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CCD characterization for a range of color cameras

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Abstract *– CCD cameras are widely used for remote sensing and image processing applications. However, most cameras are produced to create nice images, not to do accurate measurements. Post processing operations such as gamma adjustment and automatic gain control are incorporated in the camera.*

When a (CCD) camera is used as measurement instrument, it is important to have an accurate model of the imaging process and its noise. This model needs to be verified for the camera at hand and the model parameters should be estimated. Often however, a model is assumed and optimal performance is claimed without verification of the model.

In this paper we will analyze a range of different types of cameras. We verify a general model of a CDD camera including post processing using experiments. It is shown that for a typical consumer webcam, the general model does not hold.

The parameters of the model are estimated. It is shown that for most cameras the model can even be simplified under normal operating conditions by neglecting the dark current. We further show that the amount of additive noise is exceeded by the amount of multiplicative noise at intensity values larger than 10-30% of the intensity range.

Keywords *– Color cameras, Gamma, Camera noise, Intensity measurements.*

I. INTRODUCTION

CCD cameras are widely used for remote sensing and image processing applications. For many applications it is important to have a model of the imaging process and temporal image noise. For example for the correction of temporal changes in intensity [1], illumination-invariant optical flow computation [2] or object detection [3], [4].

Each author uses a model that fits his/her needs. However, little work is performed on the question how accurate these models are for a specific camera, and the importance of the different components of the model. In this paper we evaluate a camera model for a range of different camera types, from a high end 10-bit digital camera to a consumer webcam. We evaluate the model and determine the value of all model parameters.

To be able to model all possible effects of the CCD, we use the general model of a CCD camera introduced in [5]. Most modern cameras use some kind of gamma adjustment to map the image in the available quantization range for obtaining a better looking image. Therefore we add gamma correction to this model. We describe experiments to evaluate this model using a test object. The experiments are then used to verify the model and determine the model parameters for all cameras. These experiments are repeated for different image intensities to allow verification of the model at different settings of the camera (auto-)gain.

Besides verification of the model we show the effect of the individual contributions in the model to allow for simplifications. In particular, we evaluate:

- whether the gamma function in the camera is sufficiently accurately described by our model,
- what the effect of the dark current is,
- what the noise distribution is.

This paper is structured as follows. First, a theoretical model of a CCD camera will be given in section II. Then in section III we give the measurement setup and results. These results lead to simplification of the model given in section IV. Finally, conclusions are drawn in section V.

II. THEORETICAL MODEL OF A CCD CAMERA

Healey [5] describes the following model for a single pixel recorded at time t using a CCD camera

$$i_{\mathrm{t}} = g_{\mathrm{t}}(i_0 + \mu_{\mathrm{DC}} + N_{\mathrm{S}} + N_{\mathrm{R}}) + N_{\mathrm{Q}} \tag{1}$$

with i_0 the true scene intensity and i_{t} the measured image intensity. The following contributions are present: the dark current μ_{DC} which is constant over time (it is an offset). Note that we use μ_{x} for the mean of x and σ_{x} for its standard deviation . Shot noise N_{S} which has a Poisson distribution with $\mu_{\mathrm{S}} = 0$ and σ_{S} depends on $h_{\mathrm{t}} i_0$. Readout noise N_{R} with a Gaussian distribution: $\mu_{\mathrm{R}} = 0$, σ_{R} is constant. Quantization noise N_{Q} which has a uniform distribution $U(-\frac{q}{2}, \frac{q}{2})$ with q the smallest

TABLE I

THIS TABLE LISTS THE CAMERAS USED TO VERIFY THE CCD MODEL.

Camera	Description	Gain control
JAI CV-M7+CL	High end 10-bit digital camera with Bayer filter	Fixed
Siemens C810	Digital computer vision color camera	Automatic
JVC GR-DVL-157	Digital consumer color video camera	Automatic
Philips PCVC680K	Color webcam	Automatic

step in pixel value. The camera gain g_{t} can be fixed or automatically adapted to the scene (automatic gain control).

Additionally, most cameras apply a gamma adjustment to map the range of intensity values on the CCD to the available output range. Assuming it is implemented in the electronics of the camera just before digitization this changes equation 1 to

$$i_{\mathrm{t}} = g_{\mathrm{t}}^{\gamma}\left(i_0 + \mu_{\mathrm{DC}} + N_{\mathrm{S}} + N_{\mathrm{R}}\right)^{\gamma} + N_{\mathrm{Q}} \qquad (2)$$

with γ the value of gamma which is assumed to be constant over time and equal for all pixels.

