A Continuous Time Pattern Recognition Retina

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Abstract

We present in this paper a pattern recognition retina operating in continuous time. During a programming phase, the reference image is acquired by the sensor. After thresholding, the resulting binary image is stored in the sensor's pixels. During the recognition phase, the retina calculates, in an analog way and in continuous time, the zero displacement intercorrelation of the current image with the binary reference image and its complement. These two intercorrelation values are output as currents. By comparing these currents to expected values, determined during the programming phase, a shift of the pattern or a difference between the observed and programmed pattern can be detected. A 100x100 pixels validation chip was fabricated using a standard CMOS triple level metal 0.6 µm process. Characterization results are presented.

1. Introduction

A silicon retina is a particular image sensor in which an analog and/or digital signal processing circuitry is integrated next to the photosensitive or image sensing element. The role of the latter is to allow some low level processing to be done on the image signals before they are made available at the output of the circuit [1]. The type of processing that we would like to implement in the case of our retina is pattern recognition in real time. Our idea is to compare an observed image with a reference binary image programmed in the retina. The result of the comparison is two signals in the form of electrical currents that would allow the retina to detect a shift or a difference between the observed image and the programmed reference image.

In the next section of the paper we shall present the working principle of the retina and show its pattern recognition features by use of a simple example. In section 3, we shall describe the architecture of the circuit and give the block diagrams of the programmable pixel from which an array of 100x100 pixels has been fabricated in standard CMOS 0.6 µm process. In section 4, we shall describe the characterization of the retina and give the results that we have obtained. Finally, the results of the experiments that we have carried out on the retina in order to verify its ability to recognize patterns or to detect spatial shifts of patterns will be reported in section 5 before concluding by section 6.

2. Images intercorrelation

Remark : In this section, some realistic images are used to demonstrate the working principle of the retina. Since the only output of the fabricated chip is two intercorrelation values, it must be clear that these images were not obtained experimentaly with the described device.

Generally speaking and leaving aside border effects, the intercorrelation between two images X and Y can be computed as :

$$C_{XY}[\lambda,\mu] = \sum_{i=0}^{N-1}\sum_{j=0}^{M-1} X[i,j]Y[i+\lambda,j+\mu]$$

Where N and M are the width and the length of the images. The values of this intercorrelation function give two informations on the resemblance of the images. The maximum of C_{XY} describes the likeness degree, while the position (λ_0, μ_0) of this maximum indicates the displacement that must be applied to X to improve its matching with Y.

Let us see how it is possible to compute the likeness degree of two images assuming that $(\lambda_0, \mu_0)=(0,0)$.

During a programming phase, an image is projected, by some optical means, on the photosensitive part of the retina. This reference image is thresholded and stored in latches located in each active pixel element. Since these latches have complementary outputs, all occurs like if two complementary reference images were stored in the sensor, such as in figure 1.

a. Greyscale reference image — b. Positive reference image R[x,y] — c. Negative reference image $\overline{R}$[x,y]

Figure 1 : Binary reference image

During the recognition phase, the currents produced by all the pixels pertaining to respectively the black and white areas of the positive reference binary image are summed in order to give two total currents called as the black and white pixel currents. These currents, denoted by I_{black} and I_{white}, can be expressed as:

$$I_{white} = K\,C_{RX}[0,0] = K\sum_{i=0}^{N-1}\sum_{j=0}^{N-1} R[i,j]X[i,j]$$

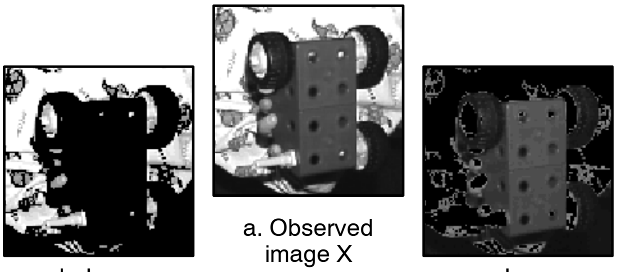
and

$$I_{black} = K\,C_{\overline{R}X}[0,0] = K\sum_{i=0}^{N-1}\sum_{j=0}^{N-1} \overline{R}[i,j]X[i,j]$$

where X[i,j] is the luminous flux falling on the pixel of coordinates (i, j) and K a constant which defines the linear relationship between the luminous flux and the current produced by the pixel.

