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Performances of Three Miniature Bio-inspired Optic Flow Sensors under Natural Conditions

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Abstract: Considerable attention has been paid during the last decade to vision-based navigation systems based on optic flow (OF) cues. OF-based systems have been implemented on an increasingly large number of sighted autonomous robotic platforms. Nowadays, the OF is measured using conventional cameras, custom-made sensors and even optical mouse chips. However, very few studies have dealt so far with the reliability of these OF sensors in terms of their precision, range and sensitivity to illuminance variations. Three miniature custom-made OF sensors developed at our laboratory, which were composed of photosensors connected to an OF processing unit were tested and compared in this study, focusing on their responses and characteristics in real indoor and outdoor environments in a large range of illuminance. It was concluded that by combining a custom-made aVLSI retina equipped with Adaptive Pixels for Insect-based Sensor (APIS) with a bio-inspired visual processing system, it is possible to obtain highly effective miniature sensors for measuring the OF under real environmental conditions. *Copyright © 2011 IFSA.*

Keywords: Bio-inspired optic flow sensor, vision-based navigation system, autonomous robotic platform, OF sensor, VLSI retina, bio-inspired visual processing system

1. Introduction

Several examples of embedded optic flow-based navigation systems have been developed during the last decade or so. As in their natural counterparts (flies, bees, etc.) where the optic flow (OF) provides vital cues, aerial robots are now being endowed with similar means of detecting and processing OF for obstacle avoidance purposes [1] [2] [3] [4], terrain following and landing [5] and wall following [6]. However, there exist very few robotic examples in which OF sensing has been successfully implemented under real indoor [7] or outdoor conditions environment [8] [9] [4]. Many OF sensors have been developed using analog VLSI technology (e.g., [10] [11]), but their relatively complex and bulky peripheral electronics have often made it impossible to implement these aVLSI sensors onboard aerial robots. The authors of some recent studies mounted off-the-shelf mouse sensors onboard terrestrial [12] [13] and aerial robotic platforms [9] [4]. However, the performances of these systems in terms of their resolution, accuracy, invariance to illuminance and contrast have not been properly assessed so far, except in [4] where a static characteristic of a mouse sensor for OF measurement is given. In this study, it was therefore proposed to compare the output signals of three custom-made bio-inspired OF sensors with a reference angular speed measured by a rate gyro. Our own OF sensors, which we have also called Elementary Motion Detectors (EMDs), process the OF by comparing the signals collected by adjacent photosensors [14][15][2]. A purely *rotational* optic flow was generated by rotating the various OF sensors placed in front of a natural indoor or outdoor scene while the reference angular speed was being recorded synchronously. By definition, the rotational optic flow is not affected by the distance to object. A description of the various OF sensors tested here is given in section II. Section III gives an account of the performance of these OF sensors placed in a real environment in a large range of illuminance.

2. Description of the OF Sensors

Our OF sensors are basically composed of a lens and two photosensors (photodiodes) placed behind the lens. Each photodiode's output signal is sent to an OF processing unit where a discrete version of an EMD circuit is running. An EMD is used here to assess the relative angular speed Ω of contrasting features in the environment (i.e., the optic flow). Our original EMD design [14][15][2] consists of an analog circuit producing an output signal that increases as the time lag Δt between its two inputs decreases. The output signal therefore increases with the angular speed Ω, i.e., with the OF. Like the fly's motion-detecting neurons from which it was originally inspired [16], our electronic analogue EMD reacts to both dark-to-light (ON) and light-to-dark (OFF) contrast transitions. The EMD-inspired signal processing steps implemented onboard the three OF sensors can be decomposed into 5 steps as follows:

- Step 1: Low-pass spatial filtering (which is achieved by defocusing the lens to obtain Gaussian blurring),
- Step 2: Band-pass temporal filtering to derivate the visual signals and to reduce the noise and interference (such as the 100-Hz interference originating from artificial lighting),
- Step 3: Thresholding for contrast detection,
- Step 4: Measuring the time lag Δt (travel time) between the thresholded signals,
- Step 5: Computing the OF by applying :

$$\Omega_{meas} = \frac{\Delta\varphi}{\Delta t} \tag{1}$$

The angles $\Delta\varphi$ and $\Delta\rho$, called interreceptor angle and acceptance angle, respectively, are adjusted by slightly defocusing the lens placed in front of the photodiodes. For each OF sensor, the angle $\Delta\rho$ determines directly the cut-off frequency of the low-pass spatial filtering (step 1) whereas the angle $\Delta\varphi$ determines the measurement range of the OF Ω. For a given resolution (here 1ms) in the measurement of the time lag Δt, the smaller the angle $\Delta\varphi$, the smaller the OF range will be. In this study, three OF sensors based on the same principle but using different technologies were compared (see Fig. 1).

