

Measured Effects of Temperature on Illumination-Independent Camera Noise

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Abstract—Noise affects all captured images, regardless of the quality of the image sensor. One of the major contributors to image noise is heat within the sensor, where variations in thermally generated currents results in a fluctuation of measured pixel values. These fluctuations can severely impact on the robustness of applications that process the resultant image. To help better understand the effect that temperature has on image noise, we measured the illumination-independent (base-line) noise characteristics of 4 different industrial cameras and tracked their noise-performance from 21°C to 55°C. Results show that camera noise is highly temperature dependent, varies significantly between camera models, and can have unexpected characteristics.

Keywords- camera noise; image noise; thermal noise.

I. INTRODUCTION

Sources of camera noise are well documented in the literature and, with the exception of flicker noise, are well understood [1-5]. Although it is commonly observed that an increase in the operating temperature of a camera increases the noise in a recorded image, no studies have been found that have experimentally quantified the effect temperature has on base-line image noise by way of experiment over a variety of cameras.

Camera noise is exhibited as spatial (inter-pixel) and temporal (intra-pixel) variations of pixel values, and its effect upon the performance of an image-processing application is dependent on how the application uses information in an image or video stream. For example, an image segmentation

algorithm may operate on a single image at a time; hence both spatial and temporal noise will affect the algorithm. An image-subtraction operation will remove spatial variation due to offset variations between pixels, resulting in temporal noise variations only after the subtraction. An application that monitors a fixed scene may average multiple images together to update a background image, effectively removing temporal noise while retaining the offset variations present between pixels. Each of the above examples will be affected by noise differently.

Temperature can have a major effect on the level of noise present in a captured image, with some noise sources (such as dark current shot noise) doubling with every 8°C rise in temperature [1]. If image noise is to be appropriately managed within an image-processing application, then it is clear that the spatial and/or temporal noise properties of the camera must be clearly understood, relative to the temperature variations expected in the operating environment of the camera.

Methods have been developed that allow for measurement of individual contributing noise sources in simple CCD cameras [6], and total temporal and spatial noises for all cameras [7]. The aim of this work is to measure and quantify the effect of temperature on illumination independent spatial and temporal noises across several industrial cameras.

II. CAMERA NOISE

Camera noise can be categorized into illumination dependent and illumination independent types. The illumination dependent noises are exhibited as pixel-value

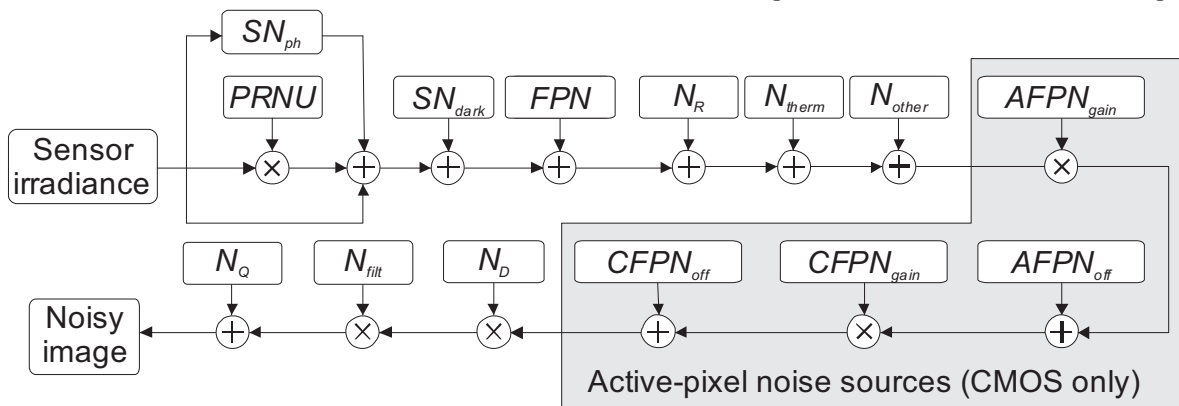


Figure 1: A diagram of the noise-flow for a typical camera. The noise sources in the shaded area represent additional noise sources present in CMOS cameras only. Plus symbols refer to additive noises, whereas crosses represent multiplicative noise sources.

variations in response to an illuminant, and include photo-response non-uniformity (the variation between the gain present at each pixel source) photon shot noise (the noise arising from the Poisson process of counting individual photons), and active gain sources (CMOS only). These noises are not evaluated in this study. Illumination independent noise sources are present at every pixel regardless of whether they are being illuminated or not, and are the focus of this study. When combined, they provide a minimum level of noise present in the captured image.