III. MEASUREMENTS

For the verification of the model given above, measurements were performed with a range of different types of cameras. A list of the cameras used is given in table I. As measurement object we used a half-transparent plate which is homogeneously back-illuminated. In front of this plate are layers of gray and brown filters with different thickness, see figure 1. There are nineteen different sections, zero to five layers of gray filter on the top row and zero to thirteen layers of brown filter on the center and bottom row. The intensity of each of the nineteen different sections differs, its average intensity is measured by a photon counter.

Imagery depicting this object was recorded with several cameras. Different sequences were recorded, each sequence consisting of 100 images to estimate the temporal mean and variance. To investigate the automatic gain control, we recorded the measurement object with different intensity-filters directly in front of the camera lens. This causes lower overall intensity. However, this is not sufficient to evaluate the model as in reality also part of the scene may change. We need to evaluate whether this effects the model parameters. For all cameras, the grayvalue range was scaled to $[0, 1]$.

Therefore a second set of data was recorded. This time for different sequences, different parts of the object were covered. This changes the covered part of the scene to black, while leaving the remainder of the scene unchanged. This will trigger the automatic gain control and any other postprocessing of the camera used while leaving some sections to measure on.

A. Gamma estimation

For each sequence of 100 images the standard deviation and average of one (the red color) channel were calculated both per pixel and for the sections with equal intensity as a whole. Saturation effects are not considered, therefore the top 10% and bottom 10% of the intensity range are not taken into account.

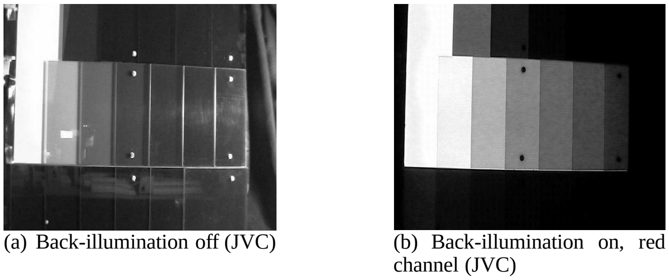
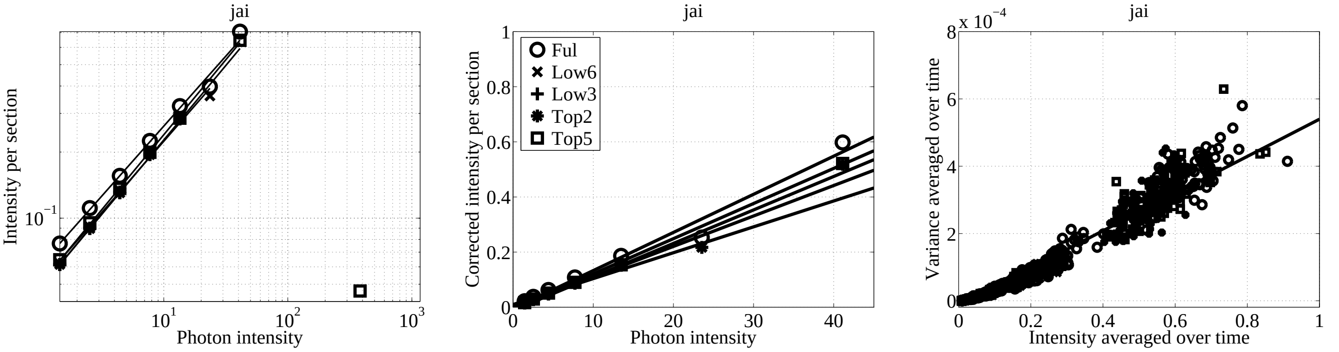

(a) Back-illumination off (JVC) (b) Back-illumination on, red channel (JVC)

Fig. 1. Two pictures of the measurement object.

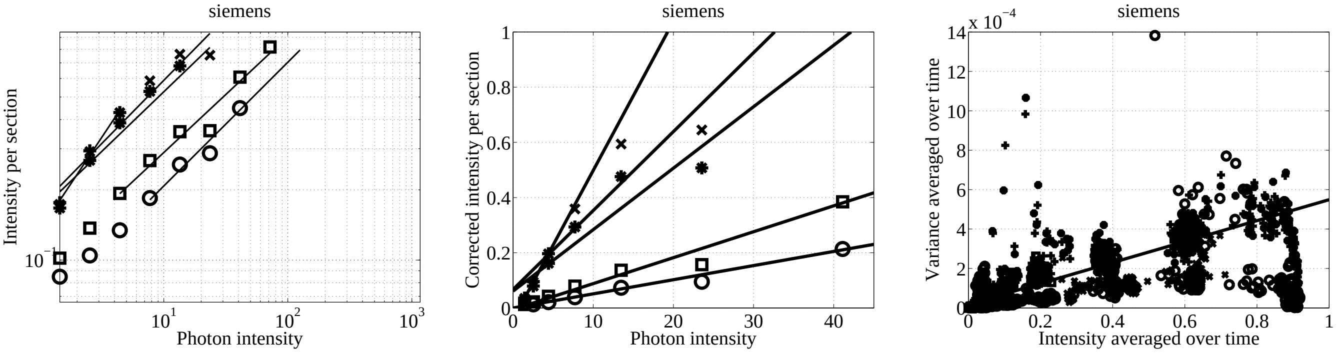
The gamma can now be estimated from a log-log plot of the average intensity per section against the true (photon counter measured) intensity of that section. All data points should lie on a straight line (at least for points with intensity much greater than the dark current) with a slope equal to gamma. For the actual results see the figures on the left in figure 2. The estimated gammas for all cameras are given in table II. As expected, all cameras have a gamma smaller than one and for most cameras the individual data points are close to a straight line. Therefore we conclude that *our model of the gamma is sufficient.* However, this does not hold for the webcam. Figure 2(j) shows that the exponential model is not a good description of the data. The estimated value of gamma differs with intensity between 0.55 and 0.73.

