Biologically Inspired Autonomous Agent Navigation Using an Integrated Polarization Analyzing CMOS Image Sensor

Mukul Sarkar[1, 2], David San Segundo Bello[1], Chris van Hoof[1], Albert Theuwissen[2, 3]
[1]imec, [2]Delft university of technology, [3]Harvest Imaging
Mukul.Sarkar@imec-nl.nl

Abstract— **The navigational strategies of insects using skylight polarization are interesting for applications in autonomous agent navigation because they rely on very little information for navigation. A polarization navigation sensor using the Stokes parameters to determine the orientation is presented. The working principle of the sensor is based on egocentric navigation predominant in insects. The Stokes parameters computed from the measured intensities using a metallic wire grid micro-polarizer are used to retrieve positional information. The computation of the Stokes parameters is simplified to allow for a future on-chip computational algorithm implementation, which would result in highly miniaturized navigational sensors. The image sensor consist of an array of 128x128 pixels, occupies an area of 5x4mm2 and it has been designed and fabricated in a 180nm CMOS process.**

I. INTRODUCTION

Navigation is essential for performing various living tasks. The role of vision and cognitive mapping in navigation has been extensively studied [1]. Cognitive mapping or survey representation of the space defines the Euclidean relations (straight line distance and direction) among relevant landmarks within a coordinate reference system centered on the environment. Route representation is another form or spatial representation of navigation where the navigator tries to learn the points in the route [2], [3].

The progress in the field of autonomous agent navigation has been slower than expected especially after the initial excitement and rapid advances in the early days of the research [4]. It is interesting to consider why autonomous navigation is so difficult. A survey into the available algorithms for autonomous agent navigation reveals that most of them are written to make them understandable for the human operator, mostly employing Cartesian coordinates (x,y,z) to represent the location of the feature [5]. This has the advantage of offering more control over the autonomous agent but may not be a better solution for navigation, than the ones used by insects, for example.

Humans navigate using geocentric navigation. In geocentric navigation, one uses its cognitive map and its orientation with respect to geocentric coordinates in order to set a course to a goal. Visual cues such as landmarks become very important to generate the cognitive maps. In the absence of information about the location of nearby objects in the environment, humans have difficulty monitoring their travel trajectories, even for short paths. On the other hand, some insect species such as the desert ant (Cataglyphis fortis) are known to use egocentric navigation [6]. Egocentric navigation relies on path integration, where the movement cues of the navigator are continuously integrated. Animals using egocentric navigation are able to track distance and direction in order to estimate their position even in the absence of visual landmarks.

Path integration is the basis of vector navigation in egocentric form of navigation [7], and it requires knowledge of the direction of travel and the distance travelled. To determine the direction of travel ants use either the celestial compass based on the pattern of the polarized skylight (polarization compass) or the direct sunlight (sun compass). A polarized skylight navigation system uses the extensive pattern of polarized skylight generated by the scattering of the light rays on collision with the air molecules. Each partially polarized skylight ray exhibits a predominant vibration direction (e-vector [1]) perpendicular to the plane of the scattering angle. The polarization pattern varies in a systematic fashion both in plane (e-vector) and degree of polarization, according to the position of the sun. These polarization patterns in the sky are used by ants as a reference for compass orientation.

This ability of insects to navigate effortlessly in complex environments without stressing their nervous system has already been a subject of research in robotics. The cheap computational strategies that these insects use to navigate have been modeled by various researchers [8], [9]-[10]. Current vision based sensors employed for navigation applications, and especially for robotic navigation, capture images using a standard CMOS or CCD camera and then process those captured images for vector calculations to determine the motion vector and the direction vector to drive the autonomous agents [11]. This is very processing intensive and power consuming.

In this work we present a biologically inspired CMOS image sensor for determining direction of motion for navigation using Stokes parameters. The Stokes parameters are computed from the transmitted intensities of the wire grid micro-polarizer oriented in various directions. Section II gives a brief overview of the theory related to the Stokes parameters. Section III describes the designed image sensor. Section IV presents the measurement results and section V presents the conclusions.

