

TOWARDS AUTOMATIC VISUAL GUIDANCE OF AEROSPACE VEHICLES: FROM INSECTS TO ROBOTS

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ABSTRACT

Equipped with a less-than-one-milligram brain, insects fly autonomously in complex environments without resorting to any Radars, Ladars, Sonars or GPS. The knowledge gained during the last decades on insects' sensory-motor abilities and the neuronal substrates involved has provided us with a rich source of inspiration for designing tomorrow's self-guided vehicles and micro-vehicles, which are to cope with unforeseen events on the ground, in the air, under water or in space. Insects have been in the business of sensory-motor integration for more than 100 millions years. They can teach us useful tricks for designing agile autonomous vehicles at various scales. Constructing a "biorobot" first requires exactly formulating the signal processing principles at work in the animal. It gives us, in return, a unique opportunity of checking the soundness and robustness of those principles by bringing them face to face with the real physical world. Here we describe some of the visually-guided terrestrial and aerial robots we have developed on the basis of our biological findings. All these robots react to the *optic flow* (i.e., the angular speed of the retinal image). Optic flow is sensed onboard the robots by miniature vision sensors called Elementary Motion Detectors (EMDs). The principle of these electro-optical velocity sensors was derived from optical/electrophysiological studies where we recorded the responses of single neurons to optical stimulation of single photoreceptor cells in a model visual system: the fly's compound eye. Optic flow based sensors rely solely on contrast provided by reflected (or scattered) sunlight from any kind of celestial bodies in a given spectral range. These passive sensors and systems offer potential applications to manned or unmanned spacecraft, from robotic landers and rovers to asteroid explorers and satellite docking, with interesting prospects in weight-reduction and low consumption.

Keywords: Vision, flies, retina, photoreceptors, optic flow, motion detection, visuo-motor control systems, biorobotics, bionics, biomimetics

Abbreviations: EMD = Elementary Motion Detector, OF = Optic Flow

INTRODUCTION

Animals and humans are natural « vehicles » [13], able to move about autonomously in complex environments. Insects, in particular, provide evidence that physical solutions to elusive problems such as those involved in robots' visually-guided locomotion existed millions of years before roboticists started tackling these problems in the 20th century. Over the past two decades, some research scientists have been attempting to tap insect biology for ideas as to how to design smart visually-guided vehicles [e.g., 13, 65, 112, 92, 90, 43, 25, 44, 7, 125, 20, 91, 96, 97, 98, 33, 130, 99, 2, 95, 88, 103, 68, 89, 16, 141, 19, 57, 71, 69, 106, 150, 4, 104, 120, 105, 151, 119, 54, 156, 122, 73, 128]. Insects have quite a wide behavioral repertoire and can teach us how to cope with unpredictable environments using smart sensors and limited processing resources. Flying insects, in particular, often attain a level of agility that greatly outperforms that of both vertebrate animals and present day mobile robots. Insects' sensory-motor control systems are masterpieces of integrated optronics, neuronics and micromechatronics. Their neural circuits are highly complex - commensurate with the sophisticated behaviour they mediate - but unlike most (no less complex) vertebrate neural circuits, they can be investigated at the level of single, *uniquely identifiable neurons*, i.e., neurons that can be reliably identified in all the individuals of the species on the basis of their location in the ganglion, their exact shape and their consistent electrical responses [Review: 135, 66, 108, 18, 24]. This great advantage of insect versus vertebrate neuroscience enables insect neuroscientists to accumulate knowledge during anything from a few days to several decades about a given individual neuron or a well defined neural circuit. This explains why many of the robots that emulate part of a nervous system were inspired by arthropods and particularly insects [7, 16, 130, 89, 19, 150, 151, 4, 8, 54].

The biologically based robots that we have been constructing since 1985 have largely contributed to creating the field of *Biorobotics*, in which natural principles or systems are *abstracted* from an animal and implemented in the form of a hardware physical model. After an introduction to the fly visual system (Section 1), we will be briefly described some of the insect based robots we conceived and constructed (Section 2 and 3). Beyond their possible usefulness as intelligent machines, these physical models make it possible to subject biological hypotheses to the rigorous tests imposed by the real world [148, 149, 47]. Section 4 will deal with some of the “biological returns” that came out from this biorobotic approach. Section 5 will deal with possible applications of these findings to aerospace.

1. FLY VISUAL MICROCIRCUITS

Flies are agile seeing creatures that navigate swiftly through the most unpredictable environments, avoiding all obstacles with little conventional aerospace avionics. Equipped with “only” about one million neurons and “only” 3000 pixels in each eye, the housefly, for example, achieves e.g., 3D navigation and obstacle avoidance at an impressive 700 body-lengths per second. All this is achieved, surprisingly, without any connections of the animal to a super-computer and an external power supply. The impressive lightness of the processing system at work onboard a fly or a bee makes any roboticist turn pale once he/she realizes that these creatures achieve many of the behaviours that have been sought for in the field of autonomous robotics for the last 50 years : dynamic stabilization, 3D collision avoidance, tracking, docking, autonomous landing, etc.

The front end of the fly visual system consists of a mosaic of facet lenslets (Fig.1) and an underlying layer of photoreceptor cells forming the retina proper (Fig. 2). Insects' photoreceptor cells, once dark-adapted, are known to respond to single absorbed photons by a miniature potential ((« bump ») of a few millivolts amplitude. They are more sensitive and reliable than any photomultiplier ever built. Flies possess one of the most complex and best organized retinas in the animal kingdom. It has been described with unprecedented details, with its six different spectral types of photoreceptor cells, polarization sensitive cells, and

sexually dimorphic cells. The analysis has revealed a typical *division of labour* within each ommatidium :

- The two central photoreceptor cells, R7 and R8, display specific spectral sensitivities [96] and are therefore thought to mediate color vision [56, 31, 55]. The ommatidia are spectrally *heterogeneous* as regards R7 and R8, which can be mapped out accurately *in vivo* using the “corneal neutralization” technique [39, 42, 49] (see Fig. 2a). 70% of the R7 cells are of the « yellow » (y) type (they appear green in Fig. 2a) and 30% of them are of the « pale » (p) type (they appear dark in Fig.2a) [79, 42, 49]). To each pR7 and yR7 receptor corresponds a specific pR8 and yR8 tandem companion, both companions showing yet other spectral sensitivities [56]. This complex but analyzable pattern actually provided the first evidence that color vision in insects relies on *spectrally heterogeneous ommatidia* [rev. 31, 32, 55], a finding that was corroborated only recently for insects with fused rhabdoms, such as bees and butterflies [114, 15, 145]. Flies achieve specific receptor spectral sensitivities through the expression of different opsin genes in photoreceptors [109].

- The outer 6 receptor cells (R1-R6) contribute in particular to *motion detection* [77, 118, 17, 61]. Consistent with this function where contrast sensitivity is at a premium, the R1-R6 photoreceptors make for a high sensitivity (“scotopic”) system whose enhanced signal-to-noise ratio is due, in part to the specific neural wiring (the “*neural superposition principle*”, [12, 76, 78]) and also to their panchromatic, ultraviolet-enhanced spectral sensitivity [80]. As inputs to the motion detection pathway, R1-R6 receptors, as we will see, play a major role in insect visual guidance based on ‘*optic flow*’ (OF).

Flying insects avoid collisions with obstacles and guide themselves through their complex surroundings by processing the *optic flow* (OF) that is generated on their eyes as a consequence of self-motion. In the animal’s reference frame, the OF is the *angular speed* ω (expressed in rad/s) at which each contrasting object of the environment moves past the animal [51, 85, 81]. Fig. 7a illustrates the case for an insect flying in translation over a terrain. Current evidence shows that the insect’s nervous system is able to perform the complex task of extracting the information necessary for short range navigation from the optical flow field [21, 23, 53, 152, 146, 17, 87, 75 22, 127, 28] and to transmit this information to the thoracic wing muscles in a « fly-by-wire » mode. This ability results from the insect head being equipped with smart sensors called *motion detecting neurons*, which are able to gauge the *relative motion* between the animal and environmental features [Rev. 59,61, 94, 11].

