A Real-Time Pattern Recognition Retina in CMOS Technology: Principle, Design, Test and Characterization

L.F.C. Lew Yan Voon†, G. Cathebras‡, B. Lamalle†, P. Gorria†, B. Bellach† and O. Aubreton†

†Laboratoire LE2I - I.U.T. Le Creusot, 12, rue de la fonderie, 71200 Le Creusot, FRANCE
‡LIRMM – Université Montpellier II, 161 rue Ada, 34392 Montpellier Cedex 5, France

Abstract - *We have designed and fabricated a programmable retina that is capable of recognizing patterns stored in memory in real-time. Each of the pixels of the retina is composed of a photodiode and an electronic device used during the programming phase to digitize the image of the pattern to recognize into a binary image stored in latches. The array of pixels is thus partitioned into two complementary disjoint sub-sets with all the photodiodes of the same sub-set connected together in order to obtain the sum total of the currents. During the analysis phase, an optical correlation between the projected image and the reference binary image memorized in the circuit is done. The result is read-out as two voltages representing the following two currents: a "white" current proportional to the luminous flux falling on the photodiodes pertaining to the "white" part of the binary reference image and a "black" current corresponding to the black part. By comparing these two voltages to expected values, a shift of the pattern or a difference between the observed and programmed pattern can be detected. The retina has been fabricated in standard 0.6 μm CMOS technology with three layers of metal from Austria Micro Systems. It consists of a 100×100 pixels image sensor with a total area, including the pads, of 34 square millimeters. The fill factor is about 37% for a square pixel of size 50.6×50.6 μm.*

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[†]Laboratoire LE2I – Université de Bourgogne
I.U.T. Le Creusot, 12, rue de la fonderie, 71200
Le Creusot
FRANCE

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I. 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, 2, 3, 4, 5]. 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, we present the working principle of the retina and illustrate its pattern recognition features by use of a simple example. In section III, we describe the programmable pixel and give both its block diagram and layout realized in standard CMOS technology. The layout of the retina is also given in this section. In section IV, we describe the test and 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, are reported in section V and we conclude by section VI.

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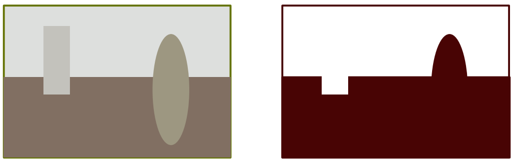
II. WORKING PRINCIPLE OF THE RETINA

The working principle of our silicon retina is based on the comparison between an image projected on the circuit by some optical means and a reference binary image obtained by thresholding the image to recognize according to a suitable threshold as shown in Figure 1. The reference binary image is stored in latches in the circuit by assigning the logic value 0 to a black pixel and the logic value 1 to a white pixel [6, 7, 8].



a) Image to recognize   b) Binary reference image $R(i, j)$

Figure 1: Binary reference image

When an image is projected on the retina, the currents produced by all the pixels pertaining to respectively the black and white areas of the 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:

$$I_{white} = K \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} R(i, j) \cdot X(i, j)$$

and

$$I_{black} = K \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \overline{R(i, j)} \cdot X(i, j),$$

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, suppose that we would like to evaluate the degree of resemblance between the image of Figure 2 and the reference image given in Figure 1. Both images differ in that the one to analyze has an additional bright triangle in the dark region of the image.

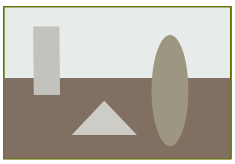


Figure 2: Image to compare with the reference image

Computing the I_{black} and I_{white} currents for both the reference image and the image to compare will result in the same I_{white} current but a different I_{black} current. Indeed, the pixels involved in the computation of the currents are the same in the case of the I_{white} current and different in the case of the I_{black} current due to the presence of the bright triangle as shown in Figure 3 and Figure 4.

