A Biologically Inspired CMOS Image Sensor for Polarization and Fast Motion Detection

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Abstract— **A CMOS image sensor replicating the perception of vision in insects is presented for machine vision applications. The image sensor can sense polarization information in real time using a metallic wire grid micro polarizer. The embedded polarizer uses the inherent property of materials to partially polarize the reflected light to classify among conductive materials. The sensor is also equipped with in-pixel analog and digital memories which allow in-pixel binarization in real time. The binary output of the pixel tries to replicate the "flickering effect" of the insect's eye to detect the smallest possible motion based on the change in state of each pixel. A built-in counter counts the changes in states for each row to estimate the direction of the motion. The image sensor consists of an array of 128x128 pixels, occupies an area of 5x4mm^2 and it has been designed and fabricated in a 180nm CMOS process.**

I. Introduction

Biological systems are a source of inspiration in the development of small autonomous sensor nodes. The compound eyes of insects, in comparison to the single aperture eyes of humans, are not suitable to form high resolution images. However, they are known to process information more efficiently and are good examples of low power vision systems. The compound eyes, besides performing their function in forming images and motion detection, are also sensitive to other properties of light, i.e. the wavelengths and vector of skylight polarization. Human eyes are, on the other hand, polarization blind. Polarization provides additional visual information to intensity and wavelength, and provides a more general description of light. Therefore, polarization provides richer sets of descriptive physical constraints for the interpretation of the imaged scene. For example, polarization information can be used for material classification. Information on the type of material can provide important information about the scene in computer or machine vision applications. According to the Fresnel reflection theory which was proposed by Wolff [1], dielectric surfaces polarize the light upon specular reflection stronger than metal surfaces, for all angles of incidence. The maximum and minimum transmitted irradiances after reflection from a material surface can be obtained by allowing the reflected light from the material surface to pass through an external linear polarizer onto a CCD or CMOS image sensor. The disadvantage of such a system is that the linear polarization filters have to be externally controlled, which complicates the automation and miniaturization of optical sensors for material classification.

Besides the polarization detection ability, the eyes of insects are also able to detect fast motion in a visual scene. This helps them in, for example, avoiding collision with obstacles, using low level image processing and with little computational power. These qualities make their visual processing interesting for real time motion/collision detection in machine vision applications. Conventionally, the motion of an object is determined from a sequence of images using temporal differencing [2]; background subtraction [3] or optical flow [4].

Temporal differencing attempts to detect moving regions by making use of the differences between two consecutive frames (two or three) in a video sequence. This method is highly adaptive to dynamic environments, but generally does a poor job of extracting the complete shapes of certain types of moving objects [5]. Background subtraction uses a model of the background and compares the current image with the reference image to separate the background and foreground [6]. The main disadvantage of the background subtraction method is that both the background scene and the camera are required to be stationary when this method is applied. This method is also extremely sensitive to dynamic scene changes, due to background illumination changes. When the optical scene or the camera is in motion, optic flow is the most used method. Optic flow is the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and the scene. Insects are also known to use optic flow to detect obstacles in their flying path.

The main constraints for real-time implementation of these algorithms are the large amount of data to be processed and the high computational cost of the algorithms employed. To solve the problems, analog VLSI chips employing early vision processing of the optical scene are becoming popular [7], [8]. They employ simple, low accuracy operations at each pixel for each image or for a sequence of images, resulting in a low-level description of a scene useful for higher level machine vision applications. This often results in compact, high speed and low power solutions. Temporal differencing at a pixel level rather than at a frame level can help to decrease the data coming from the camera as only the data from the pixel with changed state will be sent. The focal plane computations are also free from temporal aliasing, which is usually a problem in motion detection algorithms. Further temporal differencing is useful for ambient light suppression.

This paper presents a CMOS image sensor with real time polarization sensing ability using a metallic wire grid formed with CMOS metal layers. The ability to detect on chip

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polarization is explored in classifying materials based on the polarization properties of the reflected light from the material surface. The ability of the insect to detect fast motion using "flickering effect" is also replicated. The differential binary images are used to speed up low level motion detection with low complexity and power consumption. These algorithms are based on pixel changes instead of full image processing and thus improve performance.