B. Dark current estimation

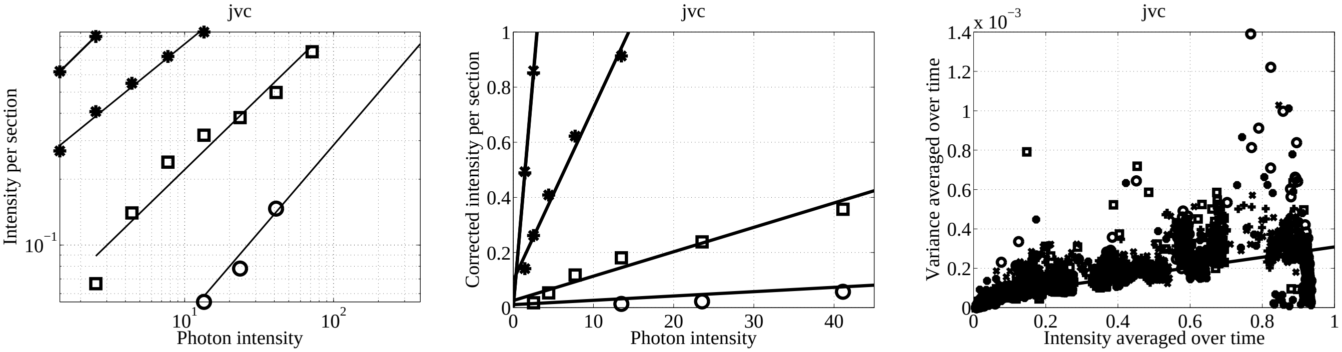
Using the gamma estimated above we correct the image sequences and recalculate the average intensity for each section. Plotting these against the true intensity of the sections should now give a straight line which intersects the section-intensity axes at a value related to the dark current, see the figures in the center of figure 2. The estimated dark current and the error of the estimate are given in table II. The dark current we estimated is for all cameras smaller then the standard deviation of the estimate, so we conclude that for pixels with a sufficiently large intensity *we can neglect the dark current.*



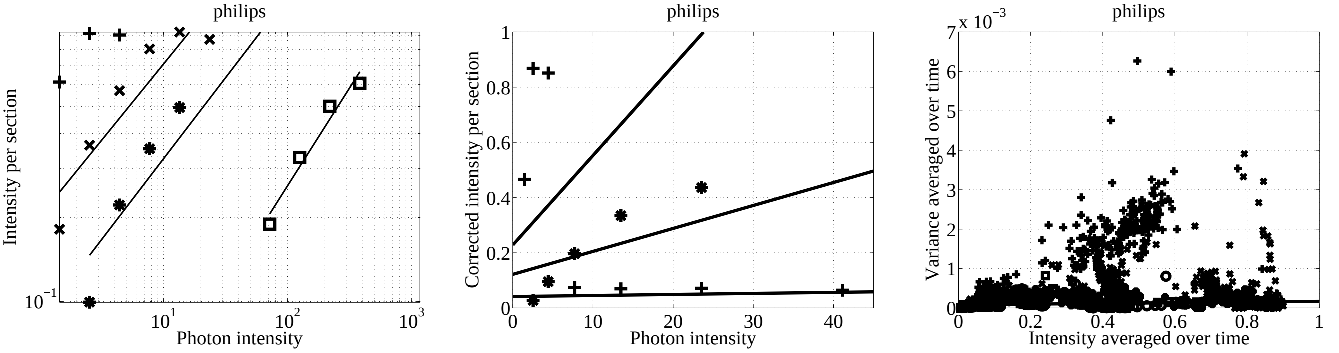
(a) JAI, gamma (b) JAI, gamma-corrected (c) JAI, noise