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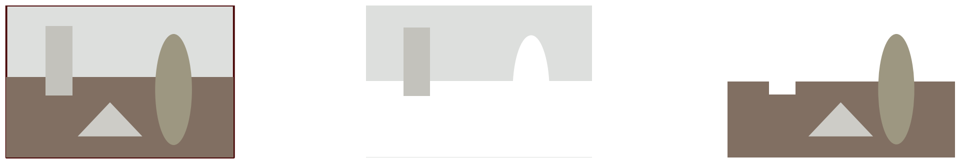
a) reference image: X(i, j) b) I_{white} c) I_{black}

Figure 3: Pixels involved in the computation of the I_{white} and I_{black} currents for the reference image



a) observed image: X'(i, j) b) $I'_{white} = I_{white}$ c) $I'_{black} > I_{black}$

Figure 4: Pixels involved in the computation of the I_{white} and I_{black} currents for the image to compare

By comparing the I_{black} and I_{white} currents, we can conclude that the images of Figure 3.a) and Figure 4.a) are different. In this particular case, only the I_{black} current is involved in the discrimination of the two images as illustrated in Figure 5. In the general case, both the I_{black} and I_{white} currents contribute to the discrimination of the images.

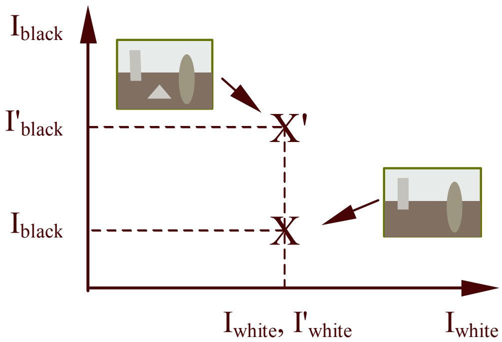


Figure 5: The I_{black}/I_{white} plane

III. THE PROGRAMMABLE RETINA

The programmable retina consists of an array of programmable pixels whose block diagram is shown in Figure 6.

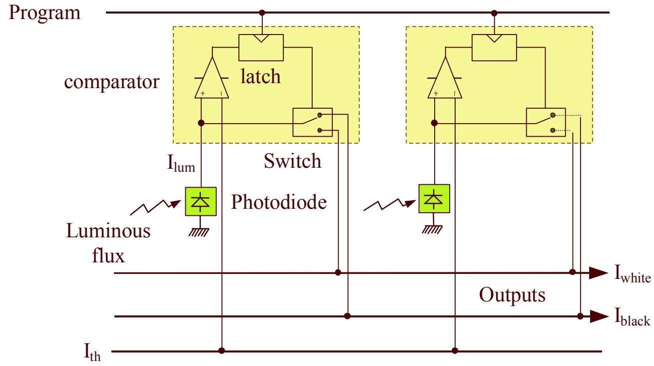


Figure 6: Block diagram of a programmable pixel

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 6). This binary value is used during normal functioning 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.