Section II describes the designed image sensor which is able to detect polarization using metallic wire grid and also to spatially integrate the generated binary 1D optic flow. Experimental results are presented in section III and conclusions are presented in section IV.

II. Sensor Description

A. Sensor for polarization detection

The image sensor consists of an array of 128 by 128 pixels, it occupies an area of 5 x 4mm^2 and it has been designed and fabricated in the 180nm CMOS CIS process from UMC [9]. The sensor has an embedded linear wire grid polarizer in each pixel, realized with the first metal layer of the process on top of a pinned photodiode (p+/n-/p-sub). The linear wire grid polarizer was implemented using thin metal strips with a line/space of 240nm/240nm (pitch of 480nm) as shown in figure 1. Normally, such a wire grid structure would function as a simple diffraction grating, but when the pitch or period of the wires is less than half the wavelength of the incoming light, it becomes a polarizer.

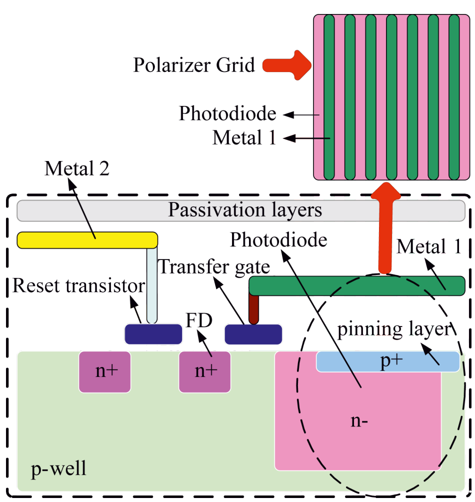

Fig. 1: *Pixel cross-section and top view of the implemented wire-grid polarizer.*

The array of 128 by 128 pixels was split into three regions as shown in figure 2:

1) A 64x128 array without a metal grid used for normal imaging applications
2) A 64x64 array (sense region 1) consisting of 2 by 2 pixel arrays where two pixels (A and B) measure the intensity while the other two measure the 0° (D), and 90° (C) polarized intensity, respectively
3) A 64x64 array (sense region 2) consisting of 2 by 2 pixel arrays where one pixel records the intensity of the light (A) while the other 3 record the 0° (B), 45° (C) and 90° (D) polarized intensity.

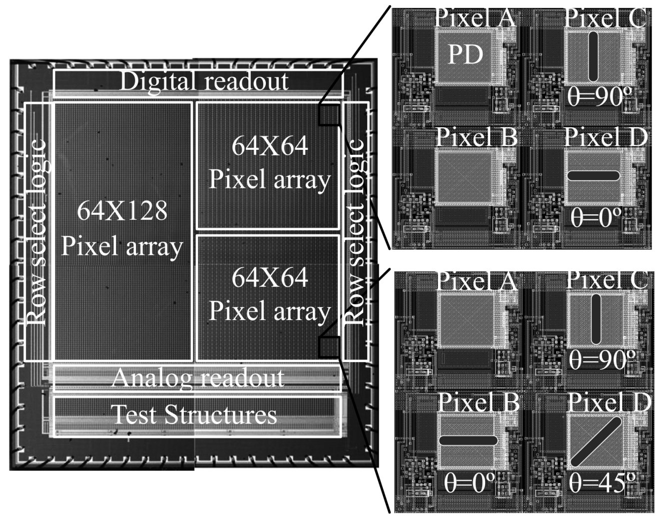

Fig. 2: *Sensor regions with different polarizing angles.*

B. Sensor for motion detection

Each pixel of the designed image sensor (figure 2), contains a pinned photodiode, an analog comparator, two banks of analog memories and two *SRAMs* for digital memory. A simplified pixel diagram is shown in figure 3.