II. THEORY

Electromagnetic radiation travels as transverse waves, i.e., waves that vibrate in a direction perpendicular to their direction of propagation. Polarization is a phenomenon peculiar to transverse waves based on the distribution of the electric field in the plane normal to the propagation direction. An unpolarized or randomly polarized wave is an

[1] The e-vector is the electric field vector of the polarized light in the sky.

electromagnetic wave in which the orientation of the electric vector changes randomly.

The mathematical representation of a wave propagating in the z direction is given by equation [1.0]

$$E = E_0 \cos(kz - \omega t + \varphi_0)\ . \qquad [1.0]$$

Where E_0 is the amplitude, k is the propagation (or wave) constant ($k=2\pi/\lambda$), ω is the circular frequency ($\omega=kc=2\pi c/\lambda$), φ_0 is the initial phase.

The polarization state of an electromagnetic wave can be conveniently described by the Stokes parameters. The Stokes parameters were developed in 1852 by G.G. Stokes and are widely used to represent partial polarization states. The components of the four-component Stokes vector s are defined as follows:

$$\begin{aligned} S_0 &= E_{x0}{}^2 + E_{y0}{}^2 \\ S_1 &= E_{x0}{}^2 - E_{y0}{}^2 \\ S_2 &= 2E_{x0}E_{y0}\cos(\nabla\varphi) \\ S_3 &= 2E_xE_y\sin(\nabla\varphi) \end{aligned} \qquad [1.1]$$

Where E_{x0} is the field strength of the parallel polarized light, E_{y0} is the field strength of the perpendicular polarized light and $\nabla\varphi$ is the phase difference between the parallel and perpendicular polarized light.

There are various ways of measuring Strokes parameters, each corresponding to the measurement of intensity of the beam after it passes through certain filter system arrangements. The four strokes parameters, S_0, S_1, S_2 and S_3 can be obtained from the intensities measured after transmission through a linear polarizer oriented at 0º, 90º and 45º. The wire-grid linear polarizer consists of fine grid of parallel metal wires with space and width less than the wavelength of light

The Poincaré sphere shown in figure 1 is used to display the three independent Stokes parameters S_1, S_2 and S_3 as points on, or inside a sphere.

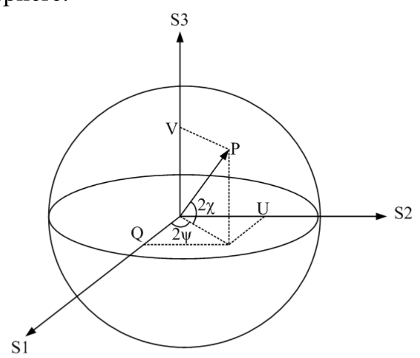

Figure 1: Poincare sphere representation

In figure 1, ψ is the polarization azimuth angle and χ is the ellipticity angle. The surface of the Poincare sphere is commonly used to give a pictorial representation of all the possible polarization states of completely polarized light. Each point on the surface of the sphere corresponds to a state of the polarization of the light. Linear polarization is represented along the equator of the sphere.

The polarization azimuth angle ψ and the ellipticity angle χ can then be expressed in terms of the Stokes parameters [12] as:

$$\sin 2\chi = \frac{S_3}{\sqrt{S_1^2 + S_2^2 + S_3^2}} \qquad \tan 2\psi = \frac{S_2}{S_1} \qquad [1.2]$$

III. Sensor Description

The image sensor used here is described in [13]. The image sensor consists of an array of 128 by 128 pixels. It occupies an area of 5 x 4 mm^2 and it has been designed and fabricated in the 180nm CMOS CIS process from UMC. The sensor has an embedded metallic wire grid micro-polarizer in each pixel on top of a pinned photodiode ($p^+/n^-/p$-sub), realized with the first metal layer of the process. 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 2.

