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ALGORITHM FOR COMPUTATION OF DARK FRAMES IN A CMOS IMAGER

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Rezumat. *Curentul de întuneric este produs de electronii excitaţi termic în banda de conducţie, care creează astfel un semnal fals ce se adaugă imaginii digitale. Se prezintă un algoritm care corectează automat acest efect în cazul unui „imager" CMOS disponibil în comerţ folosind un protocol de calibrare care să caracterizeze senzorul de imagine pentru diferite temperaturi, diferiţi timpi de expunere şi diferite setări ale amplificării. Protocolul de calibrare foloseşte pixeli fierbinţi, care au cel mai mare raport semnal/zgomot, drept indicatori ai curentului de întuneric în restul chip-ului. Curentul de întuneric al pixelilor fierbinţi cu comportare bună pot astfel să fie folosiţi pentru a prevedea curentul de întuneric al tuturor pixelilor din chip, făcând astfel posibilă o precisă corectare a întregii imagini.*

Abstract. *Dark current is caused by electrons that are thermally excited into the conduction band, adding a false signal to a digital image. We present an algorithm that automatically corrects for dark current in a commercially available CMOS imager by using a calibration protocol to characterize the image sensor for different temperatures, exposure times, and gain settings. The calibration protocol uses hot pixels, which have the highest signal-to-noise ratio, as indicators of dark current in the rest of the chip. The dark current of well-behaved hot pixels can thus be used to predict the dark current of all pixels on the chip, making possible an accurate correction for the entire image.*

Keywords: digital images, CMOS, image correction, dark current

1. Introduction

Dark current is a major source of noise in digital imagers. To decrease the generation of dark current, many camera systems are cooled. In some cases, e.g. consumer cameras, a cooling system is not feasible and dark current can become a problem even for short exposures.

A standard method for dark current correction is to take a so-called dark frame, an exposure with a closed shutter, either right before or right after the light exposure. This dark frame is subsequently subtracted from the actual image.

Previously [1], we reported on a method to compute the dark frame for a CCD imager from the actual image which we want to correct for the dark current.

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This has the following advantages: this correction can be carried out without knowledge of the exposure time or temperature and without loss of imager time to collect a dark frame. It will lead to improved image quality and will benefit image fidelity. Moreover, it can be done ex post facto and it provides the ability to remove sensor specific information [2]. It has been surmised that such computations should be feasible for CMOS imagers as well. With the rise of CMOS sensors' importance in consumer electronics, automotive applications [3], and security [2] and with the improvement of CMOS quality, this technique could be broadly applicable.

The goal of the present study is to verify the applicability of the image correction algorithm, as previously applied to scientific CCD imagers, to a commercially available CMOS sensor. This work is the extension of our previous work on the same CMOS sensor [4]. The description of the dark current in a CCD is similar to the analysis of the dark current in a diode and requires taking into account several sources of dark current [5-7]. The knowledge of how each individual pixel's dark current changes with temperature, exposure time, and gain can be used to calculate artificial dark frames. However, for many cameras the exact conditions are not precisely known.

Our proposed dark current correction method does not require this knowledge. The dark current of any pixel can therefore be used as an indicator of the temperature or exposure time. Impurities in the silicon cause some pixels to have an unusual dark count [8, 9]. These hot pixels have the highest signal-to-noise ratio and are the best dark current indicators. The basic idea is to use the dark current of hot pixels to obtain an indicator and predict the dark current of all pixels on the chip. Addressing noise in CMOS imagers has a long history [10-15]. In the first part of this work, we will present the protocol for dark current correction. The results of the image correction based on this protocol for a CMOS imager is shown in the second part.

2. Correction algorithm

In order to see what is involved in dark frame computation, we briefly summarize the correction protocol [1]. A set of dark frames at various temperatures and exposure times is taken, and the following basic steps are executed. The first step is to locate hot pixels to serve as dark current indicators. These are selected from an image with a sufficiently large dark signal. A hot pixel in this context has a large dark signal compared to its neighboring pixels. The neighboring pixels are of significance because in an actual image containing signal information, they are used to predict the light signal. Removing the light signal works accurately only if there is high degree of correlation between the light signal of the hot pixel and its adjacent pixels. In most images, this correlation between adjacent pixels is very high. The hottest pixels are found by ranking the values of:

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where (x, y) are the coordinates of the pixel and *pixel*(x, y) is its dark count.