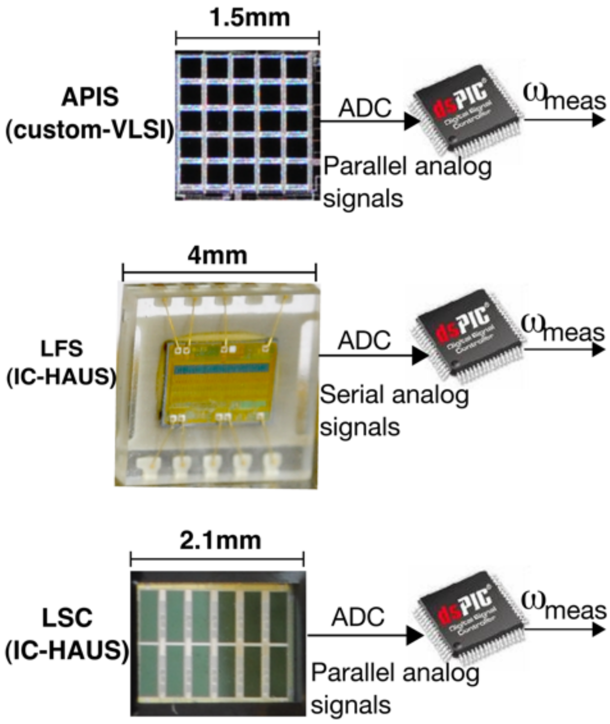

Fig. 1. General hardware architecture of the three OF sensors composed of a photodiodes array connected, via an analog-to-digital converter (ADC), to an external optic flow (OF) processing unit. The custom-made Adaptive Pixels for Insect-based Sensors (APIS) is made of 5x5 Delbrück-type [17] adaptive sensors. The off-the-shelf linear array (LFS and LSC from IC-HAUS) integrate amplifier circuits at the pixel level. For each sensor, the optic flow Ω_{meas} measured by each sensor is computed from the visual input signals provided by two adjacent pixels.

The first OF sensor, called APIS (Adaptive Pixels for Insect-based Sensor), is composed of a single lens (focal length 6.5mm) placed in front of a VLSI retina made of 2 adaptive pixels [17]. This retina was developed in collaboration with the Center for Particle Physics (CPPM, Marseille, France) [18]. The second OF sensor, called LSC, is composed of an optical assembly mounted onto an off-the-shelf photodiode array consisting of 6 pixels (IC-Haus, LSC). The LSC sensor was also endowed with an Automotic Gain Control (AGC) function implemented onboard the microcontroller. The third OF sensor, called LFS, is also composed of an optical assembly mounted in front of a 32 pixels linear imager (IC-Haus, LFS). The optic assemblies of the LSC and LFS sensors were simply borrowed from a low cost miniature camera (Velleman, focal length 4.9 mm) and a tiny CMOS color camera (CONRAD, focal length 2.2 mm), respectively. We used three different optics to make the ratio $\Delta\varphi/\Delta\rho$ equal to 1. This ratio can be also found in several insects [19]. Table 1 summarizes the main characteristics of the OF sensors.

Table 1. Main characteristics of the OF sensors.

	APIS	LFS	LSC
Photodiode size (μm)	250 × 250	65 × 65	300 × 1600
Pixel pitch (μm)	300	63.5	420
F_{number}	1.1	1.4	2.8
Focal length (mm)	6.5	2.2	4.9
$\Delta\rho(°)$	3.41	0.83	7
$\Delta\varphi(°)$	3.2	0.83	7.3

Fig. 2 shows the three OF sensors mounted on a common printed circuit board. An additional illuminance sensor was connected to an analog amplifier running in the photovoltaic mode. The photocurrent I_{ph} of this illuminance sensor is obtained as follows [20]:

$$I_{ph} = \left(e^{\frac{V_{out}}{0,25}} - 1 \right) I_{dark} \ , \tag{2}$$

where the dark current I_{dark} is equal to 1nA and V_{out} is the amplifier's output voltage.