The fly is one of the best animal models currently available for studies on motion perception [116, 52, 77, 17, 118, 32, 60, 46, 136, 82, 28]. A great deal has already been learned from neuroanatomical and neurophysiological studies on the 3rd optic ganglion, part of which (the *lobula plate*) appears as a genuine “visual motion processing center”. This region comprises approximately 60 *uniquely identifiable* neurons dedicated in particular to: (i) analysing the movement of the retinal image, i.e., the optic flow field that results from the animal’s walking or flying, and (ii) transmitting the result of this analysis via descending neurons to the thoracic interneurons that will ultimately drive the wing-, leg-, and head-muscles [135, 136, 59, 58, 60, 82, 11, 28]. The *lobula plate tangential cells* are large-field collator neurons that pool the input signals from many retinotopic “Elementary Motion Detectors” (EMDs) [59, 58]. Although the detailed neural circuitry underlying *directionally selective motion sensitivity* still remains elusive in all animals - vertebrates and invertebrates - two types of smallfield columnar neurons have been identified in flies, the transmedullary neuron Tm1 and the bushy *lobula* neuron T5, which seem to be major players for conveying smallfield motion information down to the large-field *lobula plate* neurons [27, 64].

Regardless of the detailed EMD neuronal circuitry, the problem we addressed in the 1980’s was the *functional principle* underlying an EMD. Taking advantage of the micro-optical techniques we had developed for analysing the fly retina at the single photoreceptor level [39, 40, 29, 30, 31], we were able to stimulate a single EMD in the eye of the living insect by applying optical stimuli to single *identified* photoreceptor cells on the retinal mosaic (Fig.3),

while recording from an *identified* motion sensitive neuron, called H1, in the *lobula plate* of the housefly [83, 25]. We applied pinpoint stimulation to two neighboring photoreceptors (diameter 1 μ m) of a single ommatidium by means of a special stimulation instrument (a hybrid between a microscope and a telescope, see Fig. 3, left), in which the main objective lens was the facet lens itself (diameter 25 μ m, focal length 50 μ m). This optical instrument [46] served (i) first to select a given facet lens (Fig. 3a), (ii) to select two of the seven receptors (namely R1 and R6) and illuminate them *successively* with 1 μ m-light spots. This *sequential microstimulation* produced an “apparent motion” simulating a real motion within the small visual field of an ommatidium. Although, in this type of experiment, only two out of the 48,000 photoreceptor cells of the visual system received light, the H1-neuron responded by a conspicuous *increase* in spike rate, as long as the phase relationship between the two stimuli mimicked a movement occurring in the *preferred* direction (see Fig. 3c). When the sequence mimicked a movement in the opposite, (“null”) direction, H1 showed a marked *decrease* in its resting discharge or did not respond at all [118, 32]. H1 did not respond either when the same sequence was presented to a pair of receptors (such as R1 and R2, or R1 and R3) aligned *vertically* in the eye (consistent with the fact that H1 is not sensitive to vertical motion [59, 60]), or when one of the two selected photoreceptors was the central cell R7 (confirming that this cell does not participate in motion detection [77, 118, 61]).

From many experiments of this kind, in which carefully planned sequences of light steps and/or pulses were applied to the two receptors, we established the EMD *block diagram* and characterized each block’s dynamics and nonlinearity [32, 46, 34]. The scheme we arrived at departs markedly from the popular Hassenstein-Reichardt *correlation* model that was derived 50 years ago from *behavioural* experiments carried out on walking or flying insects [115, 116, 17, 117]. While not unveiling the details of the EMD neural circuit, our analysis at the single cell level allowed the EMD principle to be understood, paving the way for its transcription into another, man-made technology.

It is on this basis that, in the mid 1980’s, we designed a miniature electronic EMD whose signal processing scheme approximated that of the biological EMD [41, 9]. Specifically, our scheme relies on measuring the time of travel of a contrasting feature between two neighboring pixels. This time of travel is further processed to give an output that grows as a monotonic function of the angular velocity, with little influence of the pattern contrast and spatial frequency. Our scheme is not a *correlator scheme* and rather corresponds to the class of *token-matching schemes*, as defined by S. Ullman’s [138]. It is therefore a true *angular velocity sensor* [41] that can serve as a worthy OF sensor (see Fig. 7b). Over the years, we miniaturized this EMD using a variety of technologies [41, 44, 124, 113, 3] and all the robots described below (Fig. 5) were equipped with either version of these fly-derived OF sensors. A very similar EMD principle has been proposed independently a decade later by C. Koch’s group at CALTECH, who spread it under the name “facilitate and sample” velocity sensor [72]. These authors patented a smart analog VLSI chip based on this principle - without any reference to a possible inspiration from the fly [126].

2. FLY-INSPIRED, VISUALLY-GUIDED TERRESTRIAL ROBOTS

In the mid 1980’s, we started designing a robot to demonstrate how an agent could possibly navigate in a complex environment on the basis of optic flow. The robot was equipped with a planar compound eye and a fly-inspired EMD array [112]. The latter was used to sense the OF generated by the robot’s own locomotion among stationary objects. The 50-cm-high “robot-mouche” (*robot Fly* in English) that we realized in 1991 (Fig. 5a) was the first OF-based, completely autonomous robot able to avoid contrasting obstacles encountered on its way, while traveling to its target at a relatively high speed (50cm/s) [10, 43, 44, 45].

The robot Fly was also based on ethological findings on real flies, whose most common flight trajectories were shown to consist of straight flight sequences interspersed with rapid turns termed *saccades* [21, 61, 147, 127, 137]. Straight flight sequences performed at speed V near

an obstacle located at distance \mathbf{D} and azimuth ϕ with respect to the heading direction generate in the robot's eye a *translational* optic flow ω expressed as follows [154] :

$$\omega = (\mathbf{V} \cdot \sin \phi) / \mathbf{D} \quad (\text{eq. 1})$$

This means that an animal (or a robot) able to measure ω could recover the distance \mathbf{D} to the obstacle, provided it would know its own speed \mathbf{V} . The robot Fly proceeds by performing a sequence of *purely translational steps* ΔL (length 10cm; duration 200ms) at a speed set at $\mathbf{V} = 50$ cm/s (via the wheel encoders). By the end of each step, the panoramic EMD-array has drawn up a map of the *local* obstacles, which is expressed in polar coordinates in the robot's reference frame. The next course to be steered is immediately given, generating an "eye + body saccade" in the new direction. Vision is inhibited during each saccade by a process akin to "saccadic suppression", a process that has also been documented in an insect [155]. The robot was tested wandering about autonomously in an arena in which obstacles (vertical poles) were arranged at random. Its jerky trajectory is very reminiscent of the flight trajectories recorded on real flies [147, 127, 137, 26]. The robot Fly is able to adapt to novel or changing environments without any need for maps or learning phases of any kind. The robot must move in order to be able to see. No "path planning" is required: the only thing that is "planned" is the direction of the next step, on the basis of what was sensed during the previous step and taking into account the direction of the target.