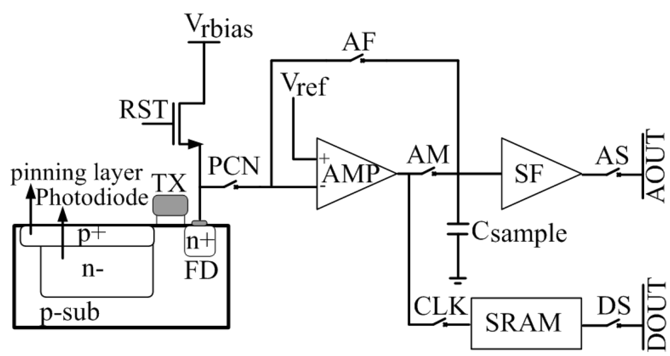

Fig. 3: *Simplified pixel architecture.*

The image capture begins with a reset of the pixel by closing the *RST* switch. The voltage at the floating diffusion node *(FD)* is then set to the reset voltage V_{rbias}. After opening the reset switch, the photodiode starts accumulating the photo-generated charge. The time spent accumulating charge is referred to as integration time. At the end of the integration time, the accumulated charge is transferred to the *FD* node. The voltage change at the *FD* node capacitance due to the transferred photo-charge is sampled onto one of the two available sampling capacitors C_{sample} when the switch *AM* is closed. The source follower *SF* loads the column bus A_{OUT} via the analog row selection switch *AS* with the signal sampled on the sampling capacitor during readout of the pixel.

After the image is captured, the photodiode is disconnected from the processing elements using the switch *PCN*. The analog signal on C_{sample} is compared with a reference voltage V_{ref},, by using the amplifier *AMP* as a comparator. The comparator in the pixel is used to detect the difference between the integrated charge from the photodiode and an external threshold voltage. This allows the generation of binary optical flow similar to the effect of "fickering" in insects' eyes. The generated optical flow can be used to detect motion both in vertical and horizontal direction with minimal processing and hardware. The resulting binary data is stored in the *SRAM* cell when the switch *CLK* is closed. Two such *SRAM* cells are available to store the binary data of the two sampling capacitors. The switch *DS* loads the column bus D_{OUT} with the binary value stored in the *SRAM* cell. The streaming binary data from the pixel, which is analogous to the 1D binary optic flow, is then spatially integrated by a row-wise 7-bit counter.

III. Analysis

A. Polarization detection and material classification

When randomly polarized light is transmitted through an ideal wire-grid polarizer, the electromagnetic fields orthogonal to the wires will be transmitted and the electromagnetic fields parallel to the wire will be reflected. The transmitted irradiance follows the "law of Malus" which states that the maximum transmitted intensity is a cosine function of the transmission axis of the polarization filter. Linear polarizers are characterized by the transmittance efficiency and the extinction ratio. The *transmittance efficiency* is the fraction of the total incident light that is transmitted through the linear polarizer. The *extinction ratio (ER)* is a measure of the polarization contrast of a linear polarizer and it is defined as the ratio between the maximum and minimum transmitted irradiances through the linear polarizer.

In order to characterize the polarization behavior of the sensor, a polarized light is obtained by passing an unpolarized light from a DC light source through a linear polarizer. The transmission axis of the external linear polarizer is varied from 0° to 180° in steps of 15° to change the polarization angle of the light reaching the image sensor. The normalized analog output of the pixels sensitive to 0°, 45° and 90° for varying transmission axis of the external linear polarizer is shown in figure 4.

For 0° polarization the maximum transmittance obtained was 38.4% while the minimum transmittance was 5.45%. For 90° polarization the maximum transmittance observed was 42.4% while the minimum transmittance observed was 0.6%. The calculated extinction ratio for the linear polarizer is 7.7.

The Fresnel reflection theory can be used to classify among conductive metallic surfaces. It is known that the light reflected from the material surface is partially polarized, whereby the polarization state of the reflected light can be represented as a sum of a completely polarized component and a completely unpolarized component [1], [9].

The partial polarization is represented by the degree of polarization *(DOP)* as shown in equation (1) [9].