Figure 1 shows the noise path in a typical image sensor. The abbreviations for the noise types are as follows:

SN_{ph}	Photon shot-noise
$PRNU$	Photo-response non-uniformity
SN_{dark}	Dark-current shot-noise
FPN	Fixed-pattern noise
N_R	Reset noise
N_{therm}	Thermal noise (Johnson-Nyquist)
N_{other}	Minor contributors such as $1/f$ flicker noise and conductor shot-noise.
$AFPN_{gain}$	Active gain FPN (CMOS only)
$AFPN_{off}$	Active offset FPN (CMOS only)
$CFPN_{gain}$	Column gain FPN (CMOS only)
$CFPN_{off}$	Column offset FPN (CMOS only)
N_D	Demosaicing effects (colour-filter array sensors only)
N_{filt}	Filtering effects (e.g., gamma, gain, etc)
N_Q	Quantization noise

Of these noise sources, N_R , N_{therm} , N_{other} , SN_{dark} , FPN , and the CMOS-only types have direct dependencies upon temperature. FPN , $AFPN_{off}$ and $CFPN_{off}$ contribute to spatial noise, whereas N_R , N_{therm} , N_{other} , SN_{dark} , $AFPN_{gain}$ and $CFPN_{gain}$ contribute to temporal noise. As the noise path is quite complex (especially for CMOS image sensors) the values for total temporal and total spatial noise will be measured by analysis of the cameras' output images. Detailed descriptions of all sources can be found in the literature [1-4, 8-12].

III. METHOD OF NOISE ANALYSIS

Spatial image noise is exhibited as variations arising between pixels in an image, and when measured in dark conditions it is dominated by FPN and $AFPN_{off}$ [13]. The generation of an image of spatial noise, $\overline{image(i,j)}$, is given by:

$$\overline{image(i,j)} = \sum_{k=1}^n P_k(i,j)/n \quad (1)$$

where n is the number of images and $P_k(i,j)$ is the pixel value for row i , column j , in the k^{th} image. The rows of the image can be concatenated and the standard deviation calculated, giving an estimated value of spatial noise $\tilde{\sigma}_{spatial}$.

Temporal noise can be measured by taking the average value of the variations exhibited by a pixel over a series of images. The equation for the estimate of temporal noise, $\tilde{\sigma}_{temp}$, is:

$$\tilde{\sigma}_{temp} = \frac{\sum_{y=1}^j \sum_{x=1}^i \sigma(x,y)}{i \times j} \quad (2)$$

where i and j are the number of rows and columns respectively and $\sigma(x,y)$ is the standard deviation of the pixel at (x,y) over n images.

Quantization affects all non-trivial data captured digitally, and can contribute noise of up to $\sigma = 0.29$, for data with significant variation [6]. However, as the images will be captured with no irradiance upon the image sensor, the resultant captured images will not contain significant variation, except when several pixel-values worth of noise is present in the image. Quantization noise for images in dark conditions was studied using simulated images with added noise. Figure 2 shows the resulting analysis on simulated images. As expected, measured noise equals the added noise when the data is unquantized. However, results from analysis of the quantized data demonstrate that noise is under-measured for values of added noise $\sigma < 0.29$ and over-measured for $\sigma > 0.29$. In the analysis of the experiments reported here, all measured values of noise will be adjusted for quantization error, giving the final measured values of spatial and temporal noise:

$$\begin{aligned} \sigma_{temp} &= \tilde{\sigma}_{temp} - N_Q(\tilde{\sigma}_{temp}), \\ \sigma_{spatial} &= \tilde{\sigma}_{spatial} - N_Q(\tilde{\sigma}_{spatial}). \end{aligned} \quad (3)$$

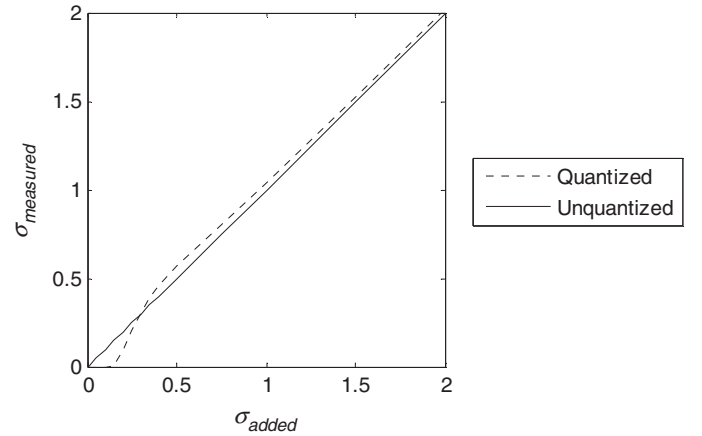


Figure 2: The measured effects of quantization noise on simulated, noisy images in dark conditions.

