A model for measurement of noise in CCD digital-video cameras

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Abstract. This study presents a comprehensive measurement of CCD digital-video camera noise. Knowledge of noise detail within images or video streams allows for the development of more sophisticated algorithms for separating true image content from the noise generated in an image sensor. The robustness and performance of an image processing algorithm is fundamentally limited by sensor noise. The individual noise sources present in CCD sensors are well understood, but there has been little literature on the development of a complete noise model for CCD digital-video cameras, incorporating the effects of quantization and demosaicing.

Keywords. Charge Coupled Devices, Noise measurement.

1. Introduction

CCD-based digital cameras are commonly used in image processing applications. The algorithms in these applications rely on contrast differences between pixels, either across an image or along a series of images. Fundamentally, the detectable difference in contrast between one pixel and another is limited by the signal-to-noise ratio within the captured images. The acquisition and conversion of photons in CCD sensors is well documented in the literature and there are many references to the sources of image sensor noise [1-4], though there is little reported work on the development of a comprehensive noise model for standard commercially available CCD digital video cameras. This paper addresses this shortfall by developing a comprehensive CCD noise model for captured images. Measurements which validate the model are described in [5].

2. CCD Architecture

Light passing through the sensor optics falls onto the imaging sensor where, depending upon the fabrication method, approximately half of the photons are captured and converted to charge in the photo detection process. The charge is then amplified, sampled, and digitally enhanced for output. Figure 1 details a typical digital image sensor for a CCD digital camera system [2-4, 6-9].

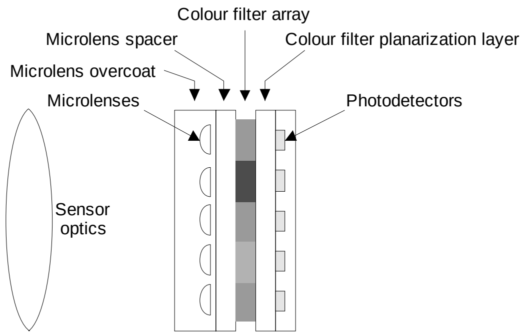

Figure 1. The components of a typical digital image sensor.

Many image sensors use microlenses to increase the amount of light incident on the photodetectors [1, 3, 10]. This also helps to reduce the problem of vignetting where, due to the optical tunnel formed by the sensor manufacturing process, light entering the sensor at an angle that is not parallel to the optical axis is attenuated prior to reaching the photodetector. In many consumer-grade colour cameras the light passes through a colour filter array (CFA) [11] in order to generate trichromatic images.

There are several readout architectures used for CCD sensors such as frame-transfer (FT), interline transfer (IL), and frame-interline transfer. IL CCD is the most popular image sensor for camcorders and digital still cameras, but suffers from a reduced fill rate due to charge storage buffers located beside each pixel [1, 12]. This reduction in fill rate varies, but values around 20-50% are not uncommon. Figure 2 shows a typical IL CCD readout architecture. The charge is read sequentially, with each charge moving along a column or row in a conveyer type fashion. In CCD image sensors the analogue-to-digital conversion (ADC), storage, and enhancement are performed on supporting integrated circuits (ICs).

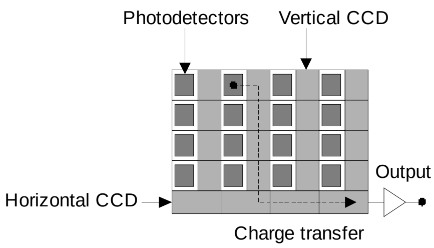

Figure 2. Architecture of an interline-type CCD sensor.

3. Camera Noise Model

3.1. Existing models

Several camera noise models and descriptions exist for CCD imaging sensors, and a brief discussion of them follows (note that noise types with an asterisk are described in the existing models using different terminology than that used in this paper).

Flory [2] describes the primary electronic sensor noise as a combination of shot and amplifier noise. Healey and Kondepudy [13] model camera noise for measuring scene variation, and include offset fixed-pattern noise (FPN)*, photon and dark-current shot noises, photo response non-uniformity (PRNU), and a read-noise equivalent. Boie and Cox [14] analyze camera noise for CCD and vidicon cameras. Their model includes photon shot and electronic shot noise, dark-current, and readout noise, and results suggest noise is localized and stationary. Mendoza [15] developed a model to analyze intrinsic CCD noise for application in pressure sensitive paint instrumentation systems, and includes thermal noise, reset noise, photon shot noise, and PRNU. Costantini and Süsstrunk [4] model a noisy image with readout noise, photon and electronic shot noise, offset FPN*, PRNU, and dark-current shot noise. Farrell et al. [16] describe a digital camera simulation tool which includes optics, sensor, and processor modules. The sensor module includes models of noise sources including readout noise, dark-current, offset FPN*, PRNU, and photon shot noise. Tsin et al. [17] developed a model to estimate the camera response function for CCD sensors that includes noise sources of dark-currents, PRNU, photon shot noise, and thermal noise.