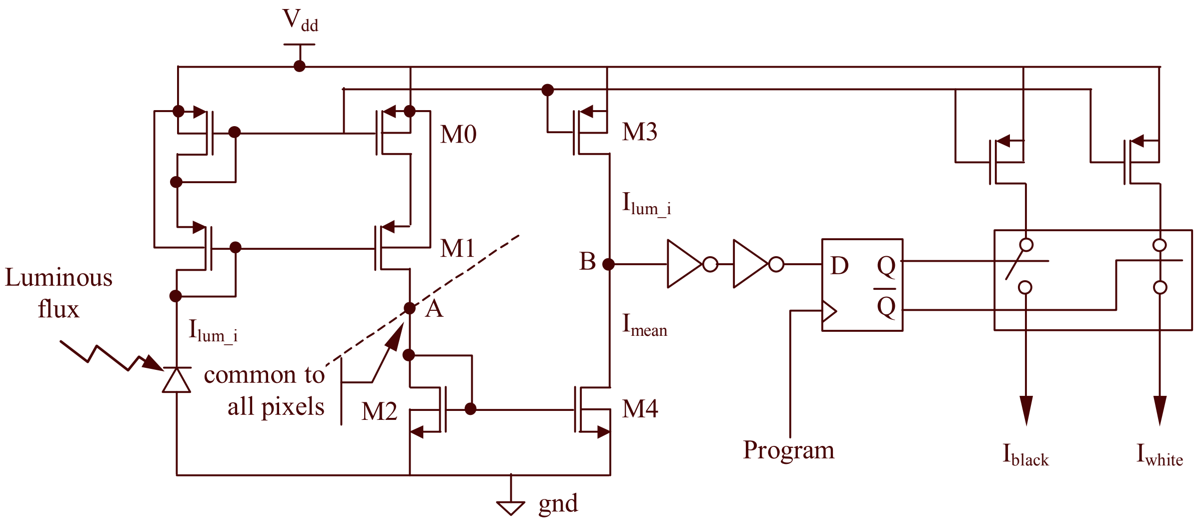


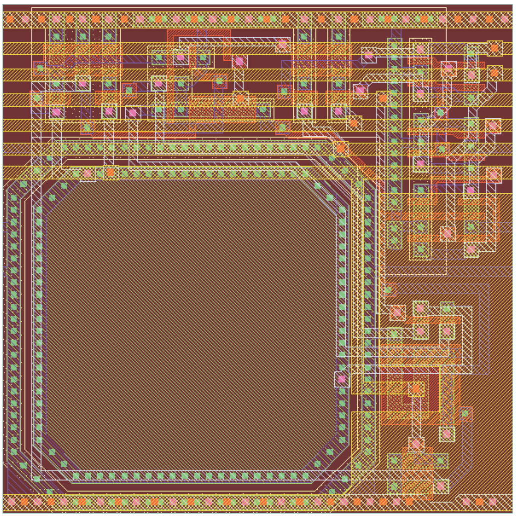
Figure 7: Simplified diagram of the electronic digitizing, storage and switching circuit

A simplified mixed (schematic-functional) diagram of the electronic digitizing and binary image storage circuit is represented in Figure 7. The two main elements of the circuit are the two current mirrors: one for generating the mean current use as the threshold current, and the other one for making a copy of the photocurrent generated by the photodiode [9]. 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 currents that arrive at this node correspond 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.

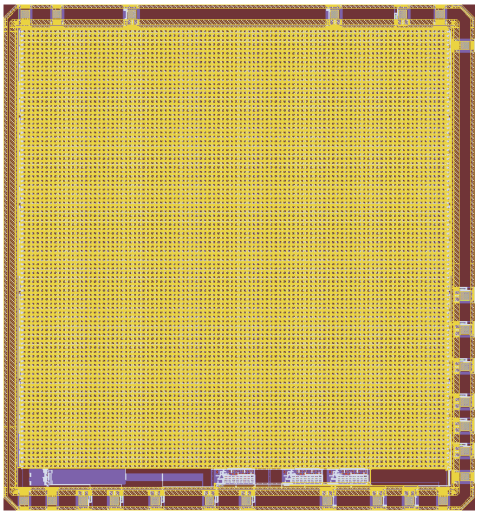
Consequently, the output of the current mirror is also the mean current, I_{th}, which is compared to the photocurrent generated by the photodiode, I_{ph}, at node B. The saturation current of transistor M3 is the photocurrent I_{ph} and the saturation current of transistor M4 is I_{th}. Since these 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 7. Current summation 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 8.a). It is a 50.6×50.6 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.



a)



b)

Figure 8: Layout of the programmable pixel and the complete chip

The layout of the complete chip is shown in Figure 8.b). It consists of a 100×100 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 7, and whose purpose is to allow an adjustment 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.b).

IV. TEST AND CHARACTERIZATION

Figure 9 shows the retina in its case with the necessary hardware for the power and for converting the output currents to voltages. Indeed, for ease of measurement, the I_{black} and I_{white} output currents are converted to voltages, V_{black} and V_{white}, using the integrated operational amplifiers with a 2.2 MΩ external feedback resistor for each amplifier.