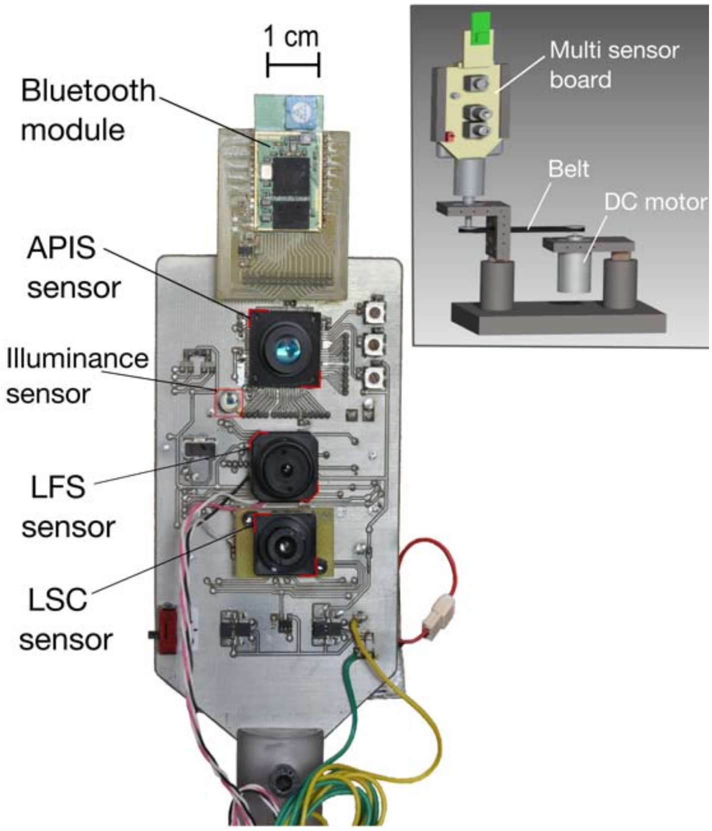

Fig. 2. The multi sensor PCB board includes three OF sensors, an illuminance sensor based on a single photodiode, a rate gyro for measuring the reference angular speed (i.e., the rotational speed of the board) and a microntroller (dSpic). The microcontroller processes the visual signals of all the three OF sensors at a sampling frequency of 1 kHz. The measured OF Ω_{meas} and the measured rotational speed Ω_{gyro} are recorded synchronously and sent to a computer through a Bluetooth module. The wireless link and the small onboard battery (LiPo, 300 mAh-3.3 V) made the multi sensor board free to rotate in complete autonomy on its two miniature ball-bearings. (Top right) A rotational speed was imposed on the board by means of a DC servomotor.

3. Experimental Results

As discussed in Section II, an optic flow sensor is an optical device that measures an angular speed Ω_{meas}. The three OF sensors were tested in indoor and outdoor environments (see Fig. 3) by comparing their output signals with respect to the angular speed Ω_{gyro} measured by a MEMS rate gyro with a maximum speed range of 300°/s. As shown in Fig. 2 (top right), the multi sensor board was coupled to a DC motor via a belt, which made it possible for the experimenter to adjust the rotational speed of the board. The board was made to rotate at a rotational speed Ω varying sinusoidally within 60°/s to 300°/s range in the case of the APIS and LSC sensors and within the 60°/s to 200°/s range in that of the LFS sensor.

Fig. 3. Panoramic view of the real indoor (top) and outdoor (bottom) environments that were used to assess the OF sensor's responses.