Now, let us consider the two images represented in figure 2.a and figure 3.a as well as the I_{black} and I_{white} currents computed for these two images using a binary reference image obtained by thresholding the first image (e.g. the image of figure 2.a). One would notice here that this image is the same as that of figure 1.a, so that the binary reference image is the one represented in figures 1.b (positive) and 1.c (negative).

Remark : In this exemple, the values computed for I_{white} and I_{black} are not effective currents but the sum of the intensity values(256 values scale) of all the pixels of the considered image.

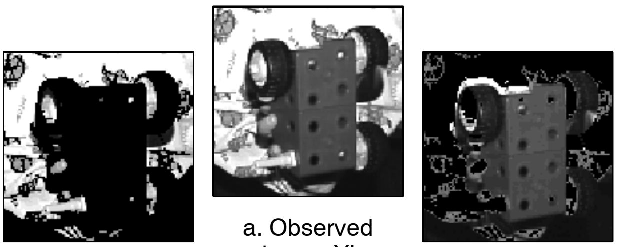


b. I_{white} = 686906

a. Observed image X

c. I_{black} = 345312

Figure 2 : Computing I_{white} and I_{black} currents for the reference image



b. I_{white} = 649703

a. Observed image X'

c. I_{black} = 373752

Figure 3 : Computing I_{white} and I_{black} currents for the image to compare

By comparing the values of the I_{white} and I_{black} currents, we can conclude that the images of figure 2.a and figure 3.a are different. For one part, the differences can be seen on figure 3.b, where some dark zones appeared in the upper half part of the image, resulting in a lowering of the I_{white} current. But it is in figure 3.c that the shifting of a part of the image becomes the most evident. Since this shift has reduced the size of the “black” zone of this image, it causes an increase of the I_{black} current. The image discrimination can be illustrated by the I_{black}/I_{white} plane shown in figure 4.

Many computer simulations have shown that this method is suitable as well to discriminate strongly different images as to detect small displacements in a scene [3].

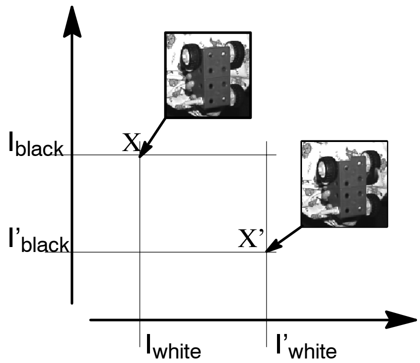


Figure 4 : The I_{white}/I_{black} plane

3. The programmable retina

The programmable retina consists of an array of programmable pixels whose block diagram is shown in figure 5. Each pixel is made up of a photodiode and an electronic digitizing, storage and switching circuit. During the programming phase, the image to recognize is projected on the circuit and the current produced by each of the photodiodes due to the luminous flux is compared to a threshold current I_{th} using a current comparator. The result of the comparison is a binary value stored in a latch by applying a pulse to the input ”Program” (figure 5). This binary value is used during normal operation mode to set the position of the switch in order to connect together all the cathodes pertaining to the same type of photodiodes. The state of the switch is maintained as long as no new memorization or programming pulse is applied.