The robot Fly actually views the world through a horizontal ring of facets (Fig.4c). Any two neighboring facets drive an EMD, and a total of 114 EMDs analyze the (self-generated) optic flow in the azimuthal plane. One peculiarity of the robot is that its compound eye is endowed with a *resolution gradient* such that the interommatidial angle $\Delta\phi$ increases according to the sine law of eq.1 as a function of the eccentricity ϕ [112, 44]. Once embedded in the anatomical structure of the eye, this resolution gradient "compensates for" the sine law inherent to the translational OF (eq.1) and ensures that any contrasting feature will be detected if, during a robot's translation by ΔL , it enters the robot's "circle of vision", the radius \mathbf{R}_v of which increases linearly with ΔL :

$$\mathbf{R}_v = k \cdot \Delta L \quad (\text{eq 2})$$

A similar nonuniform sampling is a key feature of many natural visual systems, including the human and fly visual systems. Sampling the environment *nonuniformly* in this way makes it possible to design the underlying EMD array *uniformly*, each EMD having the same time constants as its neighbors [44].

The robot Fly operates on the basis of a brainlike, parallel and analog mode of signal processing. Fig. 6 shows the odd routing pattern that connects the thousands of analog devices that blend together the input signals from the compound eye and those arising from the dorsal, target-seeking eye, eventually delivering a single analog output: the steering angle.

Simulation studies have shown that a robot of this kind can automatically adjust its speed to the density of the obstacles present in the environment if, instead of imposing on the robot constant ΔL *translation steps* (as described above), one imposes constant Δt *translation times* [91]. During any one Δt , the robot will then cover a distance ΔL proportional to its current speed \mathbf{V} :

$$\Delta L = \mathbf{V} \cdot \Delta t \quad (\text{eq 3})$$

From eq. 2 and 3, one obtains:

$$\mathbf{R}_v = k' \cdot \mathbf{V} \quad (\text{eq 4})$$

Eq 4 means that the robot will now be able to detect (and therefore avoid) obstacles within a range R_v that increases proportionally to its current speed V . The simulated robot was shown, making a detour around a dense forest, automatically accelerating in a clearing and automatically braking before traversing another, less dense forest that it “cautiously” entered at a reduced speed [91].

3. INSECT-INSPIRED VISUALLY-GUIDED AERIAL ROBOTS

A similar motion detection principle can be used to guide a *flying* agent, have it follow a rough terrain and land [96, 103]. The latter paper [103] was something of a breakthrough as it showed for the first time *how* it is possible to follow a terrain and land *without knowledge of groundspeed and groundheight*, in much the same way as the honeybee seems to operate [132, 133]. Following simulation experiments, the principle was first validated on-board FANIA, a miniature tethered helicopter having a single, variable pitch rotor [103, 104, 105]. This 0.8-kg rotorcraft had only 3 degrees of freedom (forward and upward motion and pitch). Mounted at the tip of a light whirling arm, the robot lifted itself by increasing its rotor collective pitch. By remotely inclining the servo-vane located in the propeller wake, the operator caused the helicopter to pitch forward by a few degrees and thus gain speed (up to 6 m/s). FANIA was equipped with an accelerometer and a forward-ventral looking eye with a resolution of only 20 pixels and their corresponding 19 EMDs. FANIA avoided the terrain by increasing its collective pitch as a function of the fused signals transmitted from its eye. Tests in the circular arena showed FANIA jumping over contrasting obstacles [104, 105].

Upon formalizing the optic flow sensed by a flying creature (Fig.7), we recently came up with an OF based autopilot that we call the *optic flow regulator* (Fig. 8), which is little demanding in terms of neural implementation and could be just as appropriate for insects as it would be for aircraft [120-123, 47]. We built a miniature (100-gram) helicopter, called OCTAVE, and equipped it with this autopilot (Fig.5b). Tested in its circular arena, OCTAVE is able to perform challenging maneuvers such as terrain following at various speeds and smooth take-off and landing [121, 122, 47], as shown in Fig.9. OCTAVE was also shown to react sensibly to wind perturbations [121], in much the same way as insects do [14, 47]. In this autopilot (Fig.8) a ventral EMD [124] continuously measures the ventral OF (Fig. 7b) and compares it to an OF set-point ω_{set} . The error signal ϵ essentially controls the robot’s lift L (for details see [47]) and hence its height h via the surge dynamics, so as to maintain the perceived OF at a constant set-point ω_{set} (hence the name: *OF regulator*). This occurs whatever the robot’s current groundspeed V_x , whatever disturbances (such as wind) affect that speed, and whatever disturbances (such as a gently sloping terrain) affect the robot’s current groundheight h : the *optic flow regulator* will automatically generate a groundheight proportional to the groundspeed (see Fig.9a,b). Two noteworthy results were obtained in these studies [121, 122, 47]:

1/ risky manoeuvres such as automatic takeoff, ground avoidance, terrain following, suitable wind reactions and landing are all successfully performed as a result of one and the same feedback control loop: *the optic flow regulator*.

2/ these challenging manoeuvres are all performed *without explicit knowledge of absolute altitude, groundheight, groundspeed, airspeed, ascent (or descent) speed and windspeed*.

This bioinspired autopilot therefore differs strikingly from conventional man-designed autopilots, which need a large number of (bulky, heavy and costly) metric sensors (e.g., a radar-altimeter, a baro-altimeter, a Doppler radar, a laser range finder, a GPS receiver, a Pitot tube, a variometer, etc.) to achieve aircraft altitude hold or speed hold. OCTAVE autopilot’s objective is actually not to provide for altitude hold or speed hold. Its primary objective is to adapt the groundheight to the groundspeed at all times so that the robot does not crash. It does so at any groundspeeds, raising the robot in proportion to its current groundspeed - whatever internal or external factors affect the latter - without ever *measuring* groundspeed at all [50].

Along the same line, we recently showed that a holonomous and fully actuated air-vehicle can achieve both *lateral obstacle avoidance* and *cruise control* in a corridor, by means of a *dual OF regulator* [128]. Our OF-based autopilot, called LORA III, was shown (in simulation) to automatically adjust both the robot's groundspeed and its clearance from the walls without any needs for *measuring* groundspeed and distance. In other words, the robot achieves this behaviour although it is completely 'unaware' of its own groundspeed, unaware of its clearance from the walls, and unaware of the actual corridor width. The LORA III robot navigates at sight on the sole basis of two parameters, which are the set-points of the two intertwined *OF regulators*: a sideways OF set-point and a forward OF set-point. These two parameters were shown to fully constrain the vehicle's behaviour in a straight or tapered corridor, and to impose either wall-following or centering in the corridor [128].

By performing electrophysiological recordings on *flying* flies with soft microelectrodes, we discovered that the muscle attached to the base of the retina [62] is responsible for a *retinal microscanning process*. The whole retinal mosaic (Fig.2a) is set into translation by a few micrometers repetitively (at about 5 Hz) underneath the facet mosaic, causing the visual axes to rotate by a few degrees [38]. This finding initiated two major biorobotic projects at our laboratory, which aimed to decipher the advantages of this enigmatic process. In contrast with the robots described above, the two novel robots we built, SCANIA and OSCAR, owe their visual performances to exploiting a purely *rotational* optic flow. Both projects are based on the hypothesis that the microscanning process in flies operates in connection with motion detection.

SCANIA is a 0.7-kg wheeled Cyclopean robot that is able to move about under its own visual control, avoiding the contrasting walls of a square arena despite the low resolution of its eye (only 24 pixels) [97, 98]. This ability is the result of a symmetrical anterograde retinal microscanning process, which assists the robot in *detecting* obstacles located close to the heading direction (i.e., near the frontal "pole" of the optic flow field, defined as $\phi = 0$ in eq.1). The periodic microscanning amounts to periodically adding a given amount of *rotational* optic flow ω_r to the very small *translational* optic flow ω_t generated by frontal obstacles (for which ϕ is small in eq.1). Since the amount of added OF (ω_r) is known onboard, the robot is able to subtract it out subsequently from the overall OF measured, thus recovering the purely *translational* OF (ω_t), i.e., the one OF component that depends on the distance to obstacles (eq.1). Here, the advantage of microscanning is to improve the *detection* of small translational OF that would otherwise have remained subliminal. A similar principle has been taken up again to drive a smaller robot along a contrasting wall and a miniature fly-like retinal microscanner has been built as a MOEMS (micro-opto-electro-mechanical system) sensor [100, 99, 67].

