Processing of Output Signal of CCD Sensor Exposed by Ionizing Radiation

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Abstract—High image quality CCD image sensors are needed in many applications. Low noise and high dynamic range are critical parameters required in scientific and industrial applications. In many of the applications, however, the CCD image sensor can be irradiated by a ionizing radiation, as alpha, beta, gamma or X-ray. This paper describes output signal processing of low noise, high dynamic range, 1 Megapixel Frame-Transfer CCD FTT1010-M image sensor exposed by ionizing radiation. CCD image sensor driver board with rad-hard components was designed and used during the tests. Results of the investigation will be used in system for protein crystalisation study in microgravity.

I. INTRODUCTION

A 12-bit, 1 Megapixel, high dynamic range CCD camera was designed (see Fig. 1) for application, where an ionizing radiation can be present. However, since CCD sensors are sensitive to ionizing radiation, test setup was created to analyze performance of the FTT1010-M CCD image sensor [1], [3] under ionizing radiation. During several tests the CCD image sensor was exposed by X-ray and gamma ray sources. Degradation of parameters was observed and can be seen when CCD sensor is lighted (bright condition) [6], [7] as well as when the CCD sensor is in dark environment (dark condition). This paper describes measurement results obtained in dark environment and methods of improvements. The CCD image sensor was exposed by 30 rad total dose and was unbiased during the exposure as well as in between following periodical measurements.

II. CCD SENSOR DRIVER

Figure 2 shows block schematic of the CCD image sensor driver used during the radiation tests. Radiation hard components are used to eliminate the possibility of parameter degradation by CCD image sensor driver circuitry.

FTT1010-M is Frame Transfer CCD image sensor, based on bouwblok architecture [4], [5]. Image clock gate driver shifts the image from image area to storage area after image integration period. This shifting must be fast to avoid gradient, caused by difference in integration time between the first and the last line in the image area. The only difference between image and storage area is, that storage area is covered from light. Therefore, the read-out can be relatively slow. During read-out, the storage clock gate driver shifts one line first to horizontal shift register and than horizontal clock driver shifts this line pixel by pixel to the output register of the CCD. Each pixel is processed by CCD.
signal processor using Correlated Double Sampling. Its output 12-bit digital value is stored in SRAM memory. Electrical dynamic range of the camera, measured with virgin, non radiated CCD image sensor, is approx. 65 dB.

Black pixel clamping technique was not applied during the image processing. During normal processing, the CCD signal is referenced to a well established “black level”. This black level is provided by the CCD black lines on bottom of the CCD and black columns on sides of the CCD. However, in our case are the black pixels also influenced by the ionizing radiation and the black pixel clamping would distort the results.

III. MEASUREMENT RESULTS

A. Before gamma ray exposure

The first images were acquired before the gamma ray exposure. During this image acquisition, as well as during following, always two images were acquired. The first one was during bright condition. The CCD sensor was lighted by depolished LED, which was supplied by constant current source. Camera parameters (gain, offset, integration time) were adjusted such, that the CCD was below saturation level and most of the pixels is still below 4095 DN. Histogram of this bright image is in figure 3.

![Fig. 3. Histogram before exposure in bright condition](image)

The second image is taken during dark condition. During this acquisition, the camera parameter setting is similar as above; only the light source is switched OFF. During dark condition the image shall be in an ideal case uniform black, practically is contains a DC offset (which can be modified by camera offset setting) with noise component. Histogram is in figure 4.

![Fig. 4. Histogram before exposure and in dark environment](image)

Noise during dark condition is important parameter, since it is one of the variables, which determines electrical dynamic range of the camera. Value of mean noise is calculated according to following equation:

\[
\text{mean}_{\text{noise}} = \frac{1}{N} \sum_{i=1}^{N} (x_i - \mu_d)^2,
\]

where \( \mu_d \) is the average value of the dark level, \( x_i \) is the value of pixel \( i \), \( N \) is the total number of pixels.

The value of the mean noise during dark condition before CCD exposure is 2.28 DN.

