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Bio-inspired optic flow sensors based on FPGA: Application to Micro-Air-Vehicles

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Abstract

Tomorrow's Micro-Air-Vehicles (MAVs) could be used as scouts in many civil and military missions without any risk to human life. MAVs have to be equipped with sensors of several kinds for stabilization and guidance purposes. Many recent findings have shown, for example, that complex tasks such as 3-D navigation can be performed by insects using *optic flow* (OF) sensors although insects' eyes have a rather poor spatial resolution. At our Laboratory, we have been performing electrophysiological, micro-optical, neuroanatomical and behavioral studies for several decades on the housefly's visual system, with a view to understanding the neural principles underlying OF detection and establishing how OF sensors might contribute to performing basic navigational tasks. Based on these studies, we developed a functional model for an Elementary Motion Detector (EMD), which we first transcribed into electronic terms in 1986 and subsequently used onboard several terrestrial and aerial robots. Here we present a Field Programmable Gate Array (FPGA) implementation of an *EMD array*, which was designed for estimating the OF in various parts of the visual field of a MAV. FPGA technology is particularly suitable for applications of this kind, where a single Integrated Circuit (IC) can receive inputs from several photoreceptors of similar (or different) shapes and sizes located in various parts of the visual field. In addition, the remarkable characteristics of present-day FPGA applications (their high clock frequency, large number of system gates, embedded RAM blocks and Intellectual Property (IP) functions, small size, light weight, low cost, etc.) make for the flexible design of a multi-EMD visual system and its installation onboard MAVs with extremely low permissible avionic payloads.

Keywords: Optic flow sensor; Elementary Motion Detector; Field Programmable Gate Array; Micro-Air-Vehicle; Biorobotics

1. Introduction

One recent trend in the field of Unmanned Air Vehicle (UAV) and robotic aircraft design has been the development of Micro-Air-Vehicles (MAVs) in the 1–50 cm size range. MAVs could be used as scouts in many dangerous civil and military missions without any risk to human life, and they also have many potential industrial applications such as plant supervision, power line [1] and construction site inspection, pollution and weather monitoring, forest fire and disaster control, etc. Missions of this kind require reactive vehicles equipped with onboard sensors and flight control systems capable of performing the lowly tasks of attitude stabilization, obstacle sensing and avoidance, terrain following and automatic landing [1,2]. The ability to perform these tasks would give MAVs some degree of decision-making autonomy, while relieving ground operators of the arduous task of constantly piloting and guiding a particularly agile craft that is invisible most of the time.

One lesson we have learned from insects is that they are able to sense and avoid obstacles and to navigate swiftly

Abbreviations: ASF, Angular Sensitivity Function; AWHH, Angular Width at Half Height; EMD, Elementary Motion Detector; FOV, Field of View; FPAA, field programmable analog array; FPGA, Field Programmable Gate Array; IC, integrated circuit; IP, Intellectual Property; LUT, Look-Up Table; MAV, Micro-Air-Vehicles; μC, Micro-Controller; OF, optic flow; UAV, Unmanned Air Vehicles; VHDL, Very High speed Integrated Circuit Description Language; VLSI, Very Large Scale Integration.

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through the most unpredictable environments without any need for sonars or laser range-finders. Insects' visually guided behaviour depends on *optic flow* (OF) sensing processes. The optic flow perceived by a moving animal, human or robot is a vector field that gives the *angular speed* (direction in degrees; magnitude in rad/s) at which any contrasting object in the environment is moving past the eye. Measuring this angular speed is not a trivial task. Onboard insects such as the fly, this angular speed is not given directly but is "computed" locally by a neuron called an Elementary Motion Detector (EMD), which is driven by at least two photoreceptors facing in different directions. The fly's eye has long been known to be equipped with a whole array of these smart sensors, which contribute to assessing the OF [3,4]. The fly's eye is therefore one of the best animal models available for studies on motion detecting neurons [5]. Our EMD model was inspired by the results of studies in which microelectrode recordings were performed while applying microstimulation to individual photoreceptor cells on the fly's retinal mosaics [5,6].

Psychophysical studies on motion detection in humans and neurobiological studies on motion detection in various animals have led to the development of two main kinds of models for directionally selective motion detectors. These models are based on what is known as *intensity-based* schemes (correlation techniques and gradient methods) and *token-matching* schemes [7,8]. Our fly-inspired electronic EMDs are of the second kind. We have been using them for 20 years onboard various mobile robots.