None of these models incorporates all of the noise sources that are present in an image captured with a CCD image sensor.

3.2. New Model

The noise model is developed below based on the physical characteristics in the acquisition and sampling of photons through the image capture process in a digital CCD camera. Although blooming and smearing in CCDs are also destructive to images, they are artefacts of charge overflow and are avoidable. Hence they are not considered as part of the noise model.

3.2.1. Colour filter array. After passing through the sensor optics, the photons are usually filtered through the CFA to allow colour information to be captured by the photodetectors. As the photon to electron conversion is linear [1], after passing through the CFA the image I becomes:

$$I_{CFA,k} = I \times CFA_k, \quad k=1,\ldots,n \tag{1}$$

where k is the index for the colour filter.

3.2.2. Photo response non-uniformity. PRNU describes the difference in pixel responses (gain) to uniform light sources. In uniform illumination conditions, each photodetector cell of an image sensor should exhibit the same output voltage. However, this is not the case due to variations in pixel geometry, substrate material, and microlenses. Since PRNU is caused by the physical properties of a sensor, it is nearly impossible to eliminate and is therefore usually considered a normal characteristic of the sensor array used in any CCD (or CMOS) camera. The effect of PRNU is proportional to illumination, and is prominent under high illumination levels [3]. It is sometimes referred to as gain fixed-pattern noise. The noisy image, I_{PRNU}, after incorporating PRNU (and dropping the subscript k from hereon for clarity) for each colour channel becomes:

$$I_{PRNU} = I_{CFA}+I_{CFA}\times PRNU. \tag{2}$$

3.2.3. Photon shot noise. The capture of photons is a Poisson process that arises from random fluctuations in sampling when discrete quanta are measured, increasing in proportion to the square-root of the sample mean. The image capture after photon conversion, I_{ph}, including photon shot noise SN_{ph}, is:

$$I_{ph}= I_{PRNU} +SN_{ph}(I_{CFA}). \tag{3}$$

3.2.4. Offset Fixed-Pattern Noise. Offset fixed-pattern noise (FPN) arises from changes in dark currents due to variations in pixel geometry during fabrication of the sensor. Dark current in image sensors is leakage current produced by surface generation and minority carriers thermally generated in the sensor well. It is illumination independent, does not change significantly from image to image[1], and increases with exposure time. The amount of leakage varies from pixel-to-pixel, and is alternatively referred to as Dark Signal Non-Uniformity (DSNU) [1, 4, 10, 18]. FPN increases exponentially with temperature [1] and can be measured in dark conditions. The noisy image capture, I_{FPN} , after inclusion of FPN is:

$$I_{FPN}= I_{Ph} +FPN. \tag{4}$$

3.2.5. Dark current shot noise. Dark current shot noise occurs due to leakage currents in each pixel of the CCD sensor. The number of dark-current shot noise electrons is proportional to the pixel integration time and doubles with every 8ºC rise in temperature [1, 13]. Any electronic conductor exhibits shot noise when charges act independently when moving, e.g., when charges cross a barrier in a semiconductor. However, the current movement in a metallic conductor exhibits long-range correlations and therefore far less noise than within

[1] The expected value for a pixel's dark current is constant for a given operating condition, but exhibits shot-noise temporal fluctuations.

semiconductors [19], so shot noise due to current flow through simple conductors is not considered a significant source of noise within an image sensor.

The noisy image capture model, I_{dark}, after the addition of dark current shot noise, SN_{dark}, is:

$$I_{dark} = I_{FPN} + SN_{dark}. \quad (5)$$

3.2.6. Readout Noise. Readout or read noise is generally defined as the combination of the remaining circuitry noise sources between the photoreceptor and the ADC circuitry. Readout noise varies only in the temporal domain, and includes pixel reset noise, thermal noise sources (Johnson-Nyquist), and other minor contributors like the frequency-dependent $1/f$ (flicker) noise sources and conductor shot noise.