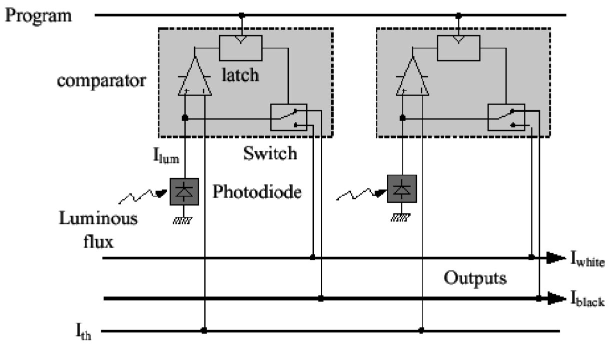


Figure 5 : Block diagram of a programmable pixel

A simplified mixed (schematic-functional) diagram of the electronic digitizing and binary image storage circuit is represented in figure 6. The two main elements of the circuit are the two current mirrors: one for generating the mean current used as the threshold current, and the other one for making a copy of the photocurrent generated by the photodiode. The threshold current mirror circuit, used for computing the threshold current, is constituted by transistors M2 and M4. Node A is common to all the pixels, and the current that arrives at this node corresponds to the sum of the photocurrents generated by all the pixels of the array. Besides, all the identical M2 transistors of the current mirror are connected in parallel in the array of pixels so that the total photocurrent is equally divided among the

M2 transistors resulting in the mean current flowing in each of these transistors.

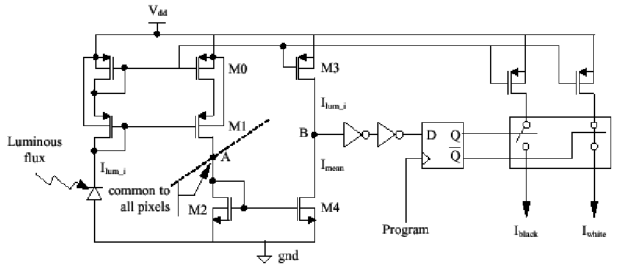


Figure 6 : Simplified schematic of the APE

Consequently, the output of the current mirror is also the mean current, I_{th}, which is compared to the photocurrent generated by the photodiode, I_{ph}, at node B. The saturation current of transistor M3 is the photocurrent I_{ph} and the saturation current of transistor M4 is I_{th}. Since these two currents are not equal, the voltage at node B is imposed by the transistor that has the higher saturation current resulting in a change of the working region of this transistor from the saturation region to the triode one.

The two inverters connected in series to node B acts as a comparator that delivers a logic value stored in the D-latch. The inverters are sized to optimize the power over speed ratio when the voltage at node B is in the vicinity of $V_{dd}/2$. The value stored in the D-latch is next used during normal working mode to switch the photocurrent to either the I_{black} or I_{white} output of the retina as illustrated in figure 6. Current summations at the I_{black} and I_{white} outputs are obtained by hardwiring.

The layout of the pixel, realized in standard 0.6 µm CMOS technology with three layers of metal from Austria Micro Systems, is shown in figure 7. It is a 50.6x50.6 µm square pixel with a photosensitive area of 957 square microns. The fill factor is thus about 37% that is rather a high value for a silicon retina.

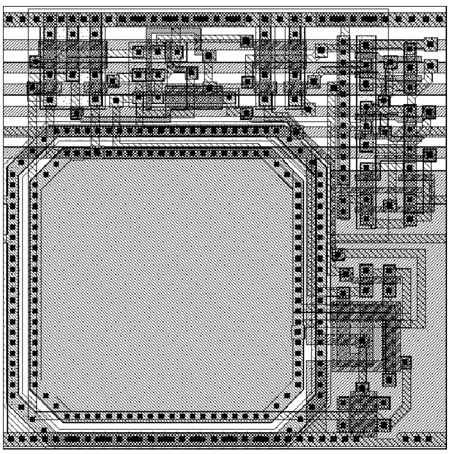


Figure 7 : Layout of the programmable pixel

We can note that, to limit charge injection in the substrate, the photosensitive area (n+ diffusion) is surrounded by a guard ring (p+ diffusion) connected to the negative supply. Since there is no need to adress the pixels individually, all the signals are distributed horizontally. This makes it possible to employ only the third metal level for the routing inter pixels.