3.1. Indoor Optic Flow Measurement

The response of the three OF sensors placed in the indoor environment is shown in Fig. 4. The measured optic flow Ω_{meas} (dark points) is superimposed on the measured reference angular speed Ω_{gyro}. Despite the strong 30-fold attenuated illuminance, the responses of the APIS and LSC sensors faithfully reflected the sinusoidal variation imposed by the mechanical rotation of the board. The response of the LFS was found to be noisier at high and very low illuminance levels due to the saturation of its output voltage and its lower sensitivity at the pixel level, respectively. The APIS and the LSC sensors were therefore selected for conducting further tests outdoors and for measuring their static characteristics.

3.2. Outdoor Optic Flow Measurement

Fig. 5 gives the responses of the two OF sensors placed in the outdoor environment. Although the illuminance was about 10-fold greater than the highest value of I_{ph} in the indoor environment, the dynamic outdoor responses of both the APIS and the LSC sensors followed the sinusoidal variations in the angular speed. The fact that a larger number of matching errors were observed in the case of the APIS sensor suggests that the specific optics used here (with a relatively large *f-number* of 1.1) was less well suited to the task in question than that of the LSC sensor (f-number of 2.8).

3.3. Static Characteristics of the OF Sensors

As shown in Fig. 6, the APIS sensor showed a high level of invariance to the illuminance while linearity of its static characteristics was well maintained. The static characteristics of the LSC sensor also showed a good linearity and a good invariance to the lighting conditions, provided the illuminance was maintained at a relatively high level.