Reset noise in CCDs is a specific type of thermal noise arising from the kTC fluctuations when resetting the charge sense capacitor to a reference voltage [20]. A commonly used method called correlated double sampling (CDS) is used to reduce the effect of reset noise [1, 21]. CDS samples the noise value on the sensing capacitor after reset, and subtracts it from the sample of pixel data after charge transfer. There are several methods of implementing CDS [22], the details of which are beyond the scope of this paper.

Thermal, or Johnson-Nyquist noise, arises from equilibrium fluctuations of an electric current inside an electrical conductor due to the random thermal motion of the charge carriers. It is independent of illumination and occurs regardless of any applied voltage [19, 23] .

Prominent sources of $1/f$ noise in an image sensor are pink-coloured noise generated in the photo-diodes and the low-bandwidth analogue operation of MOS transistors due to imperfect contacts between two materials [1, 23] . The level of $1/f$ noise in a CCD sensor is dependent on pixel sampling rate.

The noisy image model, I_{read}, after the addition of read noise, N_{read}, is:

$$I_{read} = I_{dark} + N_{read}. \quad (6)$$

3.2.7. Demosaicing. Analysis of sensor noise using the output video in commonly available digital video cameras unavoidably includes the post-image capture effects introduced by the camera. Many consumer-grade cameras use a colour filter array (CFA) to capture colour information. The commonly used Bayer CFA has three colour filters, each reducing a pixel's bandwidth to approximately 1/3 of the visible wavelengths of light. The demosaicing process [11] used to interpolate the RGB colour data for each pixel is manufacturer dependent and generally unknown. The demosaicing effect, N_D, is proportional to image content and multiplies the noise as follows:

$$I_D = I_{read} \times N_D, \tag{7}$$

where I_D is the noisy image captured after demosaicing.

3.2.8. Digital filtering. The effects of digital modification such as image gain and colour balance multiply image content and therefore image noise[2]. The equation for noisy image capture, I_{filt}, after digital filtering is:

$$I_{filt} = I_D \times N_{filt}. \tag{8}$$

3.2.9. Quantization. The conversion of non-trivial analogue values to the digital domain results in rounding errors during the quantization process. For signal variations much larger than the quantization step, noise is added to the signal according to the following equation [24]:

$$\hat{\sigma}^2_{\text{quantization}} = \frac{q^2}{12} \tag{9}$$

where q is the quantizing step (dimension-less). A q step value of 1 gives:

$$\hat{\sigma}_{quantization} = 0.29\,. \tag{10}$$

The result is an additive noise source dependent upon image content, N_Q, that completes the noisy image capture model, I_{cap}:

$$I_{cap} = I_{filt} + N_Q(I_{filt}) \tag{11}$$

Unwrapping each of the noise source stages gives:

$$I_{cap} = (I + I \times PRNU + SN_{ph}(I) + FPN + SN_{dark} + N_{read}) \times N_D \times N_{filt} + N_Q(I_{filt}), \tag{12}$$

[2] The common brightness or black level adjustment simply alters the DC offset of the image and does not affect its noise detail.

for each colour channel defined by the CFA.

A summary of the noise sources contributing to the model is given in tables 1-3, with noise segmented into the categories of illumination independent, illumination dependent, and digital processing categories. A diagram of the model is given in figure 3.

Table 1. The Illumination-independent noise types.

Noise type	Origin	Manifestation	Dependencies
N_{read}, readout noise (thermal noise N_{therm}, reset noise N_{reset}, other minor contributors N_{other}).	CCD sensor and CCD support ICs.	Additive temporal and spatial variance.	Temperature, CCD readout rate.
SN_{dark}, dark-current shot noise.	CCD sensor.	Additive temporal and spatial variance.	Temperature, exposure time.
FPN, offset fixed-pattern noise.	CCD sensor.	Additive spatial variance only.	Temperature, exposure time.

Table 2. The Illumination-dependent noise types (reproduced from [5] with permission. © 2008 IEEE).

Noise type	Origin	Manifestation	Dependencies
PRNU, photo-response non-uniformity.	CCD sensor.	Multiplicative spatial variance only.	Incident pixel illumination.
SN_{ph}, photon shot noise.	CCD sensor.	Additive temporal and spatial variance.	Incident pixel illumination.

Table 3. Digital processing noise types (reproduced from [5] with permission. © 2008 IEEE).

Noise type	Origin	Manifestation	Dependencies
N_D, demosaicing noise.	CCD support IC.	Multiplicative noise amplification or attenuation.	Demosaicing implementation, combined sensor noise.
N_{filt}, digital filter noise.	CCD support IC.	Multiplicative noise effect.	Gain parameters for digital image enhancement, combined sensor noise.
N_Q, quantization noise.	CCD support IC.	Additive noise. Image content dependent.	Variance of image data. Sets lower noise limit for non-trivial image content.