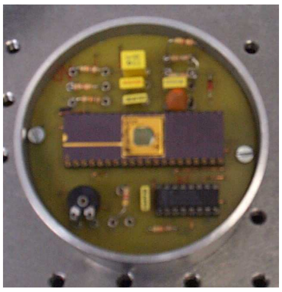


Figure 9: The retina in its case

A Spectral response

A tunable monochromatic light source capable of emitting light rays of wavelength in the range of 300 to 1200 nm is used. The determination of the spectral response, represented in Figure 10, is done in two steps:

- Measurement of the spectral characteristic of the light source. A bolometer is used to measure the radiant flux emitted by the monochromatic light source.
- Measurement of the characteristic of the retina. For each wavelength, two voltmeters are used to measure the V_{black} and V_{white} voltages.

The sensitivity of the sensor, defined as the ratio of the output currents over the radiant flux, can be deduced from these two series of measurements. Note that our measurements give the output voltages, V_{black} and V_{white}, instead of the output currents, I_{black} and I_{white}. However, the latter can be deduced from the V_{black} and V_{white} voltages knowing the trans-resistance value of the current-to-voltage converter.

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%.

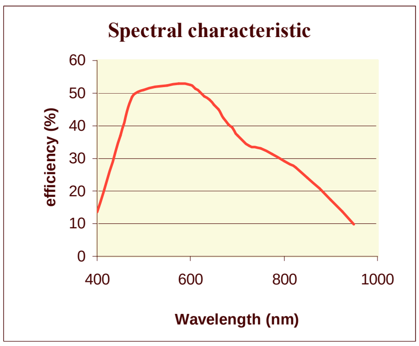


Figure 10: Spectral response of the retina

B 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 voltage. It has been found to be equal to 20 mV. This value corresponds to the smallest signal, V_{min}, that can be measured and it is due to the dark current and noise signals of the device. For a radiant flux of 16 µW (the radiant flux of the light source we shall be using for our experiments in the next section) and for V_{min} = 20 mV, we deduce that the minimal surface area is 60 pixels. Consequently, under the previous experimental illumination conditions, the smallest object that can be detected or the detectable difference in the observed and memorized image must involve at least 60 pixels.

C Read-out rate

The working principle of the array of pixels is based on an optical correlation. The settling time of the I_{black} and I_{white} currents is thus only limited by the sum of the generation time of the charge carriers due to the luminous flux falling on the photosensitive area of the pixels and the transit time for these charge carriers to travel from the photosite to the output of the array of pixels. However, the current-to-voltage conversion stage limits the response time of the retina.

To illustrate this, 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 output stage has been measured and found to be equal to 720 Hz. This cutoff frequency depends on the characteristics of the trans-resistance amplifier or current-to-voltage converter. It can easily be improved if necessary.

D Influence of the disparities in the pixel's characteristics

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.

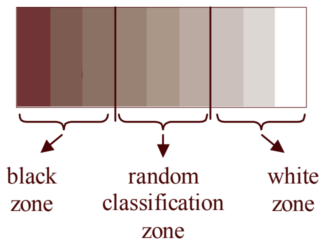


Figure 11: Random classification zone due to disparities in pixel's characteristics

To characterize the disparities in the pixel's characteristics, we have memorized the nine gray levels pattern represented in Figure 11 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 11.

V. APPLICATION

The experimental set up shown in Figure 12 is used to test the pattern recognition and spatial shift detection features of the retina [10]. The latter is 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 16×16 cm.

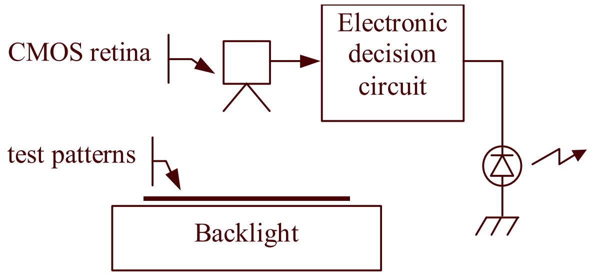


Figure 12: Experimental set up for testing the retina

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, and the two output voltages V_{black} and V_{white} are processed by an electronic circuit in order to give a binary decision.

