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Simulation of the phtodetection in the PPS CMOS sensors

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Abstract. The paper contains an analysis and simulation of passive pixel based sensors. The passive pixel CMOS image acquisition sensor (PPS) is the key part of a visible image capture systems. The PPS is a complex circuit composed by an optical part and an electrical part, both analog and digital. The goal of this paper is to simulate the functionality of the photodetection process that happens in the PPS sensor. The photodetector is responsible with the conversion from photons to electrical charges and then into current. In the optical part, the sensor is analyzed by a spectral image processing algorithm which uses as input data: the lenses array transmittance, the red, green and blue filters and the quantum efficiency of the PPS. In the electrical part of simulation, the program is computing the signal to noise ratio of the sensor taking into account the photon shot, white and fixed pattern noises. Our basic analysis is based on camera equation to which we add the noises.

Introduction

The PPS sensor senses the light that is focused by the optics in order to create a digital record of the scene. During its functionality, the PPS converts the incident light in to numerical signal. The PPS sensors are popular nowadays due to the great development of mobile phones, digital cameras, laptops etc.

At the input of the PPS is the optical part which consists of an array of phododetectors. One photodetector is called pixel [1]. A cross section schematic of the PPS is presented in the Fig. 1.

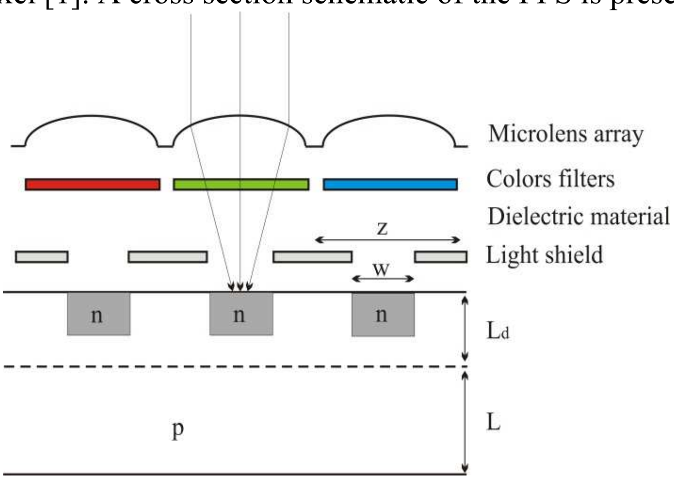


Fig. 1 A simplified pixel cross section view

where: z represents the distance between pixels, w represents the pixels width, L represents the quasi neutral region, L_d represents the depletion length.

In Fig. 1 we can see that the optical part of the PPS consists of a periodic structure of pixels. Each pixel is a photodiode which has in front of it a color filter and a lens. The color filter split the incident image in to red, green and blue colors. The lens focuses the incident light in to the photosensitive area of the photodetector. During the conversion process, appears the unavoidable noise. In the process of optical radiation detection the noises are: the photon shot noise, the thermal noise and the fixed pattern noise (FPN) [2].

In this paper is presented the photodetection process that happens during the functionality of the PPS sensor. Related simulations of the functionality of the digital camera are investigated in references [2, 3]. This paper continues the work that has presented in the reference [4]. The simulations are made using a spectral image processing algorithm. The algorithm allows us to understand how the colors of the input image changes during its propagation trough the optical part of the PPS. Once the incident light reaches the photosensitive array of pixel, the conversion process begins. The photodetector sensor, in the process of optical radiation capture, suffers of noise. We present and analyze the effect of the noises which are induced by the photodetection process.

1 The optical part

In order to be functional the PPS sensor need to be illuminated. Then the light passes through the optical part (Fig. 1) and finally it is focused on the photosensitive area. The micro lenses array and the color filter array are made by materials which are characterized by their own spectrum, which is taken from catalogs of optical components. The quantum efficiency is computed taking in consideration the model of a n+/psub diode.