Simple bilinear demosaicing of the commonly used Bayer colour filter array attenuates the noise levels to 75% of the actual value for the green channel, and 73% for the red and

blue channels [6]. Cameras that only provide bilinear demosaicing as an output option will have their noise measurements adjusted accordingly to compensate for the attenuation.

IV. EXPERIMENTAL SETUP

The total spatial and temporal noise characteristics for 4 different industrial cameras (specifications given in Tables I-IV) were measured using the method described in Section III, where 100 images were captured at each temperature, for a range of environmental temperatures for each camera. The resulting analysis returns the standard deviation of temporal noise σ_{temp} and spatial noise $\sigma_{spatial}$. The 4 cameras were placed in a sealed, temperature-controlled thermal chamber, as shown in Figure 3. Each camera had its image sensor covered to stop any light entering the sensor. The cameras were run at 30 FPS and the temperature of the chamber was set to the desired level, with 10 minutes of settling time provided before images were saved to allow the image sensors to reach thermal equilibrium with the environment. Multiple computers then captured a series of images from the 4 cameras from 21.1°C and 55.2°C in steps of 1-2°C.



Figure 3: The temperature-controlled thermal chamber with the 4 cameras under test.

All cameras had filtering disabled (e.g., gamma turned off, colour balance neutral, etc) with all options set to manual mode. Where possible the raw images were captured from the cameras.

V. RESULTS

Patches of 500x150 pixels that were visually identified free from ‘hot pixels’ (disfunctional pixels that always return maximum value) were extracted from the captured images for subsequent noise analysis. Values of σ_{temp} and $\sigma_{spatial}$ were calculated, and the results shown in Figures 4-7. All cameras were pushed beyond their specified operational temperature range, which are indicated by the dashed lines in the figures.

The spatial noise results demonstrate reasonable consistency with an expected increase in noise with temperature for the F044C (CCD), F080C (CCD) and 1210-C (CMOS) cameras, at least up to the maximum specified operating temperature. The CMOS camera results exhibit a classical exponential increase, up to and beyond the maximum operating temperature, though its overall spatial noise is up to a magnitude higher than those of the CCD cameras. The i400's spatial noise response demonstrates an unexplained bump between 37 and 50°C.

TABLE I. SPECIFICATIONS FOR THE ALLIED VISION TECHNOLOGIES GUPPY F044C CAMERA

Parameter	Value
Sensor type	Sony ICX419AKL 1/2" colour CCD, (CMYG colour filter)
Native resolution	752 x 580
Video mode	RAW 8-bits (binned pairs)
Interface	IEEE-1394a (Firewire)
Operating Temperature	5°C to 45°C