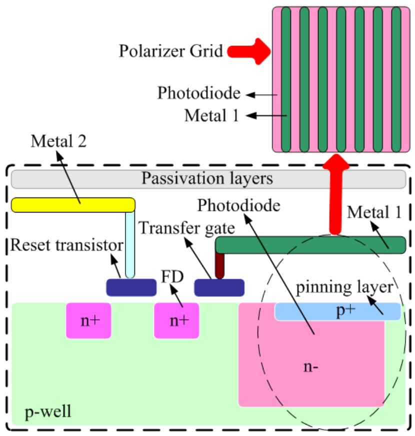

Figure 2: Wire grid Polarizer

The array of 128 by 128 pixels in the active area of the image sensor was split into three regions as shown in figure 3:

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 0º (D), and 90º (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 0º (B), 45º (C) and 90º (D) polarized intensity.

The additional pixel sensitivity to 45º polarized light in sense region 2 is used to compute the Stokes parameters. The pixels dedicated to sense the intensity in regions 1 and 2 are used to normalize the data obtained from the pixels sensitive to polarization directions.

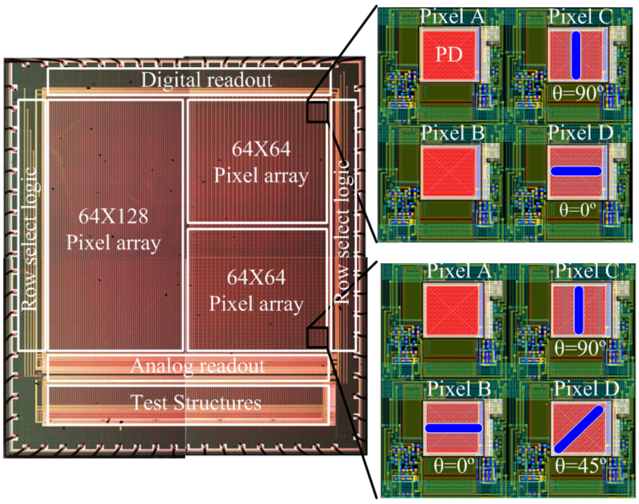

Figure 3: Sensor Regions with different Polarizing angles.

IV. PERFORMANCE ANALYSIS

The measurement setup is shown in figure 4. The DC light source generates an unpolarized light which is polarized by a linear polarizer. The transmitted intensity of the linear polarizer is then sensed by the imager and the output of the imager is fed to the PC for processing of the sensed data. The corresponding analog outputs of the pixels sensitive to 0º, 45º and 90º in the polarization sense regions are used to compute the Stokes parameters. For the first version of the sensor the Stokes parameters were computed off-chip to have a proof of concept. Control pulses for the image sensor are generated by an FPGA, so that the accumulation and readout timing can be manipulated by an appropriate VHDL program.

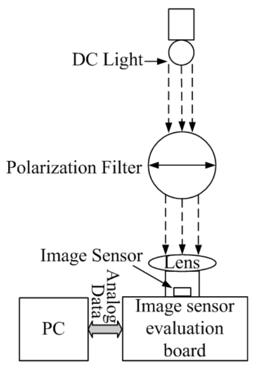

Figure 4: Measurement setup

The azimuthal position (ψ) is computed from the Stokes parameters using equation [1.1] and [1.2]. Figure 5 shows the theoretical and experimental angles of linear polarization for polarization sense region 1 and 2. The correlation coefficients[2] of 0.997 and 0.98 in the two regions indicate a strong correlation between the theoretical and the measured results.

---

[2]

$$correlation = \left[N\sum xy - \sum x \sum y\right] \Big/ \sqrt{\left[N\sum x^2 - \left(\sum x\right)^2\right]\left[N\sum y - \left(\sum y\right)^2\right]},$$

where N is the number of elements and x and y are the two variables.

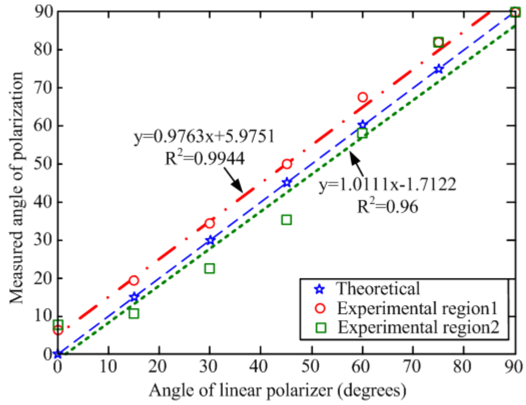

Figure 5: Measure angle of polarization in polarization sense region 1 and 2 using equations [1.2].