Our biorobotic approach consists in building terrestrial and aerial robots [9–13] based on optic flow sensing techniques. The robofly ('le robot-mouche') started off as a small, completely autonomous robot equipped with a compound eye and 114 electronic EMDs implemented in analog technology using Surface Mounted Devices (SMD). This robot was able to steer its way through an unknown field full of obstacles at a relatively high speed (50 cm/s) [10,13]. During the last 10 years, we have further used EMDs for the visual guidance of other miniature (mass <1 kg) terrestrial [14] and aerial [15–19] robots called SCANIA, FANIA, OSCAR, OCTAVE and LORA, respectively.

In the latter robots, the EMD principle inspired by the fly's EMDs was initially implemented using conventional analog technologies such as SMD and FPAA. Later on, we turned to digital technology, using a Micro-Controller (μC) [20]. The μC deals with just two photoreceptor inputs and carries out a single task.

Onboard the MAV, visual sensors have to be installed in various parts of the Field of View (FOV), and each of them requires a given number of EMDs. Arrays of adjacent EMDs can be needed in some parts to increase the MAV's guidance accuracy [10] (Fig. 1).

However, neither FPAA nor μC devices provide sufficient resources for carrying out the signal processing tasks which arise when dealing with a whole array or mosaic of EMDs. One solution consists in using Very-Large-Scale-

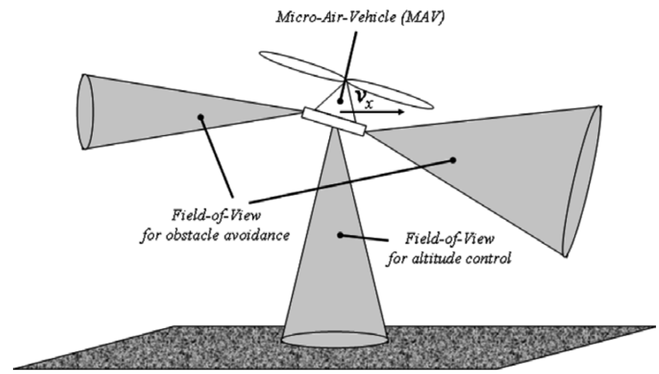

Fig. 1. Several visual sensors covering various Fields of View for the guidance of a Micro-Air-Vehicle.

Integrated (VLSI) circuits. Several electronic EMDs, such as those based on the Reichardt correlation sensor [21,22] or Franceschini et al.'s velocity sensor [23] or Barrow's design [24] were recently developed in the form of smart VLSI circuits, which included an integrated photoreceptor array forming their front-end. In this design, however, the size, number and physical characteristics of the photoreceptors are fixed once and for all, which means that it may be necessary to obtain a dedicated chip for each specific application or each specific (indoor or outdoor) environment. In addition to this lack of flexibility, another disadvantage of VLSI circuits is the relatively long design process involved: the chips are costly and they cannot be obtained quickly because the silicon brokers' deadlines tend to be rather long. A more flexible solution consists of using a single, off-the-shelf Integrated Circuit (IC) to process the signals from several photoreceptors, which may or may not all have the same physical properties and the same size. We decided to use the Field Programmable Gate Array (FPGA) technology in this 'hybrid' approach [25]. The remarkable characteristics of current FPGAs, such as large number of gates, the use of several simultaneous clock frequencies, the presence of embedded RAM blocks, embedded multipliers, and embedded Intellectual Property functions, and their small size and light weight, make it possible to design a flexible multi-EMD system and mount it onboard a MAV with a very low avionic payload [26].

In the next section, we present the bio-inspired visual system and the principles underlying EMD operation. The photodiode configuration and its use with a linear array are explained. Section 3 presents the specific top-down method used for FPGA integration of the EMDs using the Matlab (*The Mathworks software*) and ISE (*Xilinx software*) programs. In Section 4, details of the design specifications (sampling frequency limits, digital techniques, architecture) are explained. Lastly, in Section 5, we describe the hardware implementation and present the experimental results obtained on a real test bed on which various contrasting patterns were made to cross the visual field of an EMD array at various speeds.