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BIO-INSPIRED OPTICAL FLOW CIRCUITS FOR THE VISUAL GUIDANCE OF MICRO-AIR VEHICLES

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ABSTRACT

In the framework of our research on biologically inspired microrobotics, we have developed a visually based autopilot for Micro Air Vehicles (MAV), which we have called OCTAVE (Optical altitude Control sysTem for Autonomous VEhicles). Here, we show the feasibility of a joint altitude and speed control system based on a low complexity optronic velocity sensor that estimates the optic flow in the downward direction. This velocity sensor draws on electrophysiological findings on the fly Elementary Motion Detectors (EMDs) obtained at our laboratory. We built an elementary, 100-gram tethered helicopter system that carries out terrain following above a randomly textured ground. The overall processing system is light enough to be mounted on-board MAVs with an avionic payload of only some grams.

1. INTRODUCTION

The biorobotic approach we have been using at our laboratory since 1985 was adopted here to develop a visually based autopilot for controlling the altitude of a micro flying vehicle. In short, our approach leads to simulating and reconstructing biologically inspired visuomotor control loops to test their robustness and apply them to smart machines [1-7].

Present-day research on autonomous airborne vehicles has come up against a serious problem, with which aircraft designers have always been faced from the very start: how to see and avoid obstacles. The ground-observation missions on which artificial “drones” are sent require the ability to cope with changing patterns of ground relief. In the most sophisticated Unmanned Air Vehicles (UAV) and Micro Air Vehicles (MAV) or micro-drones, the eyes and brain of the human pilot are to be replaced by an on-board processing system capable of steering the aircraft through even the most cluttered environments. We consider that winged insects are particularly highly evolved autonomous flying machines that can serve as useful models for designing the micro-robots of the future. Visual stabilization and guidance in insects seem to make use of the speed at which the contrasting features they see slide across their retina (this has been called the retinal slip speed or the *optic flow*) [8]. Kennedy hypothesized that insects are able to regulate their altitude, on the basis of the retinal slip speed [9]. This part of the “optomotor theory” of insect flight dates back to 50 years ago, before the discovery of motion detecting neurons in any animal visual system. Today, we know that neurons called Elementary Motion Detectors (EMDs) play an essential part in processing the optic flow in the insect eye [10].

In 1986, Franceschini et al. built an optronic velocity sensor [11], the principle of which was based on the findings they had recently made on fly EMDs by performing electrophysiological recordings on single neurons while concomitantly applying optical microstimuli to single photoreceptor cells [12]. As early as 1989, a battery of 110 velocity sensors of this kind was used to enable a small autonomous mobile robot to steer its way through an unknown field full of obstacles at a relatively high speed (50 cm/s), based on optic flow measurements [1-2]. Later on, several electronic EMDs based on sensors such as the Reichardt correlation sensor [13] or Franceschini et al’s 1986 velocity sensor [14] were developed to serve as smart VLSI circuits.

In 1994, an account of our laboratory’s first optic flow based altitude control simulation studies was published [3]. Netter and Franceschini's tethered 850-gram mini-helicopter was subsequently developed: this was an elementary device capable of avoiding obstacles placed on the floor, thanks to the 19 stand-alone analog EMD circuits of the kind developed in 1989, which were connected to the 20 photoreceptors composing the robot's eye [5-6]. In 2001, Ichikawa et al. attempted to achieve hover flight on a miniature helicopter equipped with an on-board motion detection system implemented on an FPGA. Robust hover flight was only achieved, however, by mounting a camera on the floor, which computed the helicopter’s motion and retransmitted command signals back to the aircraft [15]. A few other recent studies have focused on how the ability of insects and birds to navigate using visual cues can be applied to giving aerial vehicles some degree of autonomy [16-19].

In addition to the many VLSI developments which have been going on during the past 15 years, conventional electronic technology can still be used to develop complete sensory-motor control systems comfortably in the shortest possible time. In section 2, we describe an altitude control principle inspired by insects, which we have named OCTAVE, standing for “Optical altitude Control sysTem for Autonomous VEhicles”. In section 3, we investigate how to design more compact and less energy-consuming EMD circuits to meet the stringent payload and energy requirements arising onboard such small craft. In section 4, we present the test-rig and microrobot that we designed. Lastly, we give some results on terrain following in section 5.