The second project that we developed on the basis of the fly's retinal microscanner ended up with a novel optronic sensor, called OSCAR [140], and a novel aerial robot, the robot OSCAR [141, 142, 123] that was equipped with this sensor. The robot OSCAR is attached to a thin, 2-meter long wire secured to the ceiling of the laboratory. It is free to adjust its yaw by driving its two propellers differentially (Fig. 5c). This miniature (100-gram) robot is able to visually fixate a nearby "target" (a dark edge or a bar) thanks to its microscanning process. It is also able to track the target at angular speeds of up to 30°/s – a value similar to the maximum tracking speed of the human eye. Target fixation and tracking occur regardless of the distance (up to 2.5 m) and contrast (down to 10%) of the target, and in spite of major disturbances such as pendulum oscillations, ground effects, (gentle) taps and wind gusts. The OSCAR sensor was shown to be able to locate an edge with a resolution of 0.1 degrees, which is 40 times finer than the interreceptor angle $\Delta\phi$ [142]: it has acquired *hyperacuity*, a property that makes the principle appealing for accurate stabilization of various platforms [48], as well as for nonemissive power line detectors on-board fullscale helicopters [144]. Inspired by the fly's thoracic halteres that have long been known to act as gyroscopes, we equipped the

OSCAR robot with an additional *rate control loop* based on a MEMS rate gyro. The interplay of the two (visual and inertial) control loops enhances both the stability and the dynamic performances of the yaw fixation and pursuit system [141, 142]. More recently we introduced a mechanical *decoupling* between the eye and the body and implemented a *vestibulo-ocular reflex* that was key to maintaining the robot's gaze perfectly fixed on the target [143]. In the latest development, the gaze of the aerial robot OSCAR II remains virtually locked onto the target in spite of drastic thumps that we deliberately applied to the robot's body by means of a "slapping machine" [73].

4. BIOLOGICAL RETURNS

When a robot mimics specific types of behavior, specific neurons or neural architectures it is likely to provide neuroethologists [148] and neurophysiologists [149] with useful feedback information. The following are some examples of the biological "returns" that our biorobotic approach has yielded:

1/ Monitoring the "optic flow" does not necessarily imply calculating the *distance* to obstacles. While our early terrestrial robots, the robot Fly (Fig.5a) and SCANIA, accessed the distance D to the obstacles according to eq.1 (i.e., by knowing θ and V and measuring ω with their EMDs) the flying robots FANIA and OCTAVE go one step further by being able to fly around at relatively high groundspeeds *without any knowledge of the actual distance to the terrain*, in much the same way as honeybees seem to operate [132, 133]. OCTAVE visuomotor control loop acts upon the lift so as to maintain a reference OF at all times, whatever the current groundspeed. The *OF regulator* allows the robot to take-off, avoid ground collisions, follow terrain, react suitably to headwinds and downwinds and land safely, *without any knowledge of local height over terrain, absolute altitude, groundspeed, airspeed, descent speed and windspeed* [120-122]. In a recent paper [47] we showed that our *OF regulator* scheme accounts for many hitherto unexplained findings published during the last 70 years on insects' visually guided performances; for example, it accounts for the observations that honeybees descend in a headwind [14], land with a constant slope [132, 133], and drown when travelling over mirror-smooth water [63].

2/ The small Cyclopean robot SCANIA described in Section 3, which uses a retinal microscanner emulating the one we recently discovered in the fly compound eye, is able to recover the negligibly small *translational* OF associated with objects oriented close to the vehicle's heading direction. With hindsight, this suggests that the fly may also use its retinal scanner for the same task, eliminating the problem caused by the *frontal pole* of the optic flow field and that caused by the relatively coarse spatial sampling of the eye ($\Delta\phi \approx 1$ to 2°).

3/ The aerial robot OSCAR, which is also based on the fly's microscanner, emits behaviors which are reminiscent of both the hoverfly's ability to clamp its rotational velocity at zero while hovering near a tree, in wait for passing mates or intruders [21], and the male housefly's ability to track the female smoothly during sexual pursuit [153]. We therefore propose that these observed fly behaviors may *result*, at least in part, from the very presence of the microscanner in the compound eye, which is known to come into play only during locomotion, leaving the retina perfectly stationary at rest [38].

Some people tend to feel that computer simulations are all we need [107], and that taking the trouble to *construct* a physical robot is a disproportionately difficult means of checking the soundness of ideas gleaned from nature. There is everything to be gained, however, from completing computer simulations with real physical simulations, for the following reasons:

- Some theories and simulations that look fine on paper (or on the computer screen) may no longer stand under real-world conditions, or may lack robustness to such an extent that they would be useless on-board an animal or a robot.
- Building a robot allows a supposedly understood biological principle to be properly tested in realistically noisy, unstructured and harsh environments.
- At a given level of complexity, it can actually be easier and cheaper to use a real robot in a real environment than to attempt to simulate both the robot and the vagaries of an environment
- Working with a real robot, with its dynamics, nonlinearities, noisy circuits and other imperfections can help one to decipher the clever tricks evolution has come up with, which can be fathoms apart from what the 21st century scholars were expecting [see also: 111, 101].

5. POTENTIAL APPLICATIONS TO MANNED AND UNMANNED AIR- AND SPACECRAFT

Our insect-inspired robots are minimalistic demonstrators that simply illustrate the fact that biology-derived principles naturally tested for millions of years can be implemented on vehicles at various scales. Further developments along this line may lead to alternatives to the sensors that are in use onboard various terrestrial, aerial or space vehicles.

OF-sensing fits a more general framework called “active perception” [5] where the *ad hoc* movement of a sensor reduces the processing burden involved in perceptual tasks [6,1]. Here, it is a *motion sensor* that moves, either as a result of locomotion (in the robot Fly, FANIA, OCTAVE and LORA III) or as a result of retinal microscanning (in the robots SCANIA and OSCAR).

An OF sensor is a small and lightweight piece of hardware that may be suitable for space applications. It has the advantage to be sensitive to *relative motion*. This could be, for example, the relative motion between a spacecraft and a landing site or between a satellite and its mothership.

An OF sensor is a *passive (nonemissive)* sensor that relies on *photons* and *contrast*. It is therefore no good at night or under poor visibility conditions (fog, dust, rain, snow) and would not compete with *active* sensors such as Flir, Laser or Millimeter Wave Radars. But photons and contrast are available in many terrestrial and extraterrestrial worlds such as the Moon, Mars, other planets, asteroids and comets. Should contrast deteriorate in the visible range for whatever reason (e.g., a brownout presented by a dust storm), it may reappear in other portions of the electromagnetic spectrum, between UV and terahertz, so that OF would still be measurable. After all, a suitable shift in spectral sensitivity into the near UV made honeybees able to detect contrast within flowers where no contrast is seen by the human eye. Bees also teach us that it is not advised to work at night in hostile environments, a lesson that may apply to future aerial Martian rovers as well.

Our visually guided robots all make use of self-generated optic flow to carry out humble tasks such as detecting, locating, avoiding or tracking environmental features. Two principles OCTAVE and LORA III may pave the way for automatic piloting without any needs for measuring groundspeed, distance or altitude, thereby eliminating the need for some cumbersome and heavy aerospace sensors. In addition, both OCTAVE and OSCAR autopilots put little constraints on the OF sensor’s *range*, owing to the inherent feedback loop of the *OF regulator*, which strives to maintain the OF around a given set-point: only *deviations* from the set-point need to be detected.