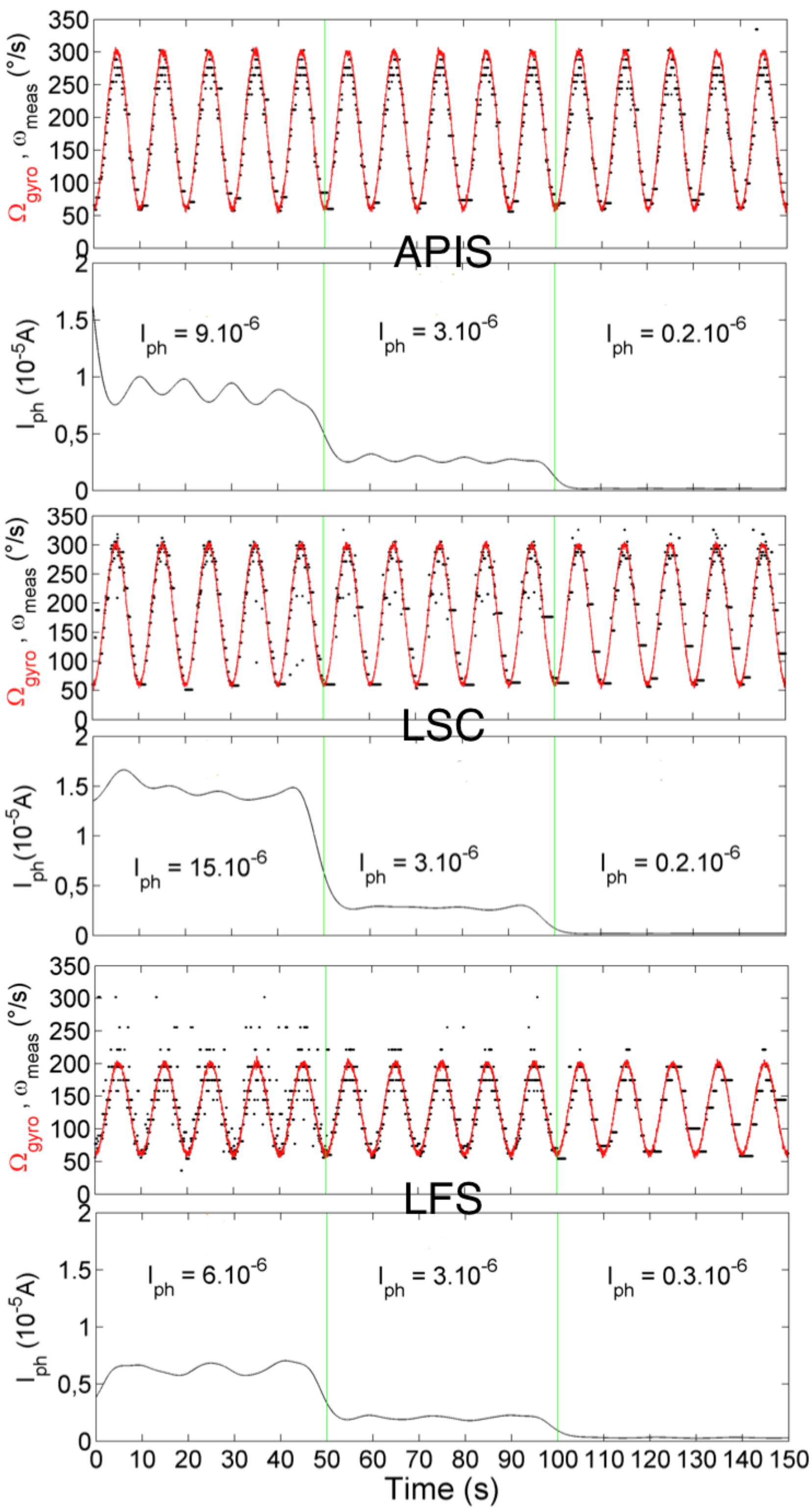

Fig. 4. Response profile of the three OF sensors to a sinusoidally changing rotational speed of the board on which they are mounted (cf. Fig. 2). The three OF sensors were placed in the *indoor* environment (Fig. 3) under three different lighting conditions. During the experiment, the mean value of the photodiode's current I_{ph}, i.e., the current measured by the illuminance sensor (red continuous line) was reduced stepwise over a range of up to 30-fold. Unlike the LFS sensor, the LSC with its AGC (cf. text) and the APIS sensor with its adaptive pixels showed a remarkable insensitivity to the illuminance.

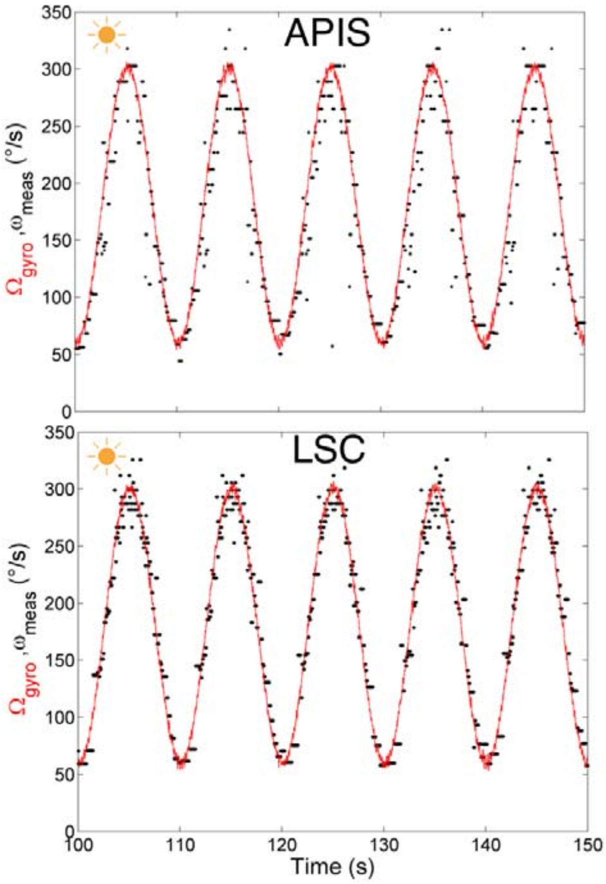

Fig. 5. Response of the LSC with its AGC and APIS sensors placed in the *outdoor* environment (Fig. 3). Despite the strong illuminance (which was 10 times higher than the maximum value of I_{ph} in the indoor environment), the two OF sensors faithfully followed the sine variation of the rotational angular speed.

