conventional camera might get its information from a photocell(s) operated in the photoconductive mode, most digital imaging arrays operate in the photovoltaic mode. Thus the exposure control system must wait through integration before having data to evaluate. In low lighting conditions or in scenes with rapidly changing content, this can adversely affect exposure accuracy. The solutions to this problem will be found in future image sensor improvements. Prototype pixel architectures have been designed with the photoconductive mode for instant pixel readings. Lower light sensitivity is always desirable for picture taking and thus studied as well.

The second problem above relates to the ability of an imaging system to capture and reproduce a full set of tones so that the scene appears natural. Jones and Condit studied the range of luminance in real world scenes.[2] They found that the median scene has a dynamic range of 160:1. To adequately capture a full set of tones for 95% of the scenes a photographer might encounter a capture range of greater than 1000:1 is necessary. Thus, a digital imaging system would need more than a 10 bit A/D to quantize without clipping tones. However, most consumer market digital cameras today still have 8 bit A/D converters or 256 tones. Thus, the dynamic range of these digital cameras is limited with respect to the tonal range possible in real scenes. High dynamic range scenes will not be reproduced with natural appearance until digital cameras can afford higher bit depth digitization and the implied reduction in noise to leverage it.

Pixels that saturate will be digitized to the maximum highlight level. Pixels that remain unexposed relative to the noise floor will be indistinguishable from the black level. The third problem highlights the need for a digital camera's exposure control system to map the most important tones in the scene into the capture range of the image sensor. Since the 8 bit digital camera does not have enough dynamic range to capture all tones in some scenes, it is important that exposures map the scene with minimal errors to exacerbate the situation.

For this reason, the calibration of the exposure control system must be accurate. If a light meter circuit is used, it must be calibrated to specification. The field of view of the light meter detector must be aligned with that of the image forming system and its output signal calibrated across a large illumination range. The photoresponsivity of the imager must also be similarly characterized. Exposure tables or programs must be altered for the imager sensor's equivalent ISO speed, by illuminant if necessary. This puts tight tolerances on metering circuit components and adds undesirable calibration steps to camera manufacturing.

Therefore, it is advantageous to utilize the image sensor itself as the source of exposure control data. It collects data that is inherently calibrated to the final imaging path.

The final problem noted is the need to calculate an exposure to collect an optimum number of signal electrons while leaving some pixel charge capacity for the noise that While highly efficient against the clock, this method can yield non-optimum exposures. The problem in this application is that the data set changes with integration time. will accumulate as well. Noise sources in photodiodes and photocapacitors have been fully described in a number of sources.[3] Typical pixel noise components include photon shot noise, dark current, dark current shot noise, read and reset noise. Some noise sources are signal level dependent some are proportional to integration time, others are temperture dependent and some are fixed. The exposure control system needs a method to allocate an appropriate amount of pixel charge capacity for noise as a function of these factors.

A method to accomplish this will be described, followed by a discussion of its use in digital camera exposure control.

Methods

Noise Charge Estimation

On power up, a small set of closed shutter captures are made at predetermined integration times and gains. Much like a designed experiment, the noise field data set is used to determine coefficients for equations that describe the dark noise charge accumulation as a function of time and gain at the current ambient temperature. Table 1 below illustrates a sample noise test series specification.

Table 1. Power On Noise Evaluation Specs

Sample	T_int, msec	Gain
1	60	1
2	4.5	1
3	4.5	2
4	4.5	4

The dark noise captures are read out with dark level clamping or dark frame removal functions disabled. The noise captures are carried through the digitization step and then a histogram operation. The histogramming step comprises the well-known operation of counting the number of pixels at each quantization value. Once the complete set of dark captures has been made and evaluated, histogram statistics are used to calculate coefficients for dark noise. The first two exposures in Table 1 differed only in the length of integration time. Linear equation coefficients describing the noise rate of change with increasing integration time may be found by

$$Noise(T\_int) = m_1 * T\_int + b_1 \qquad (2)$$

where m is the ratio of the difference in the observed histogram means in the first two captures to the difference in their respective integration times. The intercept b is calculated in the conventional manner, by solving equation 2 against either of the two observed data points.

Similarly, linear equation coefficients describing the noise rate of change with increasing gain may be found by

$$Noise(gain) = m_2 * gain + b_2 \qquad (3)$$

where m is the ratio of the difference in the observed histogram means in the next two captures to the difference in the respective gains. The intercept b is calculated in the conventional manner, by solving equation 3 against either of the two observed data points.