In the aerospace context, we anticipate that the bio-inspired OF sensors and visual guidance principles at work in the various robots presented would display the following assets and liabilities:

Potentials and limitations of OCTAVE and LORA III principles :

Both OCTAVE and LORA III could serve to provide better situation awareness for navigation-guidance and control of manned or unmanned vehicles. The OCTAVE autopilot shed light on the fact that insects may be *permanently unaware of their vertical position* and yet rarely crash. The OF sensor senses the *ratio* of vertical position to groundspeed and the *OF regulator* makes the altitude proportional to the groundspeed at all times, without the need to *measure* vertical position and groundspeed. Craft's behavior and survival are at a premium, knowledge of speed and distance is of secondary concern. The OCTAVE principle could be harnessed to guide a robotic rover on the surface of the Moon or Mars, or an aerial Martian rover flying low altitude terrain following exploratory missions. Critical, short-lived events like descent and landing of an aerial rover or a space probe could benefit from the OCTAVE principle, since it ensures automatic landing with final approach at constant slope [123, 47]. Flying rovers in Martian canyons and gullies could make use of the LORA III principle, whereby both the craft's groundspeed and its clearance from the walls are constrained by the canyon's width [128]. Each rover could be equipped with its own autonomous guidance system, without relying on any data links with a ground or orbital station. This is an advantage, considering the many potential anomalies of any data links, such as noise and "drop-outs", asynchronization of data transmissions, latency in communication, etc. Similar OF-based principles could probably be applied to safe vehicle spacing in swarms of spacecraft without a centralized control system.

Potentials and limitations of SCANIA and OSCAR's principles

A lesson from the OSCAR principle is that microscanning is an effective and computer-efficient way to improve image resolution and accuracy in localization. OSCAR provides *hyperacuity* at low cost and low weight, with potential applications to detect-sense-and-avoid systems, fine-guidance sensors and tracking systems, such as novel star trackers that reduce the need to carry other attitude sensors. OSCAR's range of vision will depend on resolution. The OSCAR principle could be applied to automatic craft stabilization with respect to another craft, thus helping autonomous proximity operations such as rendez-vous and docking maneuvers, e.g., of microsattellites with their mother orbiter. In particular, OSCAR could detect the vanishingly small relative angular velocities between two craft in their final approach. An OSCAR sensor array could be used in synergy with advanced Ladars and video guidance sensors for operations at close range from a spacecraft in refueling or other servicing missions. It could also provide nonemissive detection capability for wires and obstacles during day [144, 48]. During night and low visibility, it would need to fuse its data with those of Flir, Ladars or millimeter-wave Radars that are, however, much more power-hungry. As for the OSCAR II principle (involving mechanical decoupling between eye and body), it could serve, e.g., to reject visual perturbations caused by locomotion or wind in exploration rovers.

6. CONCLUSION

The biorobotic approach that we initiated in 1985 is a transdisciplinary approach which turns out to be most rewarding because it can kill two flies with one stone:

- It can be used to implement a basic principle abstracted from nature and check its soundness, robustness and scaling on a physically embodied machine in a real physical environment. This « reconstruction approach » opens the way to novel devices and machines, particularly in the field of cheap sensory-motor control systems for autonomous vehicles and micro-vehicles, which can thus benefit from the million-century long experience of biological evolution.

- It yields valuable feedback information in the fields of neuroethology and neurophysiology, as it urges us to look at sensorimotor systems from a new angle, raises new biological questions and suggests new experiments to be carried out on insects for iteratively improving our understanding.

Modern space technology, though extremely advanced, might benefit from taking a glance at the way ace pilots such as insects cope with most complex environments. Flying insects are not only the oldest fly-by-wire aircraft, they are able to do much with little : few neurons in the brain, few pixels in the eyes. The diminutive insects no doubt can give us lessons in sensory-motor integration and implementation. We have discussed briefly how the *optic flow* based principles that we have discovered may be relevant to autonomous spacecraft behaviors such as obstacle detection, hazards avoidance, tracking, terrain following, landing, docking, etc. Some of these principles could be implemented onboard spacecraft of very small size such as picosatellites, with a view to reduce launch weight, size and power consumption.

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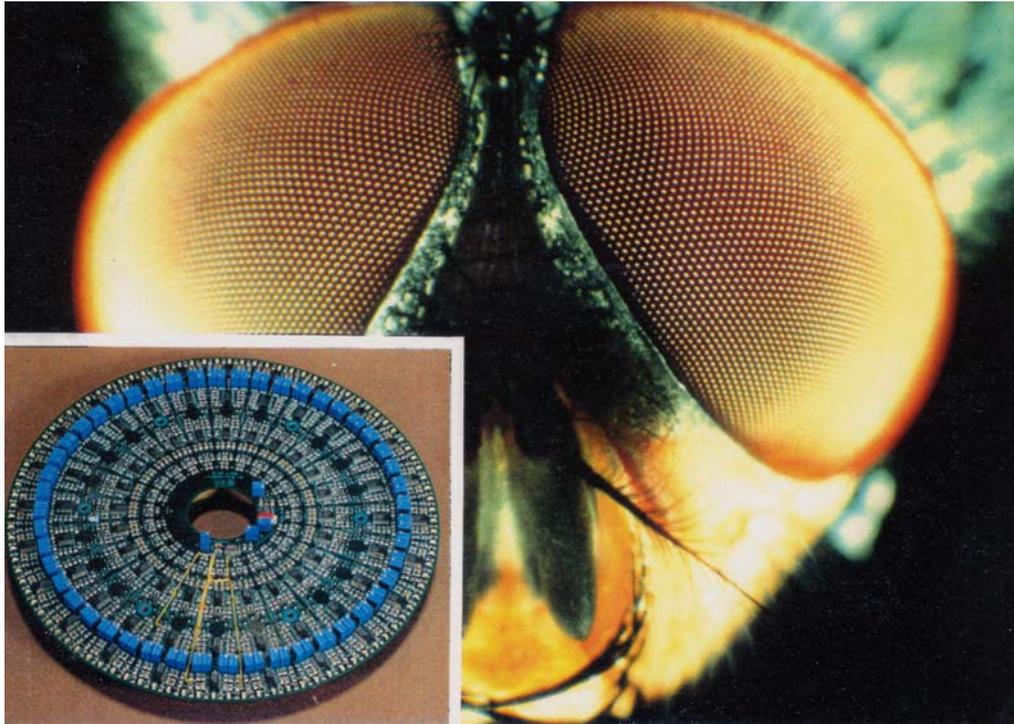


Fig.1: Head of the blowfly *Calliphora erythrocephala* (male) showing the two panoramic compound eyes with their faceted cornea. Each facet lens is the front-end of an *ommatidium* that contains a small group of photoreceptor cells (Fig.2). There are as many sampling directions (pixels) in each eye as there are facets. This photograph was taken with a laboratory made Lieberkühn microscope based on two parabolic mirrors extracted from bicycle lights. Inset: photograph of the retinotopic circuit used by the robot Fly (Fig. 5a) to guide itself at a high speed towards a target while avoiding obstacles on its way. The routing of this circuit is shown in Fig. 6 [from 37].