Only the immediate neighbors of the hot pixel are considered. However, it is possible to include a wider area and increase the range of the summation. The *weight*(i, j) depends on the relative location of an adjacent pixel.

Various weighting factors can be chosen. The sum of all the weighting factors equals zero, such that if all nine pixels are equally hot, *hotpix*(x,y) is equal to zero. The weights chosen were as follows: the center pixel has weight 1, the nearest neighbor pixels have weights of − 0.2, and the next-nearest neighbors have weights of − 0.05. This means that, if all pixels have the same value, then *hotpix* is equal to zero. The next step is to calculate the median of *hotpix*(x y) for the n hottest and well behaved pixels for frames at different temperatures and exposure times and this value is used as an indicator for the chip's dark current (DCI). Then, the value of *hotpix*(x, y) is fitted to a quadratic function of the DCI.

Hot pixels which have a poor goodness of fit are excluded. Next, one stores the coordinates of all hot pixels, as well as the three fitting parameters, in a file which contains all the information to evaluate the dark current of the chip. Note that one does not use the actual temperature or exposure time (nor does one need to know those).The next step in the protocol is to determine the counts of all pixels with respect to the DCI. To accomplish this, the counts of each pixel for different frames, are fitted with a quadratic least squares fit versus the DCI. Since this fit is used later to calculate the dark count, independent from the neighboring pixels, the actual count of the pixels (not the signal with respect to the neighboring pixels) is used to determine the fitting parameters. The three fitting parameters from the quadratic fit can then be saved as images with the same dimensions as the chip. Once the imager is characterized and calibrated with these fitting parameters, dark frames can be calculated almost instantaneously over the whole calibrated range.

3. Results

We used a Firefly MV camera with a 1/3" CMOS color sensor manufactured by Point Grey Research, Inc. to analyze the performance of the dark current correcting algorithm for CMOS sensors. The chip is a double-buffered global-shutter photodiode device (640 × 480 pixels, 6.0 × 6.0 μm pixels, manufactured by Micron – MT9V022177ATC). The Firefly camera is well behaved in that after the temperature was stabilized for a sufficient time span, the measurements were repeatable. Automatic exposure control and color conversion were turned off. The camera was placed inside a temperature-controlled chamber.

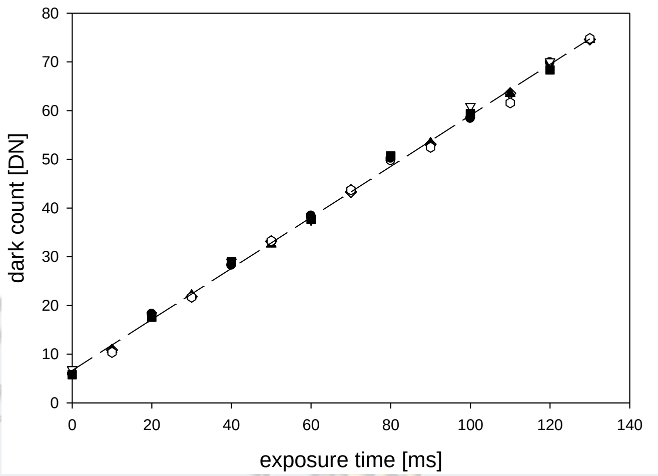


Fig. 1. Dark current indicator versus exposure time for 42 images at 35°C and 12 dB.