1.1 The light sources spectrums. In the process of optical radiation detection, first we need a light source. The spectrum of the light source will gives the hues of the scene. In colorimetry, Commission Internationale de L'éclairage (CIE) usually recommend the standard D65 (T_c = 6504 K) to be used as the preferred illuminant [5].

1.2 The lenses transmittance. In optics, transmittance is the fraction of incident light at a specified wavelength that passes through a sample. The transmittance of a sample is sometimes given as a percentage. The transmittance can be express:

$$T = e^{-\alpha x} \tag{1}$$

where: α is the attenuation coefficient and x is the path length.

In optics, transmission is the property of a substance to permit the passage of light, with some or none of the incident light being absorbed in the process. If some light is absorbed by the substance, then the transmitted light will be a combination of the wavelengths of the light that was transmitted and not absorbed. In our simulations, we consider that lenses of the PPS are made by BK7 glass from the Scott catalog. This type of glass ensures a very good transmission about 99%.

1.3 The filters transmittance. To construct a color image, a Color Filters Array (CFA) must be placed between the lens and the sensors. In general when we design a PPS sensor we need red, green and blue filters over each photodiode, in order to samples the color of the incident white light. The filters are characterized by their spectral transmittance. Red and blue filter are in proportion of 25% percent each and green filters are in proportion of 50% percent (Fig. 2). The name of this combination of colors filters is Bayer colors filters array (CFA). The filter passes the pass band of interest and provides blockage of any out-of-band light [1, 2].

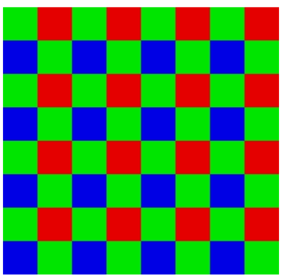


Fig. 2 The Bayer CFA

In general, the digital image capture systems can be equipped with PPS sensors which convert the incident light into digital signal. Because PPS can only sense the luminance, therefore it has to rely on the CFA to mask out all other colors except the specific color of each pixel.

1.4 The quantum efficiency of the photodetector. The photodetector converts the incident radiant power in to photocurrent. The incident photons generate e-h pairs in to silicon material. Some of the generated carries are converted in to photocurrent [1, 2]:

$$i_{ph} = \eta(\lambda) Q A_d q \tag{2}$$

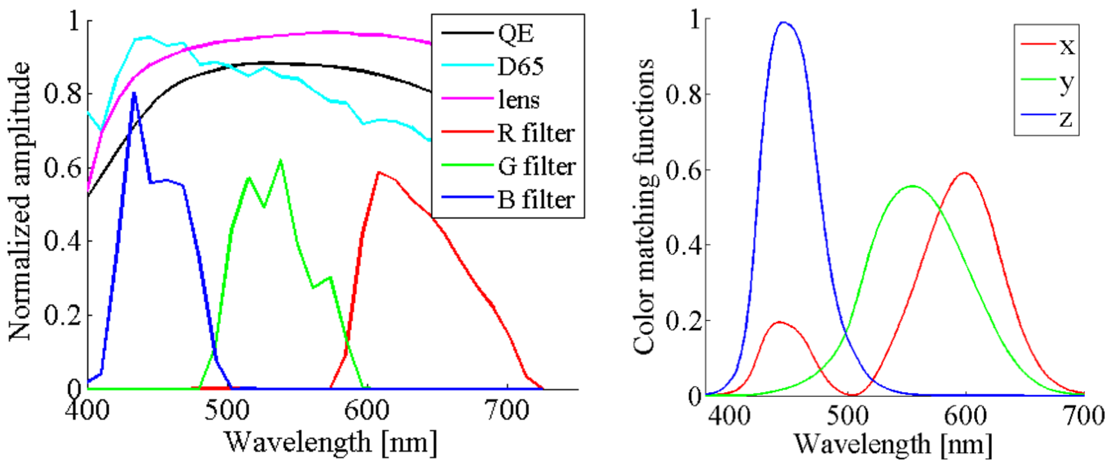
where: $\eta(\lambda)$ is the quantum efficiency, Q is the photon incidence, A_d is the area of the photodetector [cm^2], q is the electron charge.