This power-up calibration will be used to estimate the noise levels for various combinations of integration time and gain in the exposure control algorithm to follow. Note that this noise calibration accounts for fixed noise, time and gain dependent noise, but not signal dependent noise. However, this may be sufficient for systems that are not shot noise limited, largely the case in consumer digital cameras today. For completeness, the signal dependent noise may be estimated by first solving for the pixel capacity remaining after the other noise sources are accounted for.

$$Signal\_e\text{-} = Sat\_pixel\_e\text{-} - Noise(Tint) - Noise(gain) \quad (4)$$

The remaining charge capacity is then applied to standard relationships to assess signal dependent noise, if significant enough to be included. For example**,**

$$Photon\_shot = SQRT(\ Signal\_e\text{-}) \quad (5)$$

In this manner, the mean noise expected for each combination of gain and integration time can be estimated at any current ambient temperature. The exposure control algorithm can also compute and optimize the signal-to-noise ratio (SNR) and ensure that the exposure selected is optimum for pixel capacity and temperature influenced noise conditions.

The final noise estimate may be expressed as

$$Noise(Tint, gain, temp, signal) = SQRT\ \{\ Noise\ (Tint)^2 + Noise(gain)^2 + Noise\ (photon\ shot)^2\ \} \quad (6)$$

We now turn our attention to the process of capturing image data for the exposure analysis process. Again, the noise equations will be used to estimate a noise floor for each combination of integration time and gain.

Exposure Search Strategy

The type of image sensor in use will have an impact on the speed of exposure analysis and optimization execution. In imagers with the capability for non-destructive readout, a feature of some CMOS arrays, an ongoing exposure can be used to provide input data to the exposure control algorithm. In image sensors without this feature, multiple integrations must be performed to assess the scene illumination level. The latter case will be described in the following example method for selecting an optimum exposure using image sensor data.

A typical consumer scene will be used to illustrate the operations and the exposure control method.

The scene in Figure 1 has high dynamic range. Notice the bright specular reflections off the shiny chrome counter and the deep shadows under the awning. Additionally, the faces are small relative to the scene area and they are in the shadows. This will be a difficult scene for a digital camera. An efficient way to assess exposure from imager data is to histogram the pixel intensities, so a reference histogram of this scene is shown in Figure 2.

A digital camera would likely clip portions of the highlights and shadows of such an image. The portion of the scene that might be optimally captured by an 8-bit digital camera following the simple 18% gray mapping rule is illustrated in Figure 3 by the highlighted zone.

Figure 1. High Dynamic Range Image

Figure 2. Image Intensity Histogram

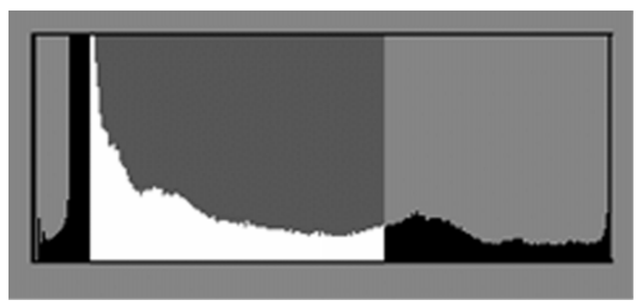

Figure 3. Image Histogram with Ideal 8 Bit Capture Range Highlighted

The basic binary chop exposure search strategy may be enacted with the following logic:

1) Select an initial integration time so that the worst case elapsed time to any exposure in the table is minimized. This generally means starting with a time that is a little longer, because many subsequent short integrations can be accomplished in the period of one longer integration.
2) Capture a scene, process and histogram it.
3) If the histogram mean is too large (indicating overexposure), then the next exposure to try is the one midway from the current exposure to the minimum possible exposure time. This is depicted in Figure 4 below. Reload and go back to step 2 for another image.
4) If the histogram mean is too small (at or close to the expected noise for this exposure, indicating underexposure), then the next exposure to try is the one

midway from the current exposure to the maximum possible exposure time. Reload and go back to step 2 for another image.

5) If the histogram is not clipping at either extreme, then the scene is one that can be adequately captured in the tonal range of this imaging system. This is depicted in Figure 5 below. For the simple tonal mapping, adjust the exposure to move the mean of the scene histogram to align with the 18% ADU range. This is the case depicted in Figure 3 above.
6) If the scene histogram is clipping at both ends, then this scene's dynamic range exceeds the camera's tonal capture capability. Continue to divide the exposure range in half until a satisfactory alignment of the scene mean and the 18% ADU range is achieved. (Figure 3).

This method employs the common binary chop approach, also known as the tree search method. By starting in between two end points, a decision is made to move up or down after each test. Two pointers are used to define the as yet untested range, insuring efficient convergence. The move distance is set to half the remaining range between the last exposure and the end pointer in the direction of the move.