A linear fit error for the measure angle of linear polarization is computed to be 2.3% and 1.1% in the sense region 1 and 2 respectively. For a similar configuration using an organic micro-polarizer, the error is reported to be 2.2% [14] and an error of 1.6% using aluminum nanowire with a wire grid pitch of 70nm [15]. These are however very specialized process and needs additional fabrication steps, while our method uses only the standard CMOS process steps.

The polarization sense region 2 has an additional 45º linear polarization sensitive pixel. The Stokes equations are modified as:

$$\begin{aligned} S_0 &= I_{0^\circ}{}^2 + I_{90^\circ}{}^2 \\ S_1 &= I_{0^\circ}{}^2 - I_{90^\circ}{}^2 \\ S_2 &= I_{0^\circ}{}^2 - I_{45^\circ}{}^2 \end{aligned} \qquad [1.3]$$

Where I_{0°, I_{90° and I_{45° are the intensity of the light after passing through linear polarizer oriented at 0º, 90º and 45º. The fourth Stokes parameter S_3 is neglected as the light is assumed to be completely linearly polarized. The azimuthal position (ψ) is then computed using equations [1.2] and is shown in figure 6.

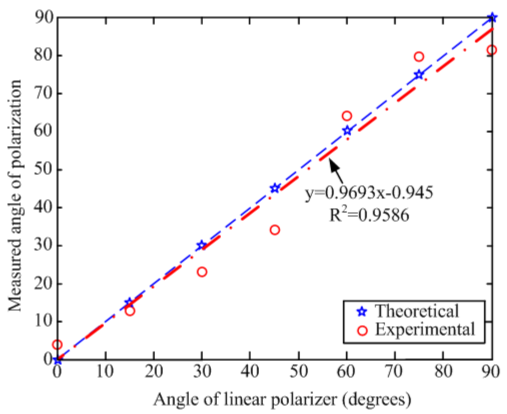

Figure 6: Measure angle of polarization in polarization sense 2 using equations [1.3].

A linear fit error for the angle of linear polarization measurements is computed to be 3.07%. A correlation coefficient of 0.97 is obtained between the theoretical and the experimental values.

The Stokes parameters used to obtain the azimuthal position (ψ) in figure 5 and figure 6 require the computation of the square of the pixel intensities, which is relatively difficult for an on-chip computation. To simplify the computation the Stokes equations can be further simplified as in [18] and are shown in equation [1.4].

$$S_0 = I_{0^\circ} + I_{90^\circ}$$
$$S_1 = I_{0^\circ} - I_{90^\circ} \qquad [1.4]$$
$$S_2 = I_{0^\circ} - I_{45^\circ}$$

Equation [1.2] is again used to compute the azimuthal position ψ and is plotted in the figure 7.

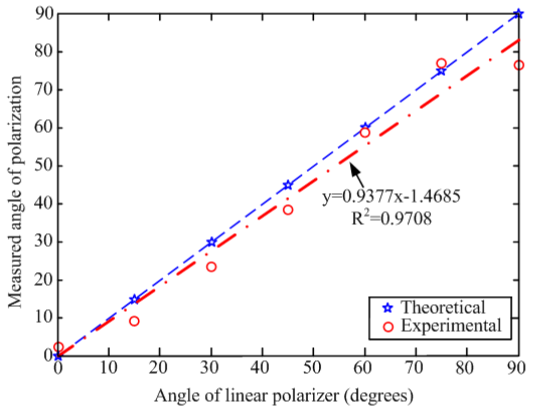

Figure 7: Measured angle of polarization in polarization sense region 2 using equations [1.4].

A linear fit error for the measured angle of linear polarization is computed to be 6%. A correlation coefficient of 0.985 is obtained between the theoretical and the experimental values showing strong correlation. The angular positional information obtained by equations [1.4] is very similar to those obtained by equations [1.3] as shown in the figures 6 and 7. Equations [1.4] are relatively easy to be implemented on-chip using simple operational amplifier as an analog adder or subtractor. The high linearity error is due to the higher metallic wire grid pitch used, limited by the choice of the process technology. With advances in the process technology the pitch can be considerably reduced providing better polarization detection ability and thus a better linear fit error.