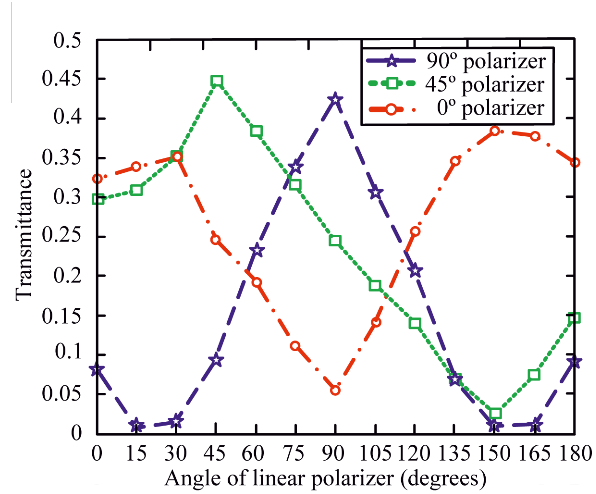

Fig. 4: *0°, 90° and 45° polarization profile in polarization sense region 2.*

$$DOP = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where I_{max} and I_{min} are the maximum and the minimum transmitted irradiances when a reflected wave is passed through a linear polarizer. The metallic grids oriented at 0°, 45° and 90° in the polarization sense regions of the image sensor (figure 2) allow the computation of the degree of polarization *(DOP)*.

The Fresnel reflection coefficients depend on the index of refraction ϵ of the material surface and the specular angle of incidence φ of the incident light. The index of refraction is known to increase with an increase in the conductivity of the material. Thus it can be said that the Fresnel equations depend on the conductivity of the material surface. As the conductivity of the materials increases, the Fresnel reflection coefficient also increases, which in turn decreases the *DOP* as a function of the specular angle of incidence. The measured *DOP* for materials with different conductivities is shown in figure 5.

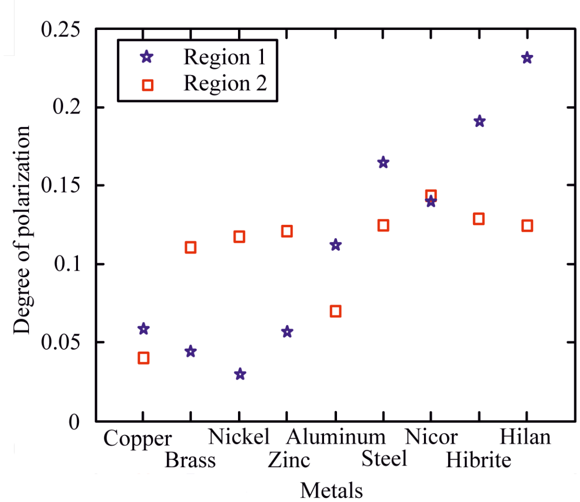

Fig. 5: *Measured degree of polarization for different metals in sense regions 1 and 2.*

The *DOP* of highly conductive materials is found to be lower than the *DOP* of low conducting materials due to increased reflection and higher Fresnel reflection coefficients. It is observed that the *DOP* of metal surfaces varies between 0 and 0.25 in both polarization sense regions. The lower conducting metal surfaces, such as steel and its varieties occupy the higher band of the range while the lower band is occupied by highly conducting metal surfaces.

B. Motion detection using spatially integrated binary optic flow

The horizontal motion of an object is detected using the pixel array binary output of the comparators [10]. The 7-bit counter counts the number of '1' in each row of the pixel for each frame. The algorithm for motion detection then compares the counter outputs to decide if there is motion. If the difference of the counters' outputs for two exposures is higher than a certain threshold, motion occurrence is flagged.

For the designed sensor the brightness control voltage is the reference voltage to which the analog signal obtained after each exposure is compared. The two *SRAM* cells in the pixels serve as frame latches and offer both past and current data. The pixel converts the image data into a one-bit data stream by the comparators.

To verify the proposed model two consecutive frames of a light source moving over the image sensor are shown in figure 6. The first image shows the light source at its initial position and the second image shows it after a slight movement. The two images look very similar, as only a very small motion was introduced. The histograms of the two images are shown in figure 6.