The camera is capable of both 8 and 10-bit linear data acquisition. For this work, we choose to present exclusively 8-bit data. The 10-bit data behaved similarly to the present data. The gain was set to 12 dB corresponding to 11.4 DN/e. The brightness setting, essentially a bias offset, was adjusted so that at 0ms all pixels had a small positive signal. The camera was set to frame rates of 7.5 Hz and exposures from 0ms to 130 ms every 10 ms were taken. The camera was set to 35°C and calibrated with three images for each exposure time resulting in a total of 42 (3 × 14) calibration frames. Out of an initial set of 2000 hot pixels 100 dark current indicators (DCI) were chosen. In addition to the large change in dark count over the calibration range, these 100 indicators showed a high degree of correlation and predictability. Figure 1 shows the DCI for the 42 images taken at 14 different exposure times. One can see that the indicators for a constant exposure time are similar. It is important to note that not all cameras are as well behaved. Some systems, in particular consumer cameras, show a change in dark current between different shots taken with the same exposure time. The dark current increases approximately linearly with the exposure time. However, the calibration algorithm does not require a linear increase in dark current signal and can be applied even if the exposure times are not known to the user. After the initial calibration, images that are taken within the calibration range can be corrected. In our case the calibration encompasses images taken at 35°C and 12 dB with exposure time from 0 ms to 130 ms. The correction can also be applied with good results to different temperatures and gains as long as the signal does not differ significantly from the calibration frames. Figure 2 shows the indicated dark current of all 100 indicator pixels for an image taken at 35°C, 12 dB and 50 ms.

The dark current indicated by the different DCI pixels varies due to noise in the system. Its median value of 33.1 can be used as a proxy for the dark current of all pixels on the chip.

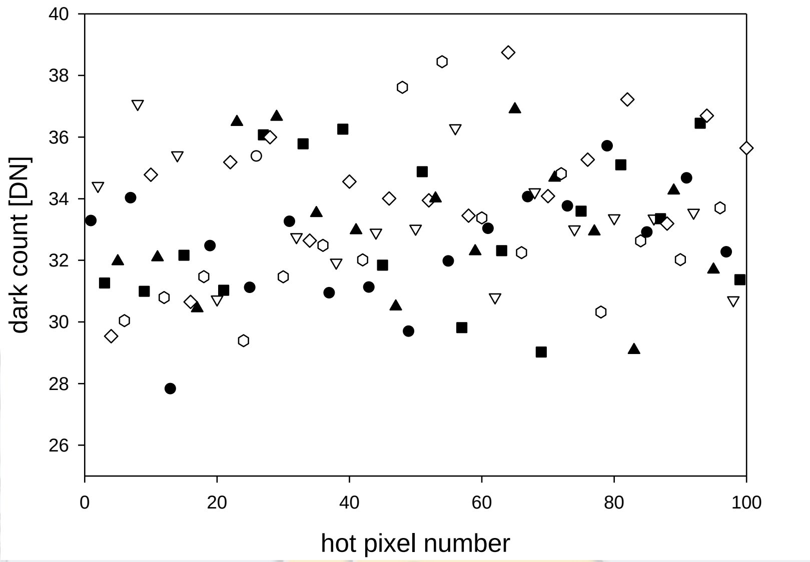


Fig. 2. Dark current indicator of the 100 DCI pixels for an image taken at 35°C, 12dB, and 50ms.

Figure 3a shows a histogram of the dark current of the 50 ms exposure of all pixels on the chip. The average dark count of the frame is given as 40.8 DN with a few pixels having counts of 150 DN and more. Although not a Gaussian distribution, the standard deviation can be used as a measure of the width of the distribution. In this instance, the standard deviation is given as 7.8 DN. Using the DCI of 33.1, we can generate the histogram for the calculated frame. The histogram in Figure 3b is similar to Figure 3a and shows the distribution of dark current of the computed frame. Subtracting the calculated frame from the 50 ms images corrects the dark current of the exposure. Figure 3c shows the distribution of the corrected frame. To avoid negative values due to noise, a constant value was added. One can see that the distribution is almost symmetrical and much narrower than the original frame. The standard deviation of 7.8 DN from the original frame has decreased to 1.96 DN. No pixel differs by more than 36 DN from the center of the distribution. Next, we wanted to see how the result compares to conventional dark frame correction. For this, nine 50 ms exposures were used to calculate a master frame, which was then subtracted from the original. The difference count, again with an added offset, is displayed in Figure 3d. The distribution has a standard deviation of 2.03 DN, similar to the result of the computed frame.