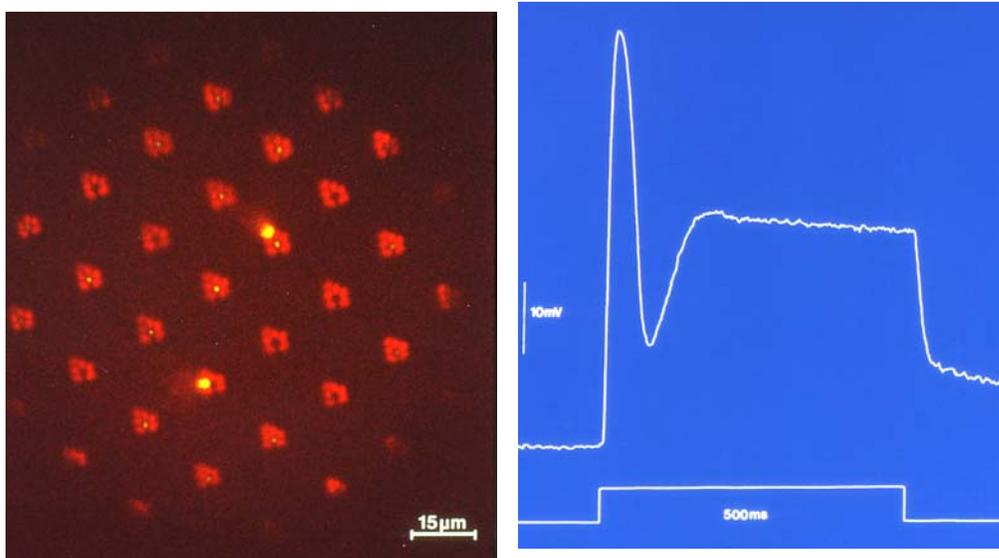


Fig.2: (a) Photoreceptor cells of the housefly retina observed *in vivo* using the “corneal neutralization” technique [39, 29, 30] combined with epi-fluorescence microscopy under blue excitation [42]. Each cluster of 7 spots stands for the seven rhabdomeres (dark spots in the inset of Fig.3a, right) located beneath each facet. While the peripheral rhabdomeres (R1-R6) all fluoresce red, the central rhabdomere (R7) falls in three classes: green fluorescent (yR7), nonfluorescent (pR7) and red fluorescent (rR7). The latter type was shown to occur exclusively *in the dorsal part of the male eye* [49]). The fluorescence colors are linked to the specific visual pigment present in each rhabdomere and constitute a genuine ‘color code’ to their spectral sensitivities [42, 49, 31] [from 31].

(b) We recorded the *receptor potential* delivered by an individual photoreceptor cell (cf [83]). Using ultrafine micropipettes filled with a fluorescent dye, we injected the dye into the cell immediately after measuring its spectral sensitivity $S(\lambda)$. The injected cells (here R2 and R3, see the numbering of cells in Fig.3a, inset) were recovered *in vivo*, allowing fast and unequivocal assignment of a given $S(\lambda)$ to a given cell type [from 31]

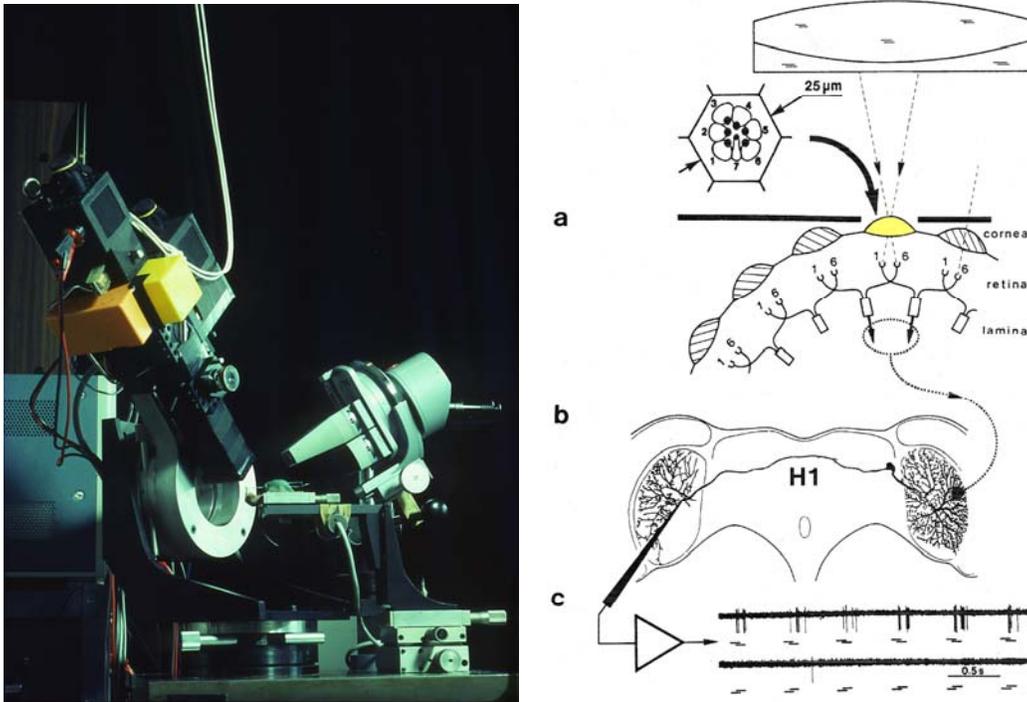


Fig3:

(left): Triple-beam incident light "microscope-telescope" built to analyze motion detection at the most elementary level. The instrument *successively* delivers a $1\mu\text{m}$ -light spot to two neighboring photoreceptor cells, R1 and R6, within a single ommatidium (see Fig. right, (a) inset). A microelectrode records the electrical response of the motion sensitive neuron H1 to this "apparent motion" [118, 32, 46]

(right) : Information flow from the objective of the "microscope-telescope" down to the H1 neuron, whose spiking activity is recorded contralaterally. Presenting two flashes (each with a duration of 100 ms) *successively* to the pair of receptors R1 and R6 consistently induced a prominent spike discharge in H1 whenever the sequence mimicked motion in the preferred direction (c, top trace) and no response when the opposite sequence was presented (c, bottom trace) [from 46]