The quantum efficiency (QE) is a quantity defined for a photosensitive device such as photodiode of a PPS as the percentage of photons hitting the photoreactive surface that will produce an electron-hole pair. In the reference [2] is calculated the QE of a diode with *pn* shallow junction with a wide depletion region:

$$\eta(\lambda) = \frac{1}{\alpha}\left[\frac{1-e^{-\alpha X_1}}{x_1} - \frac{e^{-\alpha X_2} - e^{-\alpha X_3}}{x_3 - x_2}\right] \text{electron/foton} \tag{3}$$

where: X_1 and X_2 delimitate the quasi-neutral regions *n* and *p* with the depletion region.

The result of this formula is good if we ignore the reflection at the surface of the chip, reflection and absorption in layers above the photodetector and variation of the photocurrent density over the aria. Eq. 3 computes the fraction of the incident photon flux that is transformed in to photocurrent.



a b

Fig. 3 a) The spectrums of the optical system, b) the color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ for a 2-deg field (from CIE, 1931)

1.5 The spectral image processing algorithm. The PPS sensor captures an illuminated scene. The illumination source is the D65 CIE standard. In the image capture process, the scene propagates through the optical part of the PPS and passes to the lenses array, the Bayer filter and the quantum efficiency. Each of these layers of the PPS is characterized by its specific transmittance. All these spectrums (Fig. 3 a)) are used as input data in our spectral image processing algorithm. They are represented on 31 wavelengths because the spectral image is defined as: 256X256X31.

The perception of the colored light is given by the reflected light coming from a surface, instead of light that is directly emitted from a light source. In the radiometric analysis the concern is the functionality of the optical part of the PPS, from the perspective of the final evaluator that is the humane eye. Consequently our spectral image processing algorithm will take in consideration the color perception of the human eyes. Our eyes receive the result of the scalar product of reflectance and radiance spectrum. In continuous case the human eye response is:

$$c_i = \int_{\lambda_{min}}^{\lambda_{\max}} S_i(\lambda) r(\lambda) l(\lambda) d\lambda, \quad i = L, M, S \tag{4}$$

where: L, M, and S are the responses of the long, medium, and short cones of the eye [5]. $S_i(\lambda)$ is the spectral sensitivity of the i-th type of cones L, M, S; $r(\lambda)$ is the fraction of the reflected illuminant energy, $l(\lambda)$ is the spectral distribution of light.

In order to achieve our goal to see how the colors of the scene are transformed as the light passes through the optical part of the PPS we have to multiply in the Eq. 4 the spectral reflectance of the light source with the lens and filters transmittances and with the quantum efficiencies of the photodiode [3, 4]:

$$c_k = \int_{\lambda_{min}}^{\lambda_{\max}} S_i(\lambda)L(\lambda)F(\lambda)QE(\lambda)r(\lambda)l(\lambda)d\lambda + n_k \tag{5}$$

where: $L(\lambda)$ is the lens spectral transmittance, $F_k(\lambda)$ is the spectral transmittance of the k-th color of the RGB Bayer filter, $QE(\lambda)$ is the diode spectral quantum efficiencies, n_k is the additive noise on the k channel. In Eq. 5 we have the transmission model needed in our paper simulation.