When the reference object or image is analyzed after the system has been programmed with this image, we obtain, in the V_{black}/V_{white} plane, a point of coordinates (V_{b0}, V_{w0}) that is characteristic of the reference image (see Figure 13.a)).

Now, if a test image different from the reference image is analyzed it will be characterized by a point of coordinates different from (V_{b0}, V_{w0}). The spatial distance between the two points is a measure of the difference or spatial shift between the two images.

In order to determine whether two images are the same, different or same and spatially shifted, we have defined the following metric:

$$\varepsilon = \left| V_{white} - V_{w0} \right| + \left| V_{black} - V_{b0} \right| = \left| \Delta V_{white} \right| + \left| \Delta V_{black} \right| .$$

The two images are considered to be the same image and perfectly aligned if $\varepsilon < V_{eth}$, a predefined error threshold voltage. In this case, the characteristic point of the image under analysis (V_{black}, V_{white}) will be found within the shaded area of the V_{black}/V_{white} plane or the shaded area of the $|\Delta V_{black}|/|\Delta V_{white}|$ plane if the absolute difference value is considered (see Figure 13.b)).

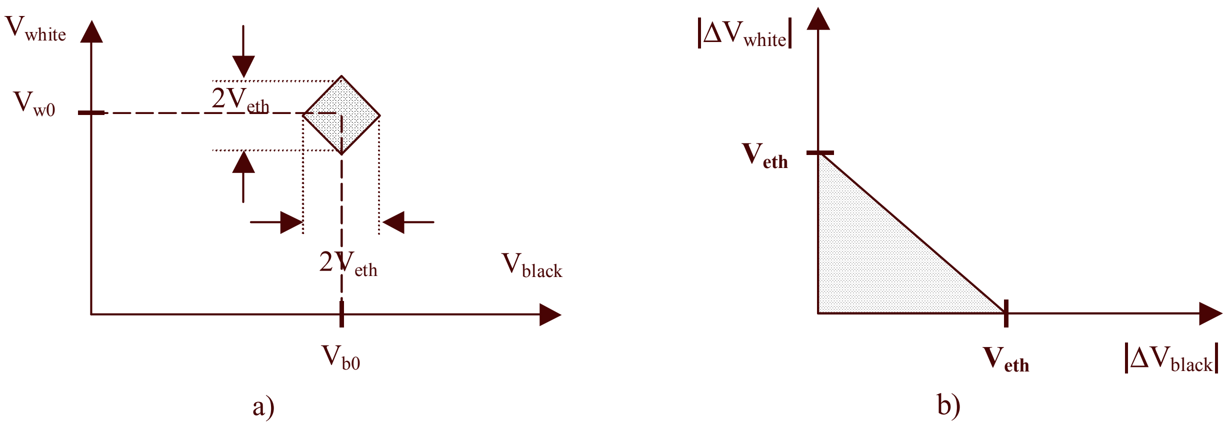


Figure 13: a) V_{white}/V_{black} plane; b) $|\Delta V_{white}|/|\Delta V_{black}|$ plane

The block diagram of the electronic decision circuit is represented in Figure 14. In this circuit, a Sample and Hold (S&H) circuit is used to memorize the reference voltages V_{b0} and V_{w0} corresponding to the reference image. During the analysis phase the error voltage ε is determined and then compared to the error threshold value V_{eth} in order to produce a binary decision result.