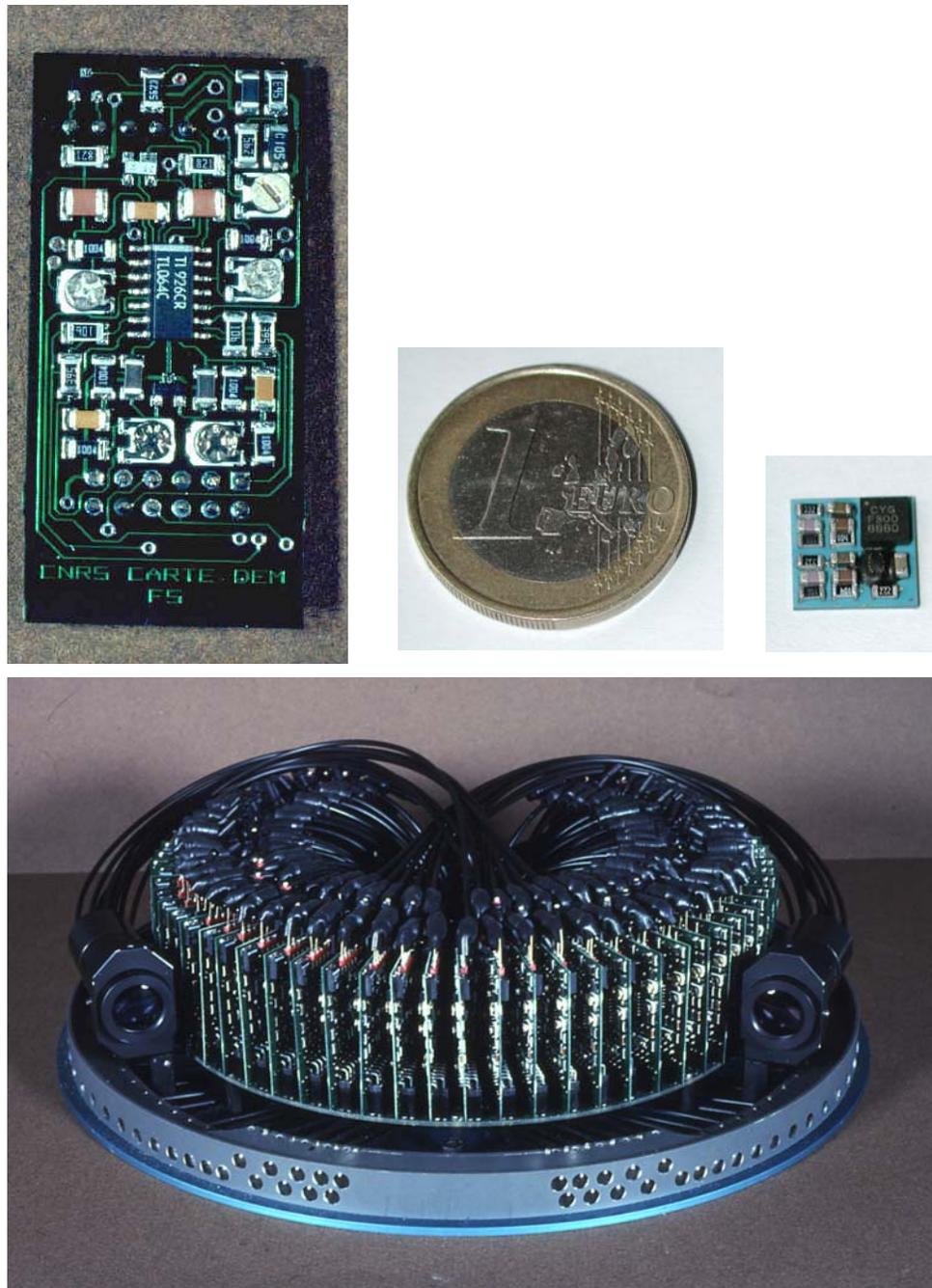


Fig.4: **(top)** Opto-electronic *Elementary Motion Detector* (EMD) based on the functional diagram of a fly EMD established via physiological analysis (Fig.3). The left, purely analog version of the EMD dates back to 1989 and weighs 5 grams. Our current EMDs are smaller hybrid (analog+digital) versions. The smallest one (bottom right), built in LTCC (low temperature co-fired ceramics) is only 7mm x 7 mm and weighs only 0,2 grams [From 113]. Others are based on FPGAs [3]. **(bottom)** Compound eye with its faceted array and its 114 EMDs (of the type shown at the top left). Despite its small number of pixels, this artificial vision system is able to drive-by-wire the robot Fly (Fig. 5a) at high speed (50cm/s), in a fully autonomous mode, through a field of unpredictable obstacles. Notice the resolution gradient from the front to the periphery of the visual field, which makes the sine function in Eq. 1 « embodied in the eye structure » [from 44].

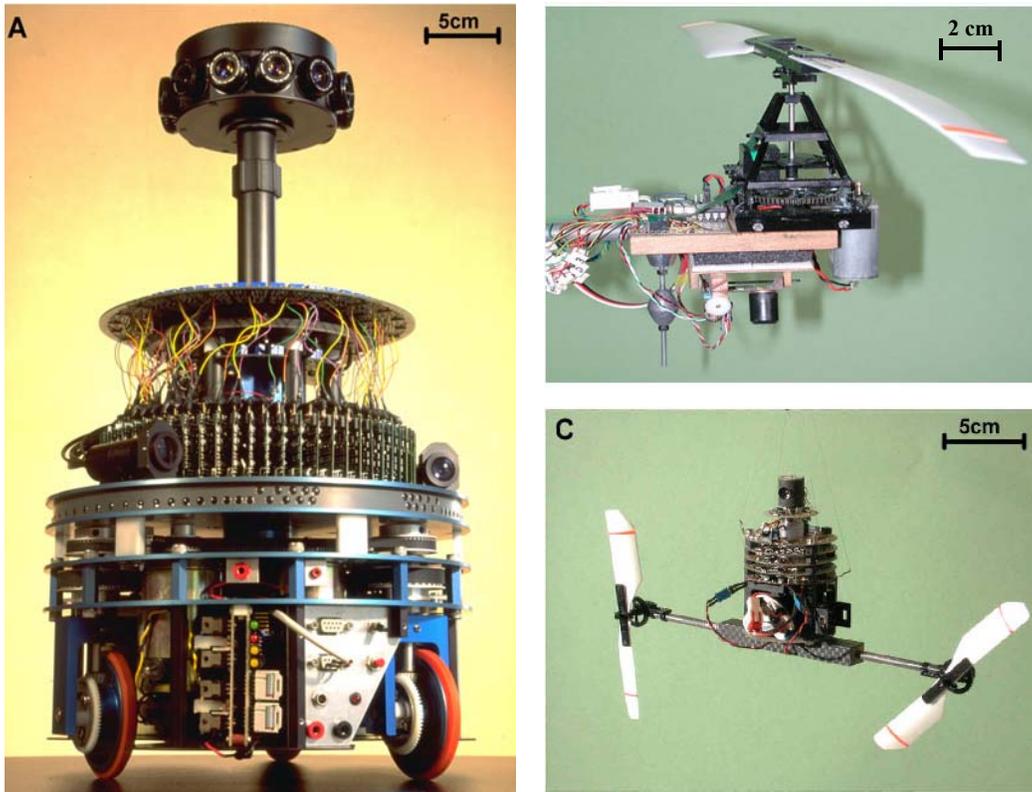


Fig.5: Three of the visually-guided robots designed and constructed at the Laboratory on the basis of our biological findings on visuomotor control in flies.

(a) The robot Fly incorporates the compound eye shown in Fig. 4 for obstacle avoidance, and a dorsal eye for detecting the light source serving as a goal. This robot (height: 50cm; weight 12kg) reacts to the optic flow generated by its own locomotion amongst obstacles [10, 43-45]. It is fully autonomous as regards its processing and power resources.

(b) The robot OCTAVE (Optic flow-based Control sysTem for Aerospace Vehicles) is a 100-gram rotorcraft equipped with a 2-pixel ventral eye sensing the OF on the terrain below (see Fig. 7b). This self-sustained aerial creature is tethered to a light rotating arm that allows only three degrees of freedom: forward and upward motion and pitch. The robot lifts itself and circles around a central pole at speeds up to 3 m/s. It ascends or descends depending on the ventral optic flow it measures [From 120-122]. **(c)** The robot OSCAR (Optic flow based Scanning sensor for the Control of Aerial Robots) is a 100-gram, twin-engine aircraft equipped with a two-pixel frontal visual system that relies on visual motion detection and on a microscanning process inspired by the fly [38]. It is tethered to a 2-meter-long nylon wire secured to the ceiling of the laboratory. Vision and rate gyro signals combine onboard to make OSCAR fixate and track a target (a dark edge or a bar) with *hyperacuity* at speeds of up to 30°/s [from 142].