TABLE II. SPECIFICATIONS FOR THE ALLIED VISION TECHNOLOGIES GUPPY F080C CAMERA

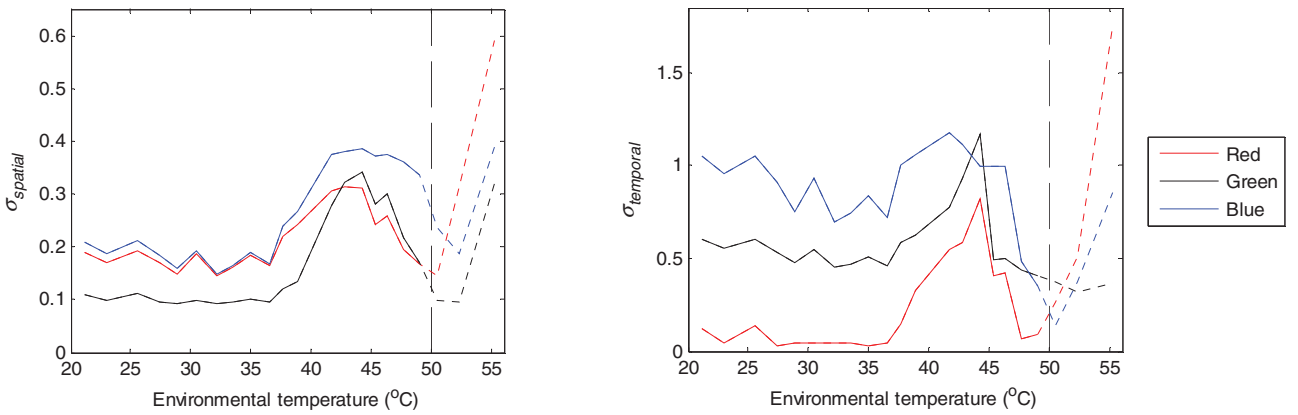
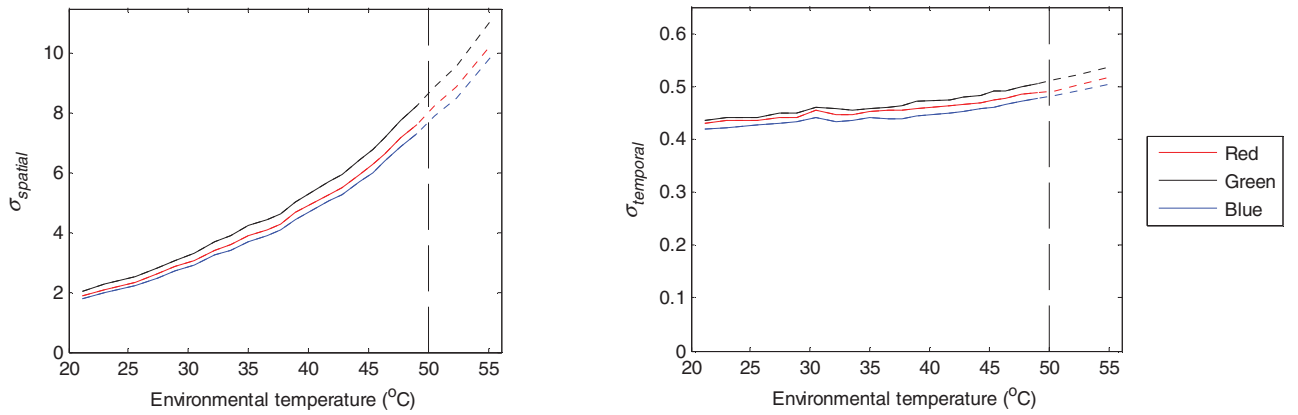
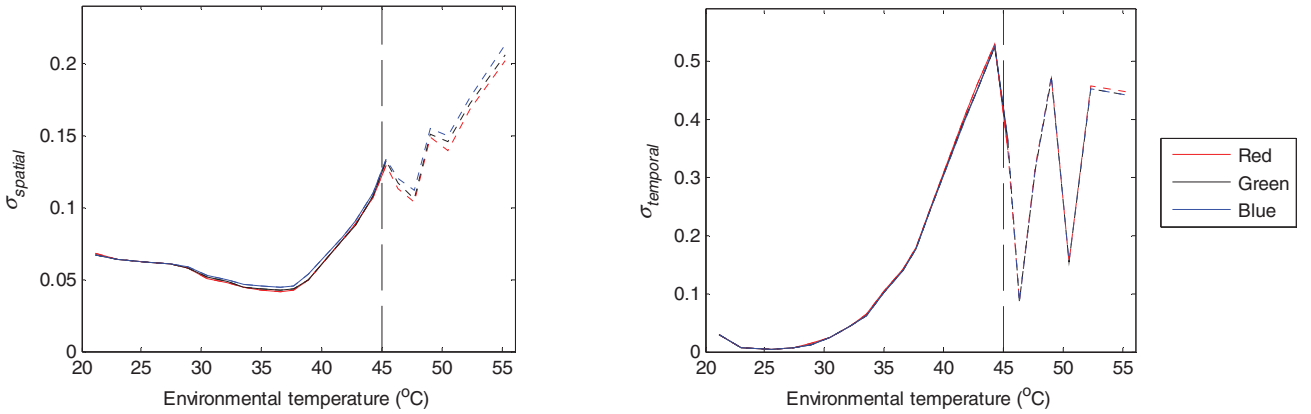
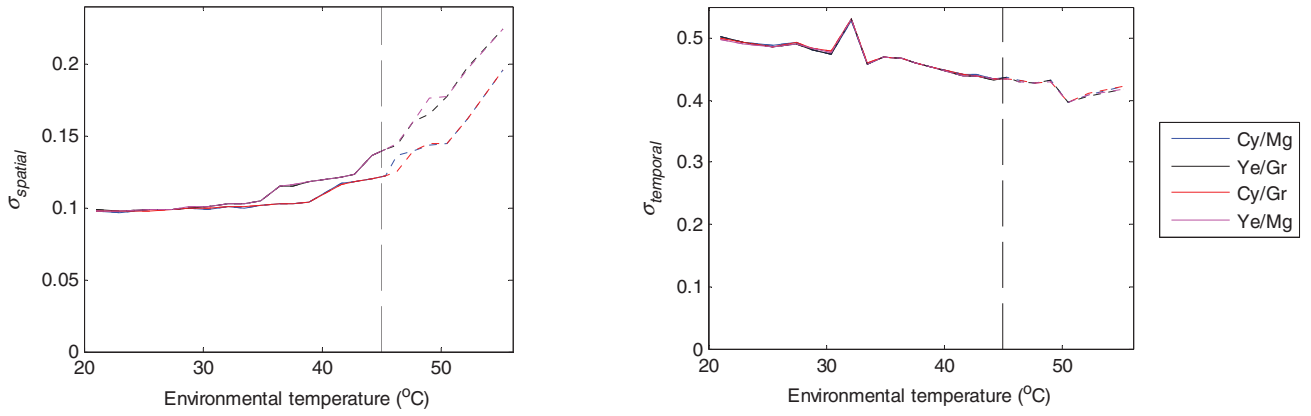
Parameter	Value
Sensor type	Sony ICX204AK 1/3" colour CCD (Bayer colour filter)
Native resolution	1032 x 778
Video mode	RAW 8-bits
Interface	IEEE-1394a (Firewire)
Operating Temperature	5°C to 45°C