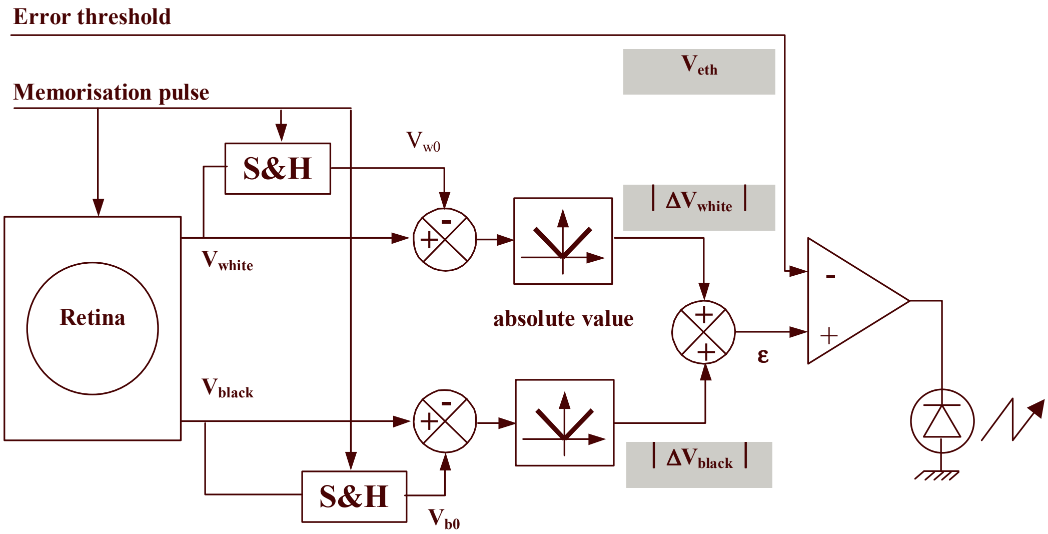


Figure 14: Electronic decision circuit

We have applied to our 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 100×100 pixels. This result is consistent with the minimum detectable surface area of at least 60 pixels found in the previous section.

For an in-depth characterization of our retina, we are currently conducting more experiments with gray level patterns of complex shapes. Moreover, we are also studying the application of our retina to the verification of the position of objects in an industrial process where decision time is a constraint and the use of vision systems requiring a personal computer cannot be envisaged. The types of industrial processes we are targeting on are the production of three-dimensional parts from plane materials by press machines. Our retina can be in these cases use to stop the press machine if the plane material is not correctly positioned under the press in order to avoid damage to the latter.

VI. CONCLUSION

We have presented 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 circuit.

The programming of the pixels into either black or white pixels is achieved by first projecting the reference image on the retina. Then, the current produced by each of the pixels is compared to a threshold value. If this current is greater than the threshold value then the pixel is considered as a white pixel, otherwise it is considered as a black pixel. The threshold current is by default the mean current of the reference image, however if necessary this value can be set to a different one using the electronic device also integrated on the circuit.

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 voltages obtained by converting the sum of the currents due to the black and white pixels into voltages. By comparing these voltages to reference values, we can decide whether the projected image is similar or not to the reference image used to program the pixels.

A 100×100 pixels retina based on this working principle has been fabricated in standard CMOS 0.6 µm process with three layers of metal from Austria Micro Systems. Its total area, including the pads, is 34 square millimeters. The pixels of the array are square with a rather high fill factor value of 37%.

The retina circuit has been characterized with respect to its spectral response, spatial sensitivity, read-out rate and influence of the disparities of the pixel's characteristics on the binary image stored in the latches. The spectral response is in good agreement with the one found in the literature. Concerning the spatial sensitivity and the read-out rate they are dependent on the experimental conditions. In our case, we have found that the minimal detectable surface area is 60 pixels and the cutoff frequency is 720 Hz.

Simple preliminary experiments done on the retina circuit using binary images have shown that the retina is capable of discriminating simple geometrical shapes such as a square, a circle or a triangle, or detecting a spatial shift of these shapes. The ability of our retina to discriminate between the observed image and the memorized image or to detect spatial shifts depends also on the experimental conditions. For our experiments, we have found, using a heaviside function, that any spatial shift that involves more than 100 pixels would be detected. This result is in good agreement with the minimal detectable surface area of 60 pixels determined during the characterization of the retina.

The application of our retina to verify the position of objects in industrial processes, such as the production of three-dimensional parts from plane materials by press machines, is currently been investigated. Our retina can be in these types of processes use to stop the machine if the material is not correctly positioned under the press.

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