From figures 6, 7 and 8 it can be observed that the polarizations angle can be retrieved using the Stokes parameters, thus providing for a way to determine the incoming polarized light direction. This would in turn serve to determine the angular positional information useful for autonomous agent navigation.

V. Conclusion

A polarization navigation sensor using the Stokes parameters computed from the polarized component of the light is presented. The sensor working principle is based on egocentric form of navigation. The positional information is retrieved from the Stokes parameters from the transmitted intensities of the implemented metallic wire grid micro-polarizer. The polarization pattern of the skylight for a given elevation of the sun is a constant, and this principle can be used as a compass clue. Though this principle is very common in insects, it has not yet been explored in sensors. The computational algorithm can be implemented on-chip which would result in miniaturized navigational sensors for autonomous agents.

Acknowledgment

The Authors would like to thank DALSA for providing the test table to characterize the sensor, INVOMEC for helping with the fabrication of the chip, A. Mierop of DALSA, G. Meynants of CMOSIS and P. Merken for their valuable contributions to the project.

References

[1] V.V. Hafner, "Adaptive Navigation Strategies in Biorobotics: Visual Homing and Cognitive Mapping in Animals and Machines". Shaker Verlag, 2004.

[2] John O'Keefe and Lynn Nadel, "The Hippocampus as a Cognitive Map". Oxford University press, 1978

[3] P.W. Thorndyke and B. Hayes-Roth, "Differences in spatial knowledge acquired from maps and navigation". Cognitive Psychology, 14, pp. 560-589, 1982.

[4] H. Moravec, "Obstacle avoidance and navigation in the real world by a seeing robot rover". Technical Report CMU-RI-TR-3, Carnegie-Mellon University, Robotics Institute, September 1980.

[5] G. N. DeSouza and A.C. Kak, "Vision for mobile robot navigation: A survey". IEEE Trans. on pattern and machine intelligence, vol 24, no. 2, pp. 237-267. 2002.

[6] R. Wehner B. Michel and P. Antonsen, "Visual navigation in insects: coupling of egocentric and geocentric information". J. of Experimental Bio. 199, pp. 129-140, 1996.

[7] M. Müller and R. Wehner, "Path integration in desert ants, Cataglyphis fortis", Proc. Natl. Acad., Sci. USA, Vol. 85, pp. 5287-5290, 1988.

[8] D. Lambrinos, R. Möller, T. Labhart, R. Pfeifer and R. Wehner, "A mobile robot employing insect strategies for navigation". Robotics and Autonomous Systems 30(1-2): pp. 39-64, 2000.

[9] D. Lambrinos, M.Maris, H.Kobayashi, T. Labhart, R.Pfeifer and R. Wehner, "An Autonomous agent navigating with a polarized light compass". Adaptive behaviour, 6(1): pp. 131-161, 1997.

[10] K. Usher, P. Ridley and P. Corke, "A Camera as a polarized light compass: preliminary experiments". Aust. Conf. on Robo. And Auto, pp. 116-120, 2001.

[11] Z. Chen and S. T. Birchfield, "Qualitative vision based mobile robot navigation". IEEE International Conf. on robotics and Automation, pp. 2686-2692, 2006.

[12] G. Gerhart and R. Matchko, "Visualization techniques for four Stokes parameter polarization". Proc. of the ground target modeling and validation conference, pp. 216-225, 2002.

[13] M. Sarkar, D. San Segundo, C. van Hoof, A.J.P. Theuwissen, "Polarization analyzing CMOS image sensor". Proc. of IEEE ISCAS, pp. 621-624, 2010.

[14] V. Gruev, J. van der Spiegel and N. Engheta, "Integrated polarization image sensor for cell detection". International image sensor workshop, 2009.

[15] V. Gruev and R. Perkins, "A 1 MPixel CCD image sensor with aluminum nanowire polarization filter". Proc. of IEEE ISCAS, pp. 629-632, 2010.