Practical reviews of the color spaces are presented in the reference [5, 6]. Information about the reconstruction of the spectral images can be found in the references [7]. The transformation of the colors of the scene during the propagation through the optical part of the PPS, is performed by taking in consideration the effect induced by the spectrums (Fig. 3 a)), in the process of conversion of the spectral image into the sRGB standard. The spectral algorithm consists of 3 steps:

1. To obtain the effect of the illumination it is necessary to multiply the spectral images [7] as in Eq. 5, with the spectrums which are presented in Fig 3 a). The dimensions of the spectral image are 256x256x33. 33 represent the number of wavelengths on which the spectral image is represented.
2. To reconstruct the image into the XYZ color standard [5] from the reflectance it is necessary to multiply the spectral image which was obtained at point 1 with the CIE 1931 color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ for a 2-deg field (Fig. 3 b)). After the multiplication, the dimensions of the image become 256x256x3.
3. The relationship between sRGB and CIEXYZ color coordinate systems are presented in the standard IEC_61966-2-1 and in the reference [6]. Without entering in details related to the sRGB standard the next step is to multiply the image obtained at point 2 with the matrix:

$$\begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & 0.2040 & 1.0570 \end{bmatrix} \tag{6}$$

and then the Gamma correction:

$$sRGB' = 12,92 \times sRGB \quad for \quad \text{sRGB} \le 0031308\,, \tag{7}$$

$$sRGB' = 1,055 \times sRGB^{1/2.4} - 0,0550 \quad for \quad \text{sRGB}>0031308\,. \tag{8}$$

2 The electrical part

The electrical part of the PPS image sensors consists of an n x m array of pixels; each pixel contains: a photodiode that converts the incident light into photocurrent, circuits for reading out the photocurrent; part of the readout circuits are in each pixel, the rest are placed at the periphery of the array. The photodiodes are semiconductor devices which capture the photons and convert them into electrons and then in to current (Fig. 4). The voltage across the photodiode increases proportional with the incident photon flux. The photodiodes work by direct integration of the photocurrent and dark current. To ensure good quality of the captured signal the sensitive array of the photodiodes should have appropriate field of view (FOV), fill factor, quantum efficiency and dimensions of the pixel [1, 2].

2.1 Detection regimes and figures of merit. Usually the potodetectors ends with a resistor [8, 9]. The resistor is useful for polarization of the photodetector. In Fig. 4 we have the general scheme of a photodetector.

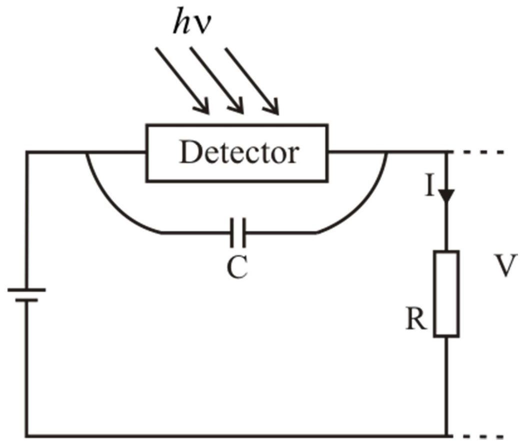


Fig. 4 The scheme of a photodetector

The output voltage or current has a band width or the cutoff frequency at 3dB given by [8,9,10]:

$$\Delta f = \frac{1}{2\pi RC}. \tag{9}$$

In the process of photo detection the photocurrent is associated with the unavoidable photon shot noise which is due to the granular or shot fluctuation of the input photons. Its mean square value is:

$$i_s^2 = 2q\left(i_{ph} + i_{dc}\right)\Delta f \tag{10}$$

where: q is the electron charge, Δf is the band width.