2. *OCTAVE* : AN ALTITUDE CONTROL SYSTEM INSPIRED BY INSECTS

Let us take a micro-aircraft flying in pure translation over an unknown terrain. As viewed from the aircraft, the angular slip speed $\mathbf{\Omega}$ – the optic flow – is given by :

$$\Omega = \frac{v}{D} \sin\varphi \qquad (1)$$

where v is the ground speed of the aircraft, D its distance to the ground point and φ the angle between the gaze direction under consideration and the heading direction. When the gaze is oriented vertically downwards (φ = 90°), D becomes the local altitude h, Ω is maximized but still depends jointly on the altitude and ground speed.

In the OCTAVE visuo-motor control loop [7], any variations in the optic flow measured downward are taken to be caused by variations in the height h above the ground. The system we developed drives the lift force and aims at maintaining the micro-flyer at a height h above the ground such that the optic flow Ω is servoed to a reference value at any time.

3. NEW ELEMENTARY MOTION DETECTOR CIRCUIT DESIGNS

An EMD is needed to assess the relative angular velocity Ω of contrasting features in the environment. The amplitude of the output signal V_{EMD} will decrease with Δt (the time taken by a contrast edge to cross both optical axes, see Figure 1a) and hence grow larger with Ω. Our first approach in developing a new EMD circuit consisted in using *a Field Programmable Analog Array* (FPAA by Anadigm) (Figure 1a-b) to implement most of the processing steps [11]:

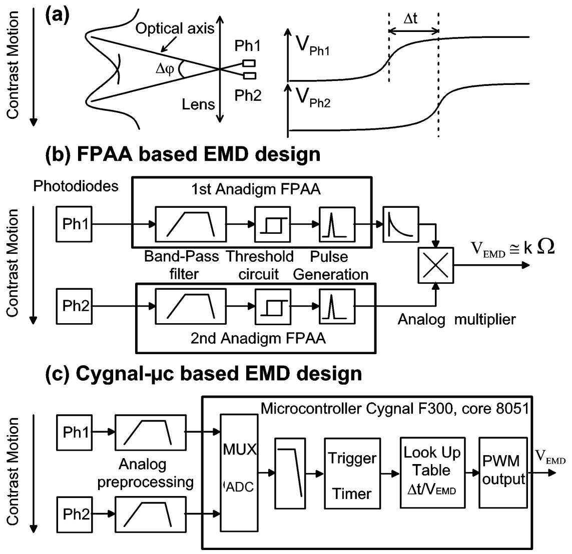

Figure 1. (a) A defocused lens mounted in front of the photodiodes determines the angle $\Delta\varphi$ between neighboring optical axes and confers on the photoreceptors a Gaussian angular sensitivity. **(b)** The FPAA-based EMD design was based on the original analog functional scheme. Every FPAA is driven by a single photoreceptor channel. **(c)** The Cygnal-μC based EMD design was adapted to make the best possible use of the microcontroller peripherals: analog pre-processing performed signal conditioning prior to digitization.

1. Low-pass spatial filtering (achieved by defocusing the lens : blurring) [5].
2. Band-pass temporal filtering on each channel to prevent DC bias and to reduce noise (e.g. 100Hz from neon lighting).
3. Thresholding and pulse generation on each channel for contrast detection.
4. Generating a long-lived decaying signal on one channel.
5. Generating a very short, unitary sampling pulse on the other channel.
6. Diode based processing to approximate Ω.

Given the on-board constraints of a MAV, the FPAA based EMD circuit turned out to be too energy-consuming and too bulky (Table 1).

Original analog SMD EMD circuit	*FPAA based EMD circuit*	***Cygnal-μC based EMD circuit***
1250mm²	2000mm²	**540mm²**
100mW	750mW	**40mW**
6 grams	4 grams	**0.8 grams**

Table 1. Comparisons between the implemented circuits show that the FPAA cannot compete with the microcontroller in our application. With 0.8g and 40mW, the μC-based EMD circuit specifications outperform the two other designs.

We therefore moved to digital technology, using a tiny 3×3mm μC (the Cygnal 8051 F300) which weighs only 0.1g. We adapted the original analog EMD scheme to this μC digital architecture (Figure 1c). The resulting μC-based EMD design is a major improvement over the analog EMDs, particularly as regards its mass and its consumption. It enables us to perform elementary optic flow processing with a small device weighing only 0.8g and consuming only 40mW (Figure 2).

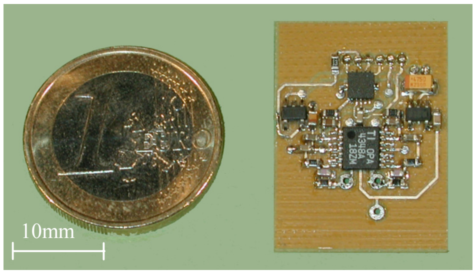

Figure 2. The μC-based EMD circuit is implemented on a 400μm-thickness PCB (size : 20×27mm, mass : 0.8g).