The layout of the complete chip is shown on figure 8. It consists of a 100x100 pixels array and its total area, including the pads is 34 square millimeters. In addition to the array of pixels, a certain number of devices have been integrated on the circuit. These devices are a set of current mirrors connected to node A of the electronic digitizing, storage and switching circuit of figure 6, and whose purpose is to allow an adjustement of the threshold current around the mean value; and three operational amplifiers that are used, with external resistors, to convert the I_{black}, I_{white} and threshold currents to voltages for ease of measurement. These devices are found at the bottom of the layout of the complete circuit shown in figure 8.

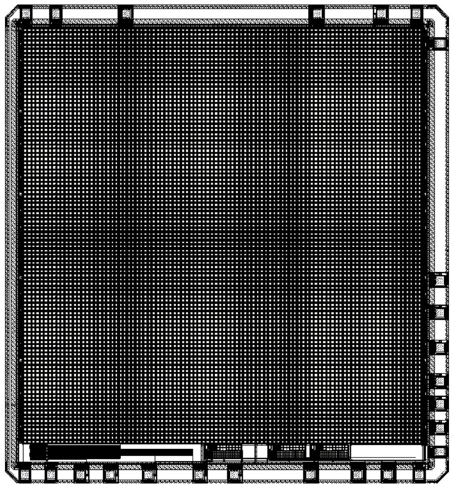


Figure 8 : Layout of the complete chip

4. Characterization

4.1. Spectral response

Figure 9 shows the spectral response of the sensor. It was measured using a tunable monochromatic light source capable of emitting light rays of wavelength in the range of 300 to 1200 nm and a bolometer.

The sensitivity of the sensor is defined as the ratio of the output currents over the radiant flux that is measured with the bolometer. The sensitivity is a function of the wavelength and for a wavelength of 550 nm, for example, it has been found to be equal to 0.23 A/W, which corresponds to an efficiency of 51%. This value is to be compared to the 0.2 A/W value given in the literature and which corresponds to an efficiency of 41%.

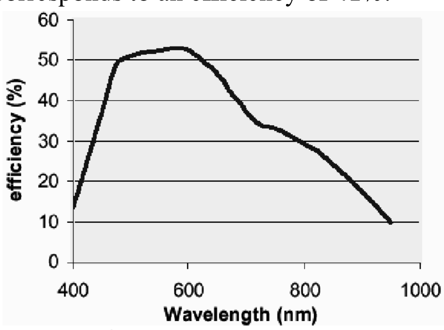


Figure 9 : Spectral response of the retina

4.2. Spatial sensitivity

We are interested here in the minimal surface area, ΔS, of an object that the retina can detect. To determine this surface area, we have placed the retina in the dark and measured the output current. It has been found to be equal to 9 nA. This value corresponds to the smallest signal,

I_{min}, that can be measured and it is due to the dark current and noise of the device. For a radiant flux of 16 μW (the radiant flux of the light source we shall be using for our experiments) and for I_{min} = 9 nA, we deduce that the minimal surface area is 60 pixels.

4.3. Read-out rate

In the current implementation, output currents are measured using a trans-resistance amplifier whose cutoff frequency is rather low. The following experiment showed that the speed of the entire system is limited by this component. We have memorized an image corresponding to a fan with the three blades in a given position. Next, we have switched on the fan and observed the variation of the read-out V_{black} and V_{white} voltages with respect to the rotation speed of the blades. The cutoff frequency of the system been measured and found to be equal to 720 Hz, the cutoff frequency of the used trans-resistance amplifier.

4.4. Pixel's characteristics disparities

Although all the pixels of the array have been designed to have the same characteristics, in practice, due to the fabrication process, the characteristics are not exactly the same. From one pixel to the other the characteristics vary slightly and as a result the pixels act differently under the same illumination conditions. This shift in the characteristics of the pixels has an influence during the programming mode mainly at the comparator level. Indeed, for pixels for which the photocurrent is close in value to the threshold current a shift in the characteristic would result in an arbitrary value of the output of the comparator.