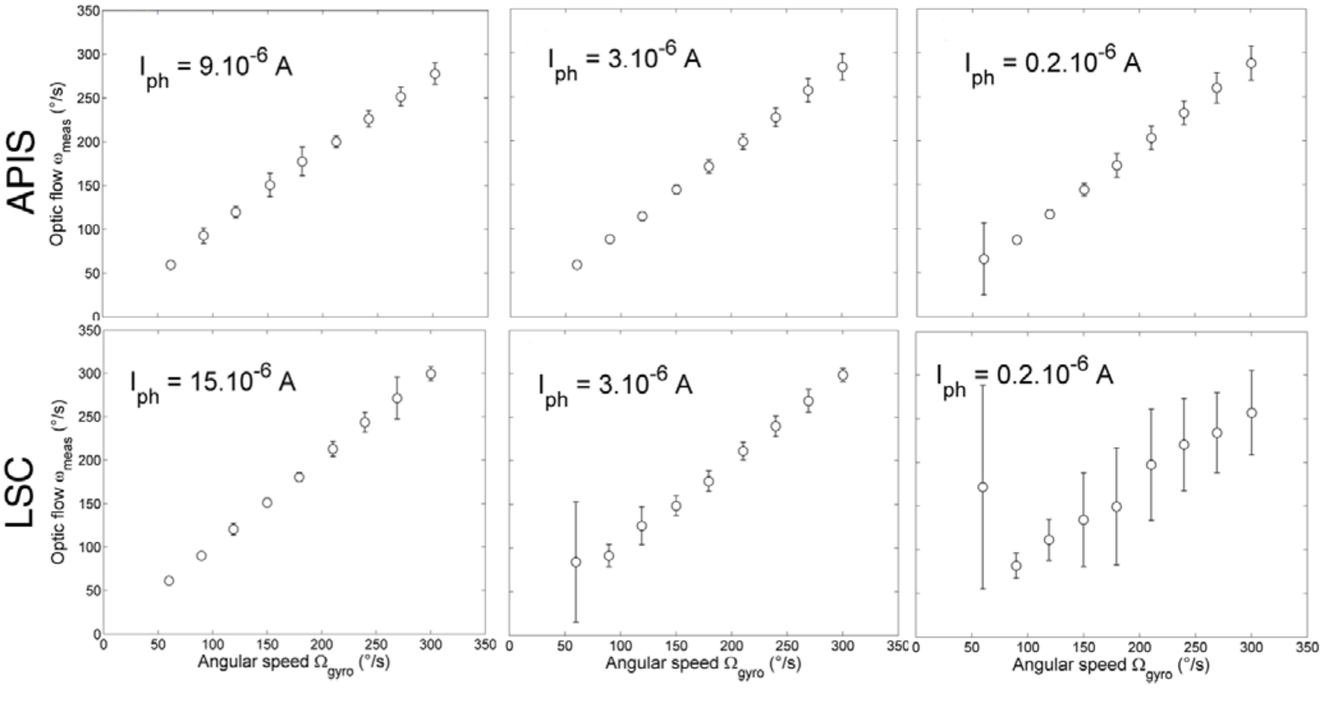

Fig. 6. Static characteristics of the LSC with its AGC and APIS sensors assessed by varying the rotational speed from 60°/s to 300°/s in 30°/s-steps. The different values of the average photocurrent I_{ph} given in this figure indicate that the illuminance of the indoor environment was attenuated by 30 dB.

4. Conclusion

Three OF sensors were tested here in real indoor and outdoor environments and under various lighting conditions. It turned out from the results of these tests that the APIS sensor based on a custom aVLSI retina equipped with adaptive pixels gave the best features in terms of invariance to the illuminance and precision. However, under outdoor conditions, the LSC sensor with its AGC made fewer matching errors (OF measurement errors) probably thanks to its better suited optics (smaller optical aperture, larger *f-number*). We therefore intend to modify the APIS optics to improve this sensor's dynamic responses in outdoor environments. To summarize, it was established here that OF sensors consisting of low cost optics and classical electronic components combined with appropriate visual signal processing methods can give accurate and reliable results under *natural conditions* (indoor or outdoor environments). This study brings us one step further towards implementing tiny, light and robust OF sensors that could invest many application fields as domestic, biomedical, automotive, robotic and aerospace sensors.