For example, compare the two histograms with overlaid capture windows in Figures 4 and 5. The mean in the data set captured and histogrammed from the exposure depicted in Fig. 4 is rather different than the data set histogrammed from the exposure depicted in Fig. 5. This shift in the data set is a natural aspect of the task at hand, but can cause the desired optimum exposure can be excluded from consideration in the normal methodology of the binary chop. The shifting capture data window is inconsistent with the binary chop search algorithm, which expects to sort on a constant unchanging data set.

Figure 4. Overexposure with Capture Mean of 213 ADU

Figure 5. Centered Exposure with Capture Mean of 117 ADU

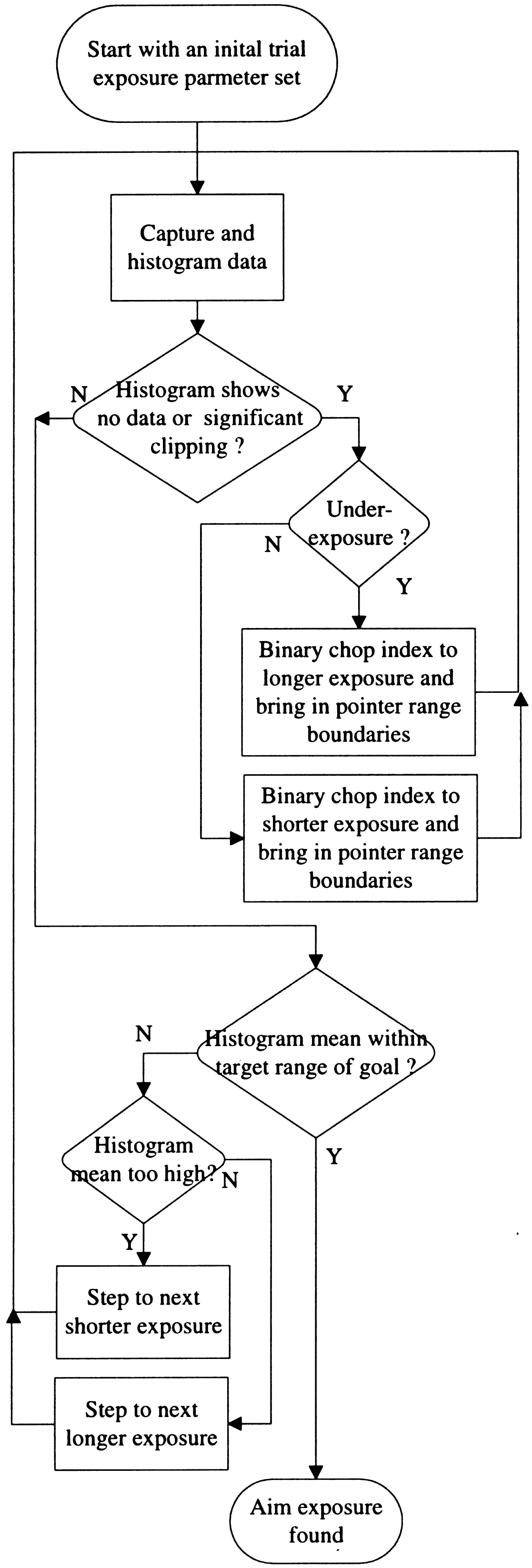

Figure 6. Modified Binary Chop Exposure Search Flowchart

Exposure Search Strategy—Modified Binary Chop

With a modified or hybrid approach to selecting the best exposure for a scene, the efficiency of the binary chop can be maintained. The Modified Binary Chop algorithm is outlined in the flowchart in Figure 6.

The logic in the modified approach is initially similar to the original binary chop method given earlier. The same steps 1-4 are employed. However, once the histogram mean is centralized, with the extremes of the histogram either fully within the capture capability of the image sensor as in step 5 (also Figure 5) or extending beyond the both capture window boundaries, the binary chop halving should cease. It is more effective to make a linear step in the desired direction. This stepping continues, typically in quarter stop increments, until the best alignment is found or straddled.

Conclusion

The methods proposed demonstrably solve the key implementation issues in using an image sensor to provide data to a camera exposure control module. In doing so, it overcomes the cost of additional light meter circuitry and associated calibration and alignment operations in camera manufacturing. It has the further benefit of robust operation across varied temperature conditions.

The power-up calibration of noise levels as a function of exposure time and gain serve to establish a key reference point for the exposure control system.

The modified binary chop algorithm is efficient and precise in searches for optimum exposure parameters. It overcomes the inadequacy of the standard binary chop method in this application.

The use of imager data has the further benefit of enabling the exposure control module to optimize image capture for final SNR.

References

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