TABLE III. SPECIFICATIONS FOR THE IDS UEYE UI1210-C CAMERA

Parameter	Value
Sensor type	1/2" Zoll colour CMOS (Bayer colour filter)
Native resolution	640 x 480
Video mode	24-bit RGB (8-bits/channel), Bayer demosaiced
Interface	USB 2.0
Operating Temperature	0°C to 50°C

TABLE IV. SPECIFICATIONS FOR THE UNIBRAIN FIRE I400 CAMERA

Parameter	Value
Sensor type	Sony Wfine ICX098BQ 1/4" color CCD (Bayer colour filter)
Native resolution	640 x 480
Video mode	24-bit RGB (8-bits/channel), Bayer demosaiced
Interface	IEEE-1394a (Firewire)
Operating Temperature	-10°C to 50°C



Temporal noise results demonstrate a higher consistency of values across the cameras, although additional unexplained trends are present. The F044Cs temporal noise decreases with temperature, while the F080Cs noise increases semi-exponentially up until the maximum rated temperature before exhibiting substantial amounts of oscillation. The 1210-C has a slight exponential trend with increasing temperature while the i400 demonstrates very low temporal noise for the red channel, with very high relative temporal noise for the blue channel. Again, from 37°C and upwards the i400 demonstrates an unexpected bump, followed by a sudden jump when operating above its recommended operating temperature.

VI. DISCUSSION & CONCLUSIONS

Each camera measured has a unique noise response, with only the CMOS camera demonstrating what could be described as a 'classical' increase in noise with temperature. It is likely that the complex electronic circuitry required for charge transfer and readout of CCD image sensors contributes significantly to the unusual noise characteristics displayed by them. The F080C and i400 CCD cameras demonstrated unexpected behavior, especially when in an environment that surpassed their maximum rated operational temperature. Further, all CCD cameras exhibited lower temporal noise responses at 51°C than at 41°C. The i400 shows a significant jump in both temporal and spatial noises when in a 55°C environment – just 5°C higher than its rated maximum operating temperature.

This research has highlighted two important facts: base-line noise between different models of camera can vary significantly, and some cameras demonstrate unpredictable noise characteristics when running beyond their maximum rated temperature. The AVT F080C demonstrates the lowest noise levels when operating in conditions below around 35°C, while the uEye 1210-C response is the most smooth and predictable, especially at the higher temperatures. The implications for camera-based applications are significant if the camera will experience substantial changes in environment temperature.

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