(d) Siemens, gamma (e) Siemens, gamma-corrected (f) Siemens, noise



(g) JVC, gamma (h) JVC, gamma-corrected (i) JVC, noise



(j) Philips webcam, gamma (k) Philips webcam, gamma-corrected (l) Philips webcam, noise

Fig. 2. Results for all cameras. On the left we see a log-log plot of the image intensity per section against the true intensity of the sections. The center graphs show a plot of gamma-corrected image intensity per section against the true section intensities. The right graphs show for a number of pixels the standard deviation over time plot against the average over time. The different sets of data are recorded with different parts of the measurement object, see the legend in subfigure (b): Full, the entire object is visible; Low6, only the six sections at the bottom are visible; Low3, Only the darkest three sections are visible; Top2, the two darkest sections of the middle row and the entire bottom row are visible; Top5, the five darkest sections of the middle row and the entire bottom row are visible.

TABLE II

RESULTS OF THE CAMERA CHARACTERIZATION FOR EACH OF THE CAMERAS. ALL ESTIMATES ARE LEAST SQUARES ESTIMATES OF THE AVAILABLE DATA. BETWEEN BRACKETS ARE THE STANDARD DEVIATIONS OF THE ESTIMATES. THE AMOUNT OF MULTIPLICATIVE NOISE IS GIVEN FOR THE HIGHEST PIXEL VALUE (ONE IN OUR CASE).

Camera	Gamma	Dark Current μ_{DC}	Additive noise N_{R}	N_{Q}	Multiplicative noise N_{S}
JAI CV-M7+CL	0.66 (0.02)	-0.005 (0.012)	0.003	0.0003	0.021
Siemens C810	0.53 (0.02)	0.07 (0.21)	0.003	0.001	0.021
JVC GR-DVL-157	0.72 (0.06)	0.05 (0.10)	0.005	0.001	0.019
Philips PCVC680K	0.70 (0.10)	0.09 (0.09)	0.012	0.001	0.011

C. Noise estimation

The distribution of the noise in the CCD model contains both additive and multiplicative noise. We plot the standard deviation over the gamma-corrected images against its average for a number of pixels to see the effect of both contributions, see the figures on the right in figure 2. The intersection of a straight line fitted to this data with the standard deviation axes gives us the contribution of the additive noise and the slope of the line gives the amount of multiplicative noise. Estimates of the amount of additive and multiplicative noise are given in table II. The amount of multiplicative noise exceeds the amount of additive noise at intensities greater than 10 to 30% of the intensity range. Therefore we conclude that for all cameras except the Philips webcam *we can neglect the additive part of the noise* for practical applications. We can also neglect the quantization noise.

For the webcam the additive part of the noise is more important than the multiplicative part for the entire intensity range, see figure 2(l).

D. Artifacts

The Philips webcam seems to have some artifacts, see figure 2, bottom row. Among others a gamma that changes with intensity and is not sufficiently modelled by the exponential. Therefore this camera violates the general model given in equation 2.

IV. SIMPLIFICATIONS TO THE CCD MODEL

Our experimental validation concludes that we can neglect the contribution of the dark current as the measured value lies within one standard deviation from zero. This simplifies equation 2 to

$$i_{\mathrm{t}} = g_{\mathrm{t}}^{\gamma}\left(i_0 + N_{\mathrm{S}} + N_{\mathrm{R}}\right)^{\gamma} + N_{\mathrm{Q}} \; . \tag{3}$$

The remaining noise terms all are zero-mean. The shot noise N_{S} is multiplicative and the readout noise N_{R} and the quantization noise N_{Q} are additive.

Our experiments also showed that the additive noise contributions (N_{R} and N_{Q}) are equal to or smaller than the multiplicative noise contribution for sufficiently large intensity values (larger than 10-30 % of the intensity range). For sufficiently large intensity this simplifies the above equation to

$$i_{\mathrm{t}} = g_{\mathrm{t}}^{\gamma}\left(i_0 + N_{\mathrm{S}}\right)^{\gamma} \; . \tag{4}$$

V. CONCLUSIONS

In this paper a model of a CCD model was introduced and experimentally evaluated using a range of different types of cameras. Experiments showed that the model of the CCD is sufficient for most cameras. The gamma correction in these cameras is sufficiently accurately described by the exponential gamma in the model.

Experiments further demonstrated that for sufficiently large pixel intensities the model can be simplified. The dark current can be neglected for these pixels and the additive noise is exceeded by the multiplicative noise at intensities of 10-30% of the intensity range.

Using this model, all cameras except for the webcam can be used for accurate measurements. Using the webcam for computer vision can introduce problems as its response cannot be predicted using a common CCD model. The gamma is not accurately modelled by the general model and depends on the image intensity.

Results on the webcam show that it is wrong to pick a general model and assume its validity. It is important to validate the model for the specific camera used.

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