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References

[1]. W. E. Green et P. Y. Oh, Optic-Flow-Based Collision Avoidance, *Robotics & Automation Magazine, IEEE*, Vol. 15, No. 1, Mar. 2008, pp. 96-103.
[2]. N. Franceschini, F. Ruffier, J. Serres, et S. Viollet, Aerial vehicles, T. M. Lam, Éd. Vienna: *In-Tech*, 2009, pp. 747-770.
[3]. M. Srinivasan, S. Thurrowgood, et D. Soccol, Competent vision and navigation systems, *IEEE Robotics & Automation Magazine*, Vol. 16, No. 3, Sep. 2009, pp. 59–71.
[4]. A. Beyeler, J. Zufferey, et D. Floreano, Vision-based control of near-obstacle flight, *Autonomous Robots*, Vol. 27, No. 3, Oct. 2009, pp. 201–219.
[5]. F. Ruffier et N. Franceschini, Optic flow regulation: the key to aircraft automatic guidance, *Robotics and Autonomous Systems*, Vol. 50, 2005, pp. 177-194.
[6]. J. Serres, D. Dray, F. Ruffier, et N. Franceschini, A vision-based autopilot for a miniature air vehicle: joint speed control and lateral obstacle avoidance, *Autonomous Robots*, Vol. 25, No. 1, 2008, pp. 103–122.
[7]. J. Zufferey et D. Floreano, Fly-inspired visual steering of an ultralight indoor aircraft, *IEEE Transactions on Robotics*, Vol. 22, 2006, pp. 137-146.
[8]. M. Garratt et J. Chahl, Visual control of an autonomous Helicopter, in *Proceeding of American Institute of Aeronautics and Astronautics*, 2003.
[9]. S. Griffiths, J. Saunders, A. Curtis, B. Barber, T. McLain, et R. Beard, Maximizing miniature aerial vehicles, *Robotics & Automation Magazine, IEEE*, Vol. 13, No. 3, Sep. 2006, pp. 34-43.
[10]. R. R. Harrison et C. Koch, A Robust Analog VLSI Motion Sensor Based on the Visual System of the Fly, *Autonomous Robots*, Vol. 7, No. 3, Nov. 1999, pp. 211–224.
[11]. R. Moeckel et S. Liu, Motion Detection Circuits for a Time-To-Travel Algorithm, in *Circuits and Systems, 2007. ISCAS 2007. IEEE International Symposium on*, 2007, pp. 3079-3082.
[12]. J. D. Jackson, D. W. Callahan, et J. Marstrander, A Rationale for the use of Optical Mice Chips for Economic and Accurate Vehicle Tracking, in *Proc. of the IEEE International Conference on Automation Science and Engineering CASE 2007*, 2007, pp. 939–944.
[13]. H. Dahmen, A. Millers, et H. A. Mallot, Flying insects and robots, D. Floreano, J. C. Zufferey,

M. V. Srinivasan, et C. P. Ellington, Éd. Springer, 2009, pp. 115-126.

[14].C. Blanes, Appareil visuel élémentaire pour la navigation à vue d'un robot mobile autonome., Master Thesis in Neurosciences, *Univ. of Marseille*, France, 1986.

[15].F. Ruffier, S. Viollet, S. Amic, et N. Franceschini, Bio-inspired optical flow circuits for the visual guidance of Micro-Air Vehicles, in *Proc. of the IEEE Int. Symposium on Circuits and Systems (ISCAS)*, Vol. III, 2003, pp. 846-849.

[16].N. Franceschini, A. Riehle, et A. L. Nestour, Directionally Selective Motion Detection by Insect Neurons, in Facets of vision, D. G. Stavenga, R. C. Hardie, Eds., *Springer*, Berlin, 1989, pp. 360-390.

[17].T. Delbrück et C. A. Mead, Adaptive photoreceptor with wide dynamic range, in *Proc. of the IEEE International Symposium on Circuits and Systems ISCAS '94*, Vol. 4, 1994, pp. 339–342.

[18].F. Aubépart, M. Menouni, T. Loubignac, B. Dinkelspieler, et N. Franceschini, Capteur de flux optique basé sur une rétine intégrée et un FPGA, in *Colloque Interdisciplinaire en Instrumentation*, 2007, pp. 508-520.

[19].M. F. Land, Visual acuity in insects., *Annu Rev Entomol*, Vol. 42, 1997, pp. 147–177.

[20].J. D. Riggs, Notes on Silicon Photodiode Detectors, *International Amateur-Professional Photoelectric Photometry Communications*, Vol. 14, Déc. 1983, pp. 30-44.

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Guide for Contributors

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