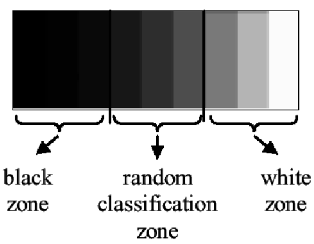


Figure 10 : Random classification zone due to disparities in pixel's characteristics

To characterize the disparities in the pixel's characteristics, we have memorized the nine gray levels pattern represented in figure 10 with the threshold current set to the average current value of the image. Without any disparities in the characteristics, the pixels would have been classified into a black and a white zone separated by a well-defined vertical frontier. However, due to the disparities in the characteristics, we notice that for gray levels for which the corresponding pixel current is close in value to the threshold current, the pixel is randomly classified as a black or white pixel. In the case of the nine gray levels pattern, which we have used for our experiment, we have determined the random classification zone represented in figure 10.

5. Application

For the following measurements, the retina was fixed in a case with a 25 mm lens and located at a distance of 45 cm from the light source (a 150 W backlight emitting a maximal radiant flux of 16 μW). With this set up the view area is 16x16 cm. Binary test patterns of simple geometrical shapes realized on transparencies have been considered. Any of the test patterns can be used as the reference image that is first programmed in the circuit. Then, the same or a different test pattern is projected onto the retina for comparison. We have applied to the pattern recognition (or spatial shift detection system) a set of binary test images composed of simple black geometric shapes over a white background such as squares, circles, triangles, etc. The system has been found to be able to distinguish the different shapes.

In order to quantify the minimum detectable spatial shift, we have memorized a heaviside function which is next shifted in a direction perpendicular to the black to white transition line. We have found that the smallest detectable shift is about 1 mm. According to the characteristics of our experimental set up, in particular the view area, this image shift of 1 mm corresponds to a pixel shift on the retina of 1 pixel in the direction of the shift. The number of pixels involved in the shift is thus 100 since the array is composed of 100x100 pixels. This result is consistent with the minimum detectable surface area of at least 60 pixels found in the previous section.

6. Conclusion

We have presented in this paper a programmable retina with real-time pattern recognition and spatial shift detection features. The working principle of the circuit is based on the classification (or programming) of the pixels into either black or white pixels representing a binary reference image, and on the determination of the total current produced by all the pixels of the same type when an image is projected on the sensor.

The programming of the pixels into either black or white pixels is achieved by first projecting the reference image on the retina. During the analysis phase, an optical correlation between the observed image and the memorized binary reference image is realized and the result read-out in the form of two currents. By comparing these currents to reference values, we can decide whether the projected image is similar or not to the reference image used to program the pixels.

A 100x100 pixels retina based on this working principle has been fabricated in standard CMOS 0.6 μm process. Its size is about 6x6 mm with a fill factor of 37%.

This retina circuit has been characterized with respect to its spectral response, spatial sensitivity, read-out rate and influence of pixel's disparities on the binary image stored in the latches.

7. References

[1] Y. Ni, F. Devos, M. Boujrad and J.H. Guan, "Histogram-Equalization-Based Adaptive Image Sensor for Real Time Vision", *IEEE Journal of Solid State Circuits*, Vol. 32, No. 7, July 1997, pp. 1027- 1036.

[2] P. Gorria, B. Lamalle and G. Cathebras, "Dispositif d'intercorrélation d'une image", *Patent* N°99 00008, January 04, 1999.

[3] B. Lamalle, P. Gorria, L.F.C. Lew Yan Voon and G. Cathebras, "The Study and Design of a Programmable Silicon Retina for Real Time Pattern Recognition", *Proceedings of EOS/SPIE Symposium on Applied Photonics*, Thistle Hotel, Glasgow, SCOTLAND, UK, 22-25 May 2000, Vol. 4076, pp 225-234.