4. APPLICATION TO AN AERIAL ROBOT

A pantographic whirling arm [5] covering a mean distance of 12 meters at each rotation has made it possible for the tethered MAV to lift itself and move on both the vertical and horizontal planes (Figure 3). The 100-gram rotorcraft is mounted on the horizontal axis of a position servo system located at the end of the whirling arm, which makes it possible for the experimenter to set the robot's pitch angle, on which the horizontal speed v depends. The robot was therefore deliberately allowed only a few degrees of freedom so that the experimenter could carry out basic visuo-motor tests reliably and reproducibly, while recording several parameters. The width of the bands (which ranged between 1 cm and 30 cm) and their low effective contrast (which ranged between 4% and 30%) were chosen at random in order to test the robustness of the processing to the characteristics of the contrasting features encountered in the environment.

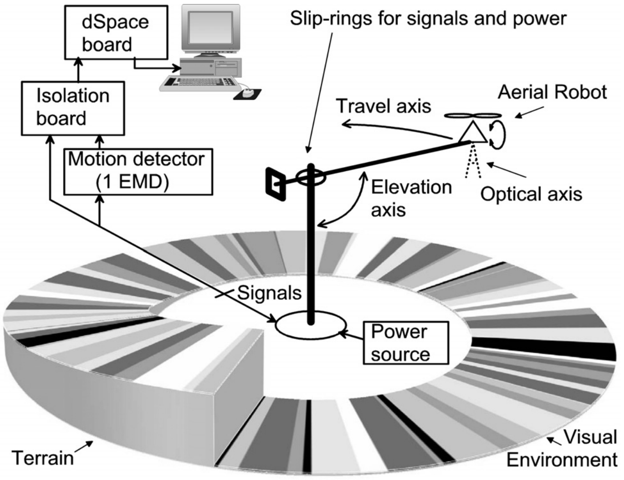

Figure 3. The test-rig is composed of a pantographic whirling arm supporting a MAV which flies over a 4.5-meter outside diameter arena. The textured environment below consists of randomly distributed, variously contrasting sectors.

A computer equipped with a dSpace DSP board with analog I/O connected to a Matlab/Simulink software environment elaborated the rotor speed and the pitch angle of the MAV while monitoring various parameters such as the speed of travel, the altitude, the pitch angle, the rotor speed and the EMD output. All these signals were transmitted to or from the computer via a miniature low friction slip-ring assembly.

The elementary robot consists of a motor driving a single fixed pitch propeller via a reducer. The motor is controlled by Pulse Width Modulation (PWM); its speed is measured by an on-board optronic sensor and servoed to the reference value dictated by the visuo-motor control system.

The robot's eye consists of a lens (diameter 5 mm) and a pair of silicon PIN photodiodes driving a single EMD. The interreceptor angle $\Delta\varphi$ is equal to 4° – a value close to that found between adjacent facets in the fruitfly eye. When the robot is pitched forward, its eye automatically counterrotates so as to keep aiming downwards (Figure 4a). Eye counterrotation is achieved by an onboard 2.5 gram microservo (Figure 4b).

The EMD picks out the longitudinal component of the optic flow. At this stage, we used the biomimetic FPAA-based EMD circuit described in section 3, placed off-board, to assess $\boldsymbol{\Omega}$.

5. TERRAIN–FOLLOWING WITH THE *OCTAVE* SYSTEM

To test the automatic terrain-following performances of the robot based on the use of the optic flow, we placed one third of the randomly textured disc (corresponding to a 4-meter portion) on a sloping plane (the "circular ramp": Figure 3). Figure 4 shows that the OCTAVE visuo-motor control loop controls the speed of the rotor so as to cause the altitude of the robot to vary automatically according to the change in relief of the land (Figure 4c). This automatic altitude control device is robust and efficient within a wide range of forward speeds (1 to 3 m/s in figure 4d), and does