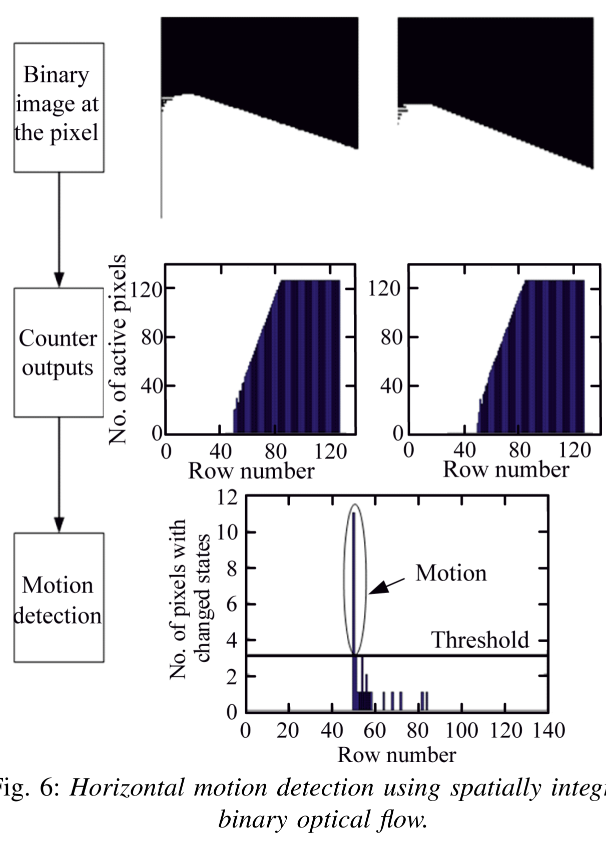

Fig. 6: *Horizontal motion detection using spatially integrated binary optical flow.*

The subtraction of the two images results in a difference image, and the histogram of the pixels which changed states are shown at the bottom of the figure. By selecting a proper threshold, accurate detection of motion can be done.

IV. Conclusion

A CMOS image sensor inspired by the compound eyes of insects to detect polarization using a metallic wire grid and fast motion analysis was designed. An extinction ratio of 7.7 was obtained for the wire grid linear polarizer. The polarization state of the reflected component of the light wave varies with the conductivity of the metallic surface and this has been used to distinguish between high conductive and low conductive metallic surfaces. The designed sensor replicates the motion detection ability of the insects using temporal differential and spatial integration of one-dimensional binary optical flow. This method allows the design of simple, miniaturized, low power and narrow path autonomous navigating agents.

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References

[1] L. B. Wolff, "Polarization based material classification from specular reflection". IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 12, no. 11, pp. 1059-1071, 1990.

[2] C. Anderson, P. Burt, and G. van der Wal, "Change detection and tracking using pyramid transformation techniques". Proceedings of SPIE-Intelligent Robotics and Computer Vision, vol. 579, pp. 72-78, 1985.

[3] I. Haritaoglu, L. S. Davis, and D. Harwood, "W4 who? when? where? what? a real time system for detecting and tracking people". International Conference on Automatic Face and Gesture Recognition, pp. 222-227, 1998.

[4] J. L. Barron, D. J. Fleet, and S. S. Beauchemin, "Systems and experiment performance of optical flow techniques". International Journal of Computer Vision, vol. 12, no. 1, pp. 43-77, 1994.

[5] G. Doretto and S. Soatto, "Editable dynamic textures". Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition, vol. 2, pp. 137-142, 2003.

[6] A. M. Elgammal, D. Harwood, and L. S. Davis, "Non-parametric model for background subtraction". Proceedings of IEEE European Conference on Computer Vision, pp. 751-767, 2000.

[7] J. Tanner and C. Mead, "An integrated analog optical motion sensor". VLSI Signal Processing II, New York: IEEE Press, pp. 59-76, 1986.

[8] A. Moini, A. Bouzerdoum, K. Eshraghian, A. Yakovleff, X. T. Nguyen, A. Blanksby, R. Beare, D. Abbott, and R. E. Bogner, "An insect vision based motion detection chip". IEEE Journal of Solid-State Circuits, vol. 32, no. 2, pp. 279-283, 1997.

[9] M. Sarkar, D. San Segundo, C. Van Hoof and A. J. P. Theuwissen, "Integrated polarization analyzing CMOS image sensor for real time material classification". IEEE Sensors Journal, vol. 11, no.8, pp. 1692-1703, 2011.

[10] M. Sarkar, D. San Segundo, C. Van Hoof and A. J. P. Theuwissen, "A biologically inspired collision detection algorithm using differential optic flow imaging". Proceedings of Biomedical Circuits and Systems, pp. 250-253, 2010.