The noise associated with the resistance R is the Jonson or thermal noise. Its mean square value for current is:

$$i_J^2 = \frac{4kT\Delta f}{R}. \tag{11}$$

The reset noise appears at the capacitance node when the MOS switch is turned OFF. On the ON mode the reset noise is due to the thermal noise of the channel resistance of the MOS switch. The noise bandwidth of the RC circuit is:

$$\Delta f = \frac{1}{4RC}. \tag{12}$$

The bandwidth is inserted into the Jonson noise equation:

$$i_{reset}^2 = \frac{kT}{RC}. \tag{13}$$

Since the two noises are statistically independent, it is necessary to combine their quadratic mean values to give the total fluctuation as:

$$i_n^2 = 2q\left(i_{ph} + i_{dc}\right)\Delta f + \frac{4KT\Delta f}{R}. \tag{14}$$

The total noise is the square root of the sum of shot noise and thermal noise [8, 9]:

$$N = \sqrt{2q\left(i_{ph} + i_{dc}\right)\Delta f + \frac{4KT\Delta f}{R}}. \tag{15}$$

Thus the signal to noise ratio (SNR) is:

$$\frac{S}{N} = \frac{i_{ph}}{\sqrt{2q\left(i_{ph} + i_{dc}\right)\Delta f + \frac{4kT\Delta f}{R}}}. \tag{16}$$

2.2 The temporal noise. In the array sensor, after the photodiode, there is the readout electronics which consists in MOS transistors. The electronics introduce the temporal noise: the readout circuit noise and the flicker noise. In MOS transistor the channel material is resistive it exhibits thermal noise, which is a major source of noise in MOS transistors. Because MOS transistors conduct current near the surface of the silicon where surface states act as traps that capture and release current carriers, their flicker noise component can be large [1].

The MOS thermal noise is given as:

$$i_{d-tm}^2 = 4kT\frac{2}{3}g_m\Delta f \tag{17}$$

where: g_m is the transconductance of MOS transistor.
The flicker noise is given as:

$$i_{d-f}^2 = K\frac{I_D^\alpha}{f}\Delta f \tag{18}$$

where: K is a constant for a given device, α is a constant between 0.5 and 2, I_D drain bias current.
The MOS drain current is given as sum between the thermal and flicker noises:

$$i_d^2 = 4kT\frac{2}{3}g_m\Delta f + K\frac{I_D^\alpha}{f}\Delta f. \tag{19}$$

2.3 The statistics of the temporal noises. When photons strike a CMOS image sensor, interactions immediately produce a signal variance associated with the photon shot noise. The photon shot noise is due to the random arrival of photons at the image detector. This kind of noise represents the fundamental limit influencing the performance of the light detection systems. Shot noise is always associated with the current flow and it stops when the current flow stops. It is independent of temperature, is spectrally flat and has uniform power density. The photon shot noise is governed by the Poisson statistics [2, 3, 10]:

$$P(k,\lambda) = \frac{e^{-\lambda}\lambda^k}{k!} \tag{20}$$

where: $k = 1 \div n$, λ is a positive real number.

Read noise consists of all noise sources that are signal independent and it is called white noise. The noise is assumed to have the normal white Gaussian distribution with mean zero and a fixed standard deviation which is proportional to the amplitude of the noise [2, 10]:

$$G\left(x;\mu,\sigma^2\right) = \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{21}$$

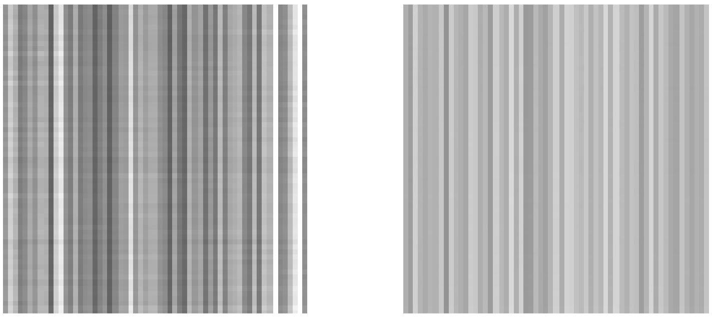
where: μ is the mean or expectation of the distribution σ is the standard deviation and its variance is therefore σ^2.