Hence, the calculated frame gives an excellent dark current correction that cannot be improved even with a more time consuming master frame correction.

Conclusions

We have demonstrated that hot pixels can be used as indicators of the dark current for all pixels on the chip. The protocol described allows the correction of images for dark current over a range of temperature, exposure times or gain settings even when the operating conditions of the device is not known. This computation of dark frames allows the use of a large number of calibration frames and therefore a large signal to noise ratio to obtain a fast and accurate dark current correction.

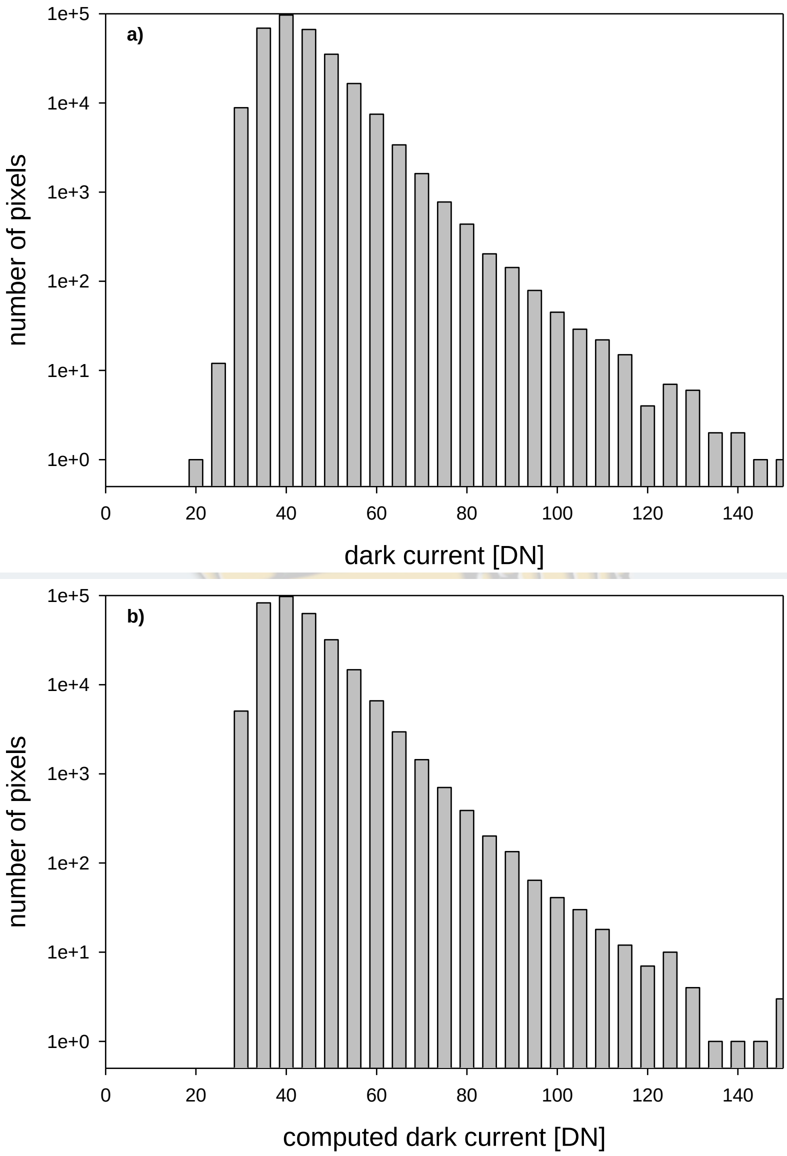
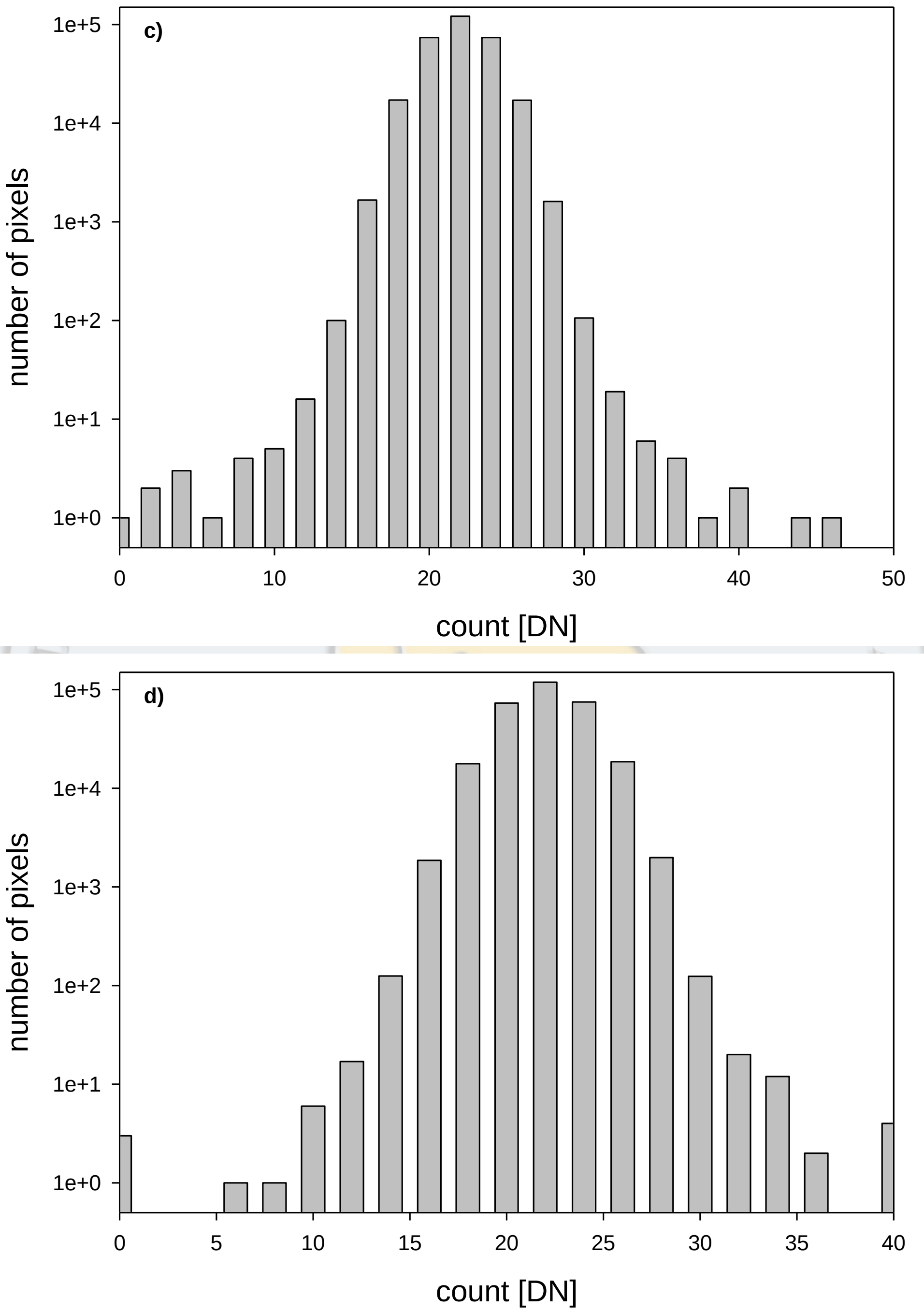


Fig. 3.



Panel a: Histogram for the number of counts of an image (not part of the calibration) at 35°C, 12 dB, and 50 ms.
Panel b: Histogram of the computed frame.
Panel c: Dark current correction with computed frame.
Panel d: Dark current correction with master frame calculated from 9 images taken at 50 ms.

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