![Fig. 5. Average value of pixels in rows before exposure](image)

Figure 5 shows average value of pixels in rows of the CCD image sensor (note, the sensor is in configuration of 1024 x 1024 pixels, only window of 1000 x 1000 pixels was used for evaluation). From figure 5 is seen, that difference between average value of pixels in row 0 (row on top of the image) and average value of pixels in row 1000 (row on bottom of the image) is approx. 4.5 DN.

B. After gamma exposure

Images were taken immediately after the gamma ray exposure and as well periodically after to observe the tendency of degradation. The CCD image sensor was unbiased in between the measurements. The degradation was measured immediately after the exposure; value of mean noise was 4.47 DN. Seven days after exposure the noise increases to approx. 7.8 DN. One year after exposure the noise saturates on approx. 14 DN. Image taken 520 days after exposure shows noise 14.17 DN.

The effect of the degradation on image taken during dark condition can be seen in figure 6. The image is equalized to highlight the effect.

![Fig. 6. Average value of pixels in rows after exposure](image)

Figure 7 shows average value of pixels in rows of the CCD image sensor image (at dark condition). From the graph can be seen, that difference between average value of pixels in row 0 (row on top of the image) and average value of pixels in row 1000 (row on bottom of the image) is approx. 57 DN. The curve shows linear slope. The steepness is determined by read out time of the image from the CCD image sensor. If the pixel read out rate would be two times lower, the difference between top and bottom row would be two times higher.
in the FPGA, which controls the CCD camera operation. Black pixels located at the side of each line of the image area were taken as reference pixels and value of image pixels was recalculated with respect to them. The steepness of the curve from figure 7 is reduced by approx. 30% by this technique. This shows different radiation damage of the pixels in image area and of the covered black pixels. This effect will be studied. A lot of information can be found in [2].

Disadvantage of digital black pixel clamping technique is that the reference pixels are burden by post processing noise (CCD signal processor conversion noise and nonlinearities, noise introduced by CCD sensor biasing ...). As a result, this error influences values of all pixels in each image area row. This effect was suppressed by averaging of several black pixels of each row. From our measurement results we conclude, that black pixel clamping, as already mentioned in this paper, is not efficient method to cancel the effect of the ionizing exposure damage.

D. Image subtraction method

Another method to improve performance of CCD image sensor exposed by ionizing radiation was method of image subtraction. Principle is based on subtraction of an image and of a reference image. Reference image must be acquired with similar camera setting as desired image, but is taken at dark. The corrected image is than calculated according to formula (2):

$$ DIF_{i,j} = (IMG_{i,j} - REF_{i,j}) + OFFSET, \quad (2) $$

where $DIF_{i,j}$ is value of pixel in row $i$ and column $j$ of the subtracted image, $IMG_{i,j}$ is value of pixel in row $i$ and column $j$ of the desired image, $REF_{i,j}$ is value of pixel in row $i$ and column $j$ of the reference image taken at dark condition and $OFFSET = \text{ABS}(\text{PIXVMIN})$ when $\forall_{i,j} : \text{PIXVMIN} = \text{min}(IMG_{i,j} - REF_{i,j}) < 0$ else $OFFSET = 0$.

Figure 9 shows histogram of corrected image. Value of the mean noise, calculated according to formula (1), is 3.27 DN. This value of mean noise is comparable with value before CCD image sensor exposure.

Figure 10 shows average value of pixels in rows of the CCD image sensor. From the graph can be seen, that difference between average value of pixels in row 0 (row on top of the image) and average value of pixels in row 1000 (row on bottom of the image) is approx. 4 DN. This result is
Figure 10. Average value of pixels in rows 520 days after exposure and with correction by image subtraction method

IV. CONCLUSION

Measurements were performed on camera with FTT1010-M CCD image sensor. Images were acquired before and after 30 rad total dose gamma ray exposure. Degradation of parameters of this image sensor was found. This paper describes methods of canceling of the error due to the degradation. Digital black pixel clamping method was examined. This method is not efficient method to cancel the effect of the ionizing exposure damage. Image subtraction method was efficient to cancel error in dark. Used algorithm is implemented in software on a personal computer. Algorithm can be implemented as well in FPGA or DSP on the camera hardware.

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