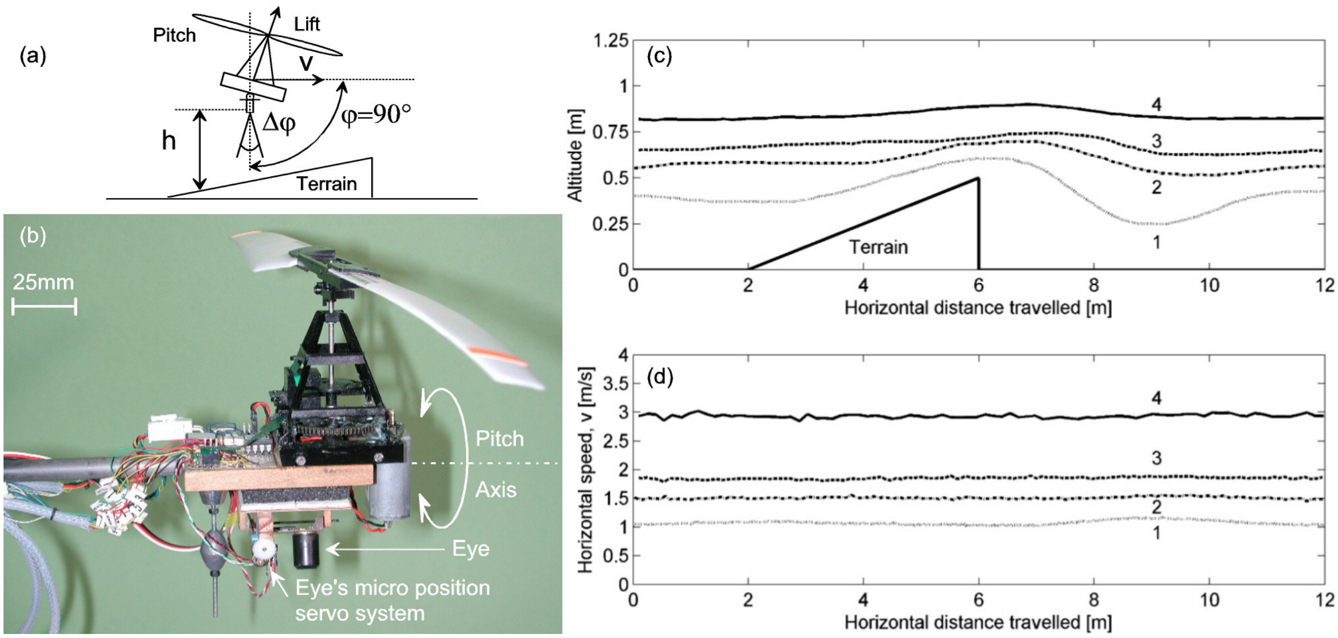

Figure 4. **(a)** The gaze direction of the MAV is kept vertical whatever the pitch angle **(b)** The 100-gram MAV is equipped with a fixed-pitch rotor and an electronic board. **(c)** The OCTAVE system makes the robot follow the terrain smoothly whatever the ground speed. The resulting trajectory depends on the horizontal speed of the aircraft: the faster it is travelling, the greater its altitude will be. **(d)** The horizontal speed can be seen to have remained fairly constant in each of the four cases studied.

not need to be trimmed to a particular speed.

The higher the speed at which the helicopter is flying, the higher its altitude will be. On the other hand, the avoidance which occurs when the robot is rising above the upward ramp (figure 4c) is less pronounced at high flying speeds (curve n°4 $\approx$ 3 m/s) than at low speeds (curve n°1 $\approx$ 1 m/s). A "safe altitude" is thus automatically generated, which increases very suitably with the flying speed. The robot is able to follow the terrain despite changes in the relief. It does so reliably without crashing and without any information about the actual values of the altitude and speed being ever available on-board.

6. CONCLUSION

In this paper, we have presented a quantitative study showing how a tethered micro-air vehicle is able to control its altitude visually so as to keep clear from the ground, despite moderate changes in the relief. A simplified eye equipped with an optic flow detector allows a "safe altitude" to be generated, which suitably increases with speed. One and the same visuomotor control loop copes with various ground speeds of the aircraft.

Even with an optronic equipment reduced to its simplest form of expression – in this case, only two photoreceptors and one EMD capturing the optic flow downward – the micro-air vehicle is able, as we have seen, to perform some terrain-following tasks robustly and reliably. The complete visuo-motor control loop requires few resources. A next step will be to mount the 0.8 gram EMD onboard and to close the loop locally. The low processing requirements result in major savings in terms of weight, bulk, energy consumption and cost. All these parameters are crucial factors in designing the MAVs of the future, the avionic payload of which will be expressed in grams rather than kilograms.

Our biomimetic approach to designing visually guided UAVs differs from other approaches in that it does not rely from the outset on a large scale image processing system. The visual guidance system used here adapts to new environments and need not rely on a previously established and stored map of the ground covered, as long range visually guided navigation systems do [20]. Future versions of the OCTAVE system could therefore be suitable for use on micro-aircraft, spacecraft and benthic submarines designed to travel safely through uncertain environments.

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