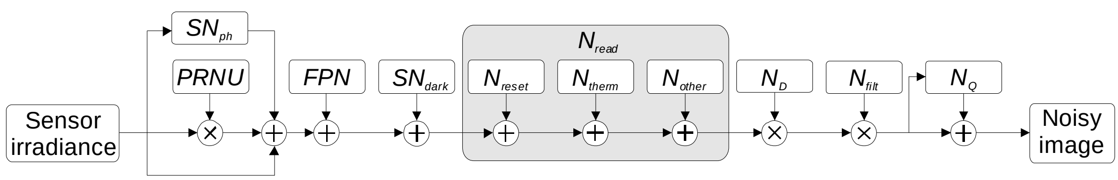

Figure 3. The derived noise model for image capture in a standard CCD digital video camera (generalized form of that presented in [5] to include quantization noise in images of a trivial nature).

3.3 Validation

The new camera noise model was tested on a commercially available colour (RGB) CCD digital-video camera (*Unibrain Fire-i400)*, where the camera's output-referred measurement of irradiance is the pixel value, measured as the mean pixel-value over an area of an image or an image set.

Measurements of FPN, N_{read}, and SN_{dark} were performed in dark conditions. A Gretag Macbeth ColorChecker Color Rendition Chart[3] was illuminated with controlled lighting to provide a range of reflectances for measurement of $PRNU$, SN_{ph}, and N_D. Captured images were low-pass filtered by defocusing the lens thereby reducing the effect of any high-frequency content present in the scene.

The maximum camera exposure time of 35 ms was used to minimize any "flickering" effects from the high-frequency operation of the fluorescent bulbs, and all post-capture digital effects were disabled. The noise values or function of each noise component of the camera was measured [5] by analyzing the noise variances in 100-image sets. Simulated images were used for N_Q analysis. The results are shown in table 4, where R, G, and B represent the red, green, and blue responses of the camera. Of particular interest is the variance of quantization noise with image content. Images containing significant variation exhibit quantization noise of σ=0.29, which reduces as image variation decreases. This highlights the importance of including quantization noise in the CCD noise model, as almost every image containing non-trivial scene variation will have a minimum noise level of σ=0.29.

Table 4. Measured noise for a Fire i400 CCD camera.

Noise quantity	Measured value
FPN	σ_R=0.30 σ_G =0.12 σ_B =0.25
$PRNU$	σ_R=0.010R-0.008 σ_G =0.006G+0.122 σ_B =0.013B+0.024
SN_{ph}	$\sigma_R = 0.21\sqrt{R} + 0.47$ $\sigma_G = 0.52\sqrt{G} + 0.01$ $\sigma_B = 0.22\sqrt{B} - 0.04$
N_{read}	σ_R =1.61 σ_G =0.61 σ_B =1.24

[3] http://www.gretagmacbeth.com

SN_{dark}	=0
N_D	σ_R =0.73R σ_G =0.75G σ_B =0.73B
N_Q	≤0.29
N_{filt}	N/A (disabled)

Calibration of our noise model requires the integration of the statistical variation of each noise component. The results of our calibrated model are shown in figure 4, where the modeled noise compares favorably with the measured noise values for each colour channel.

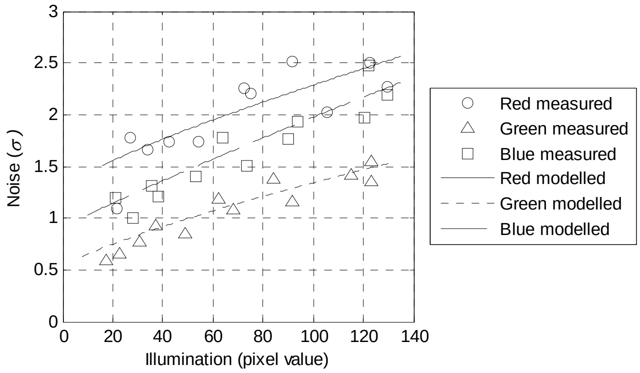

Figure 4. The results of modeled and measured CCD camera noise (reproduced from [5] with permission. © 2008 IEEE).

4. Conclusion

This research has shown that the CCD noise model is much more complex than those presented in previous studies (see section 3.1). A CCD camera noise model has been derived that includes noise sources from the CCD and supporting ICs, colour processing, and quantization. The derived noise model has been calibrated with measured data, and compares favourably with measured total image noise.

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