2.4 The fixed pattern noise. In addition to temporal noises the array sensor suffers of spatial noise which is knows as fixed pattern noise (FPN). During the uniform illumination appears the pixel to pixel output variation due to the device and interconnect mismatches across the image sensor array. These variations cause two types of FPN: offset FPN, which is independent of pixel signal, and gain FPN or photo response nonuniformity (PRNU), which increases with signal level.

The offset FPN is fixed from frame to frame but varies from one sensor array to another. It 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 [1, 2, 3].

The PRNU noise is produced in a sensor due to the fact that each photon receptor has slightly different characteristics with respect to the other ones. This means that the same amount of photons reaching the sensor in different locations results in a different number of electric charges at these locations. This constitutes a noise that is signal dependent, since it goes to zero when no radiation arrives at the sensor.

Detailed explanations related to FPN have been presented, in the reference, at section [2]. In this paper we focus our attention on the effects of the FPN on the image quality, without the computing of the FPN. Correlation double sampling (CDS) is used in many analog circuits to reduce offsets and reset noise. Its effects' are presented in Fig. 5.



a b

Fig. 5 a) the PPS FPN without CDS, b) the PPS FPN with CDS

2.5 The signal to noise ration of the PPS CMOS sensor. When several noise sources exist that are uncorrelated, the total noise power is given by:

$$< n_{total}^2 > = < \sum_{i=1}^{k} n_i^2 > \tag{22}$$

where: < > is the statistical average, n_{total}^2 is the total noise variance of the system, n_i^2 is the noise variance for current source *i*, *k* is the number of the noise sources.

The total noise of the system is the square root of the sum obtained from *i-k* noises [2, 8, 9]:

$$<n_{total}> = \sqrt{<i_{shot}^2>+<i_{reset}^2>+<i_{read}^2>+<i_{FPN}^2>}. \tag{23}$$

Taking in consideration the analysis of the noises presented in this paragraph the SNR can be express ass:

$$SNR=\frac{i_{ph}}{<n_{total}>}=\frac{i_{ph}}{\sqrt{<i_{shot}^2>+<i_{reset}^2>+<i_{read}^2>+<i_{FPN}^2>}}. \tag{24}$$

3 The result of the simulations

In this paper, in the previous paragraphs, we presented the fundamentals of main functional blocks involved in the photo detection process in PPS sensors. In this paragraph a brief demonstration on photodetection of the PPS sensor is analyzed, using demonstration images and specific modules developed in Matlab.

a b c d

Fig. 6 The original image illuminated with D65 standard, b) the image at the output of the optical filters, c) the Bayer sampling, d) the sampled image with the noises

The Fig. 6 a) presents the scene which is illuminated with D65 illumination standard. Fig. 6 b) presents the results of the spectral analysis in which was taken in consideration the effect of the optical filters. Fig. 6 c) presents the Bayer color sampling. The Bayer sampled image is covered by the photon shot noise. This kind of noise is inversely proportional with the light's intensity. In addition, we have the FPN which is specific to PPS. The read noise consists of the unavoidable white Gaussian noise which is due to the heating of the semiconductor (Fig. 6 d)).

Conclusions

In this paper, using Matlab, an application was created simulating the photodetection process that happens in a PPS sensor. The software describes the functionality of the PPS sensor using demonstration images. The simulation presented in this paper is continuing the work done previously in the reference [4]. This part of software is a module of the more general process simulation related to the modeling of the functionality of photodetection image sensors. The software was created taking in consideration the signal processing aspects that are involved in the functionality of the image sensors. In our simulations is presented the photodetection process basing on the camera equation. The simulation consists of the spectral image processing algorithm in which is analyzed the effect of the input radiation and PPS's filters: the light source D65, the lens transmittance, the Bayer filters the quantum efficiencies of a photodiode. During the process of conversion from photons to charges and finally in to the current the converted radiation is covered by noise. In our analysis we take in consideration the: photon shot noise, the rest noise, the white noise and the fixed pattern noise. This software is a controlled medium of simulations which allows to students to understand the functionality of a PPS sensor.

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