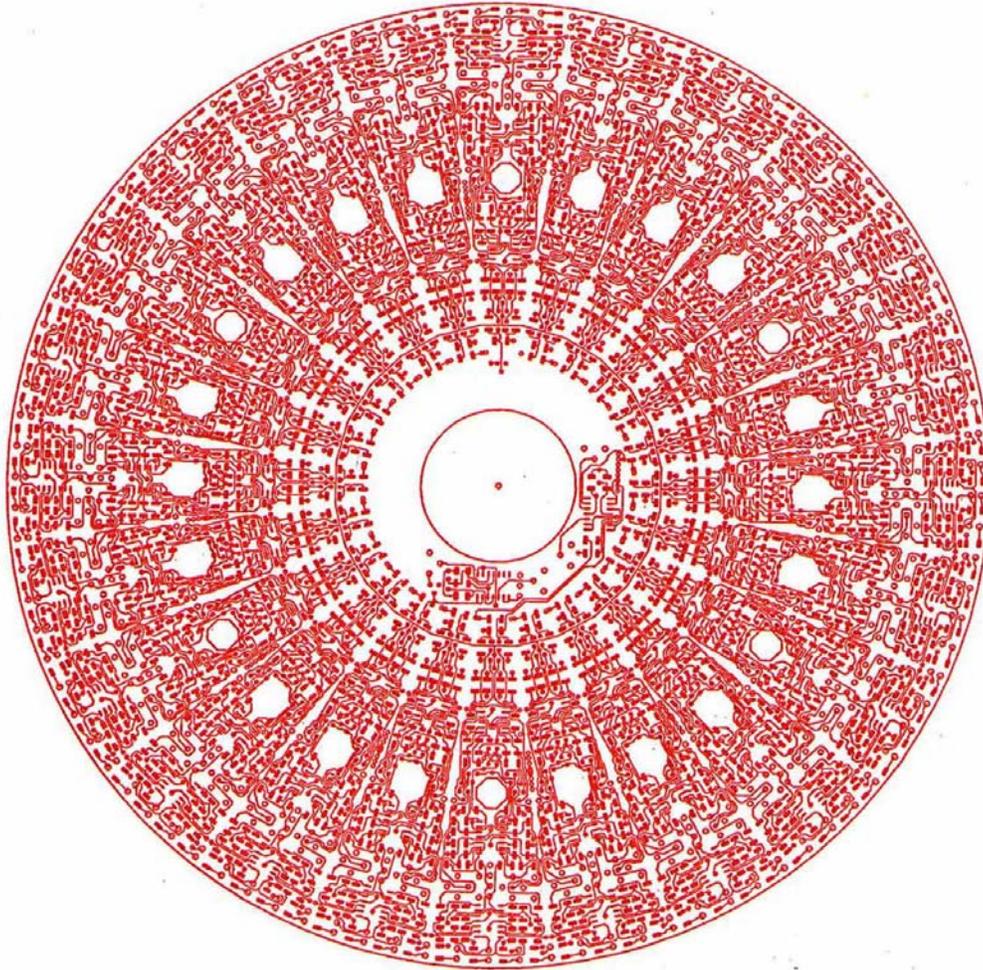


Fig.6 : Routing diagram of one face of the printed circuit board (PCB) that integrates information about the obstacles and the target on-board the “robot-mouche” (Fig. 5a). This six-layered PCB has 210 parallel inputs (114 EMD inputs + 96 inputs from the target seeker) and a single output (near the centre of the pattern). The latter gives (in Volts) the next steering angle required to reach the target while avoiding all obstacles. The mosaic layout of this circuit is reminiscent of the neural architecture of insects’ visual ganglia: the rose-window-like pattern results from the retinotopic projection of numerous repeat units [from 44].

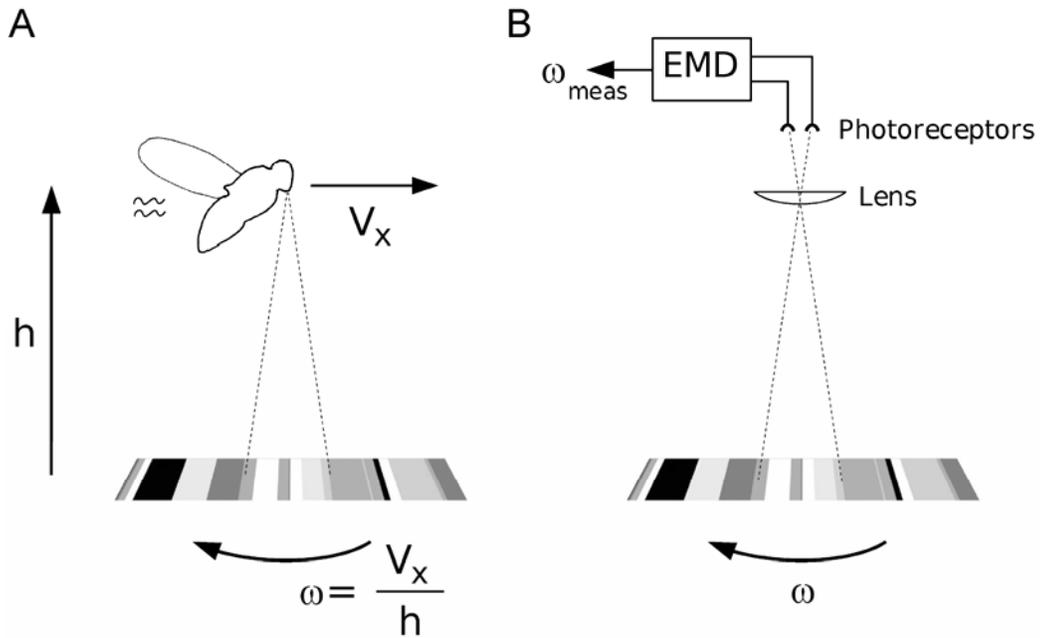


Fig.7: Definition (ω) and measurement (ω_{meas}) of the ventral optic flow (OF) perceived by an animal or a robot flying in translation in the longitudinal plane. **(a)** The ventral optic flow perceived by an animal flying at groundspeed v_x and groundheight h is the angular speed ω at which a point in the ground texture directly below seems to move in the opposite direction. By definition, ω (in $\text{rad}\cdot\text{s}^{-1}$) is the ratio between groundspeed and groundheight. The one-dimensional randomly textured ground shown here is a magnified sample of that shown below Figure 9a. **(b)** The OF sensor used onboard the robot OCTAVE (Fig.5b) comprises a microlens and two photoreceptors driving a fly-based Elementary Motion Detector (EMD). The output ω_{meas} from the OF sensor serves as a feedback signal in the control scheme shown in Figure 8 [from 47].

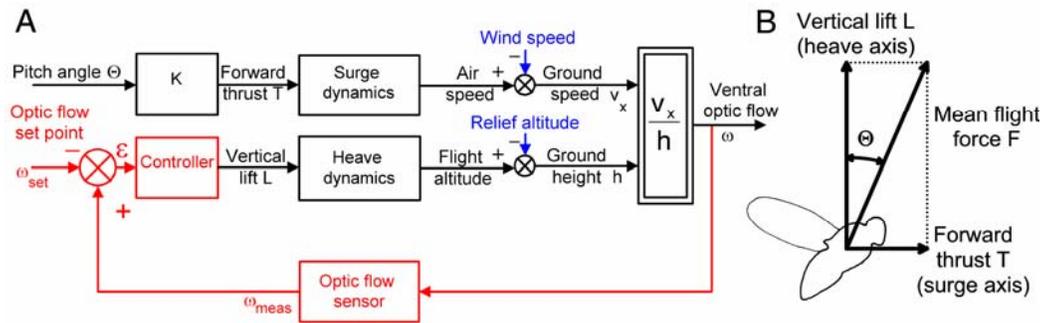


Fig. 8 : *Optic Flow Regulator* implemented onboard the robot OCTAVE. The control loop adjusts the vertical lift **L** at all times to maintain the ventral OF (ω) constant and equal to the set point (ω_{set}).

(a) The upper (open loop) pathway describes how an increase in pitch angle Θ (see b) causes a proportional increase in forward thrust **T**, and thus in groundspeed v_x . The bottom (red) pathway shows how the ventral OF measured (ω_{meas}) is compared with an OF set-point (ω_{set}). The error signal ($\epsilon = \omega_{meas} - \omega_{set}$) delivered by the comparator drives a controller adjusting the vertical lift **L**, and thus the groundheight **h**, so as to maintain the OF (ω) constant and equal to ω_{set} . The right part of this *functional diagram* defines the ventral OF: $\omega = v_x/h$, and shows the specific points at which two disturbances impinge on the system: relief altitude and wind speed.

(b) Like flies, bees, and helicopters, OCTAVE gains speed by pitching its mean flight force vector forward at a *small* angle Θ with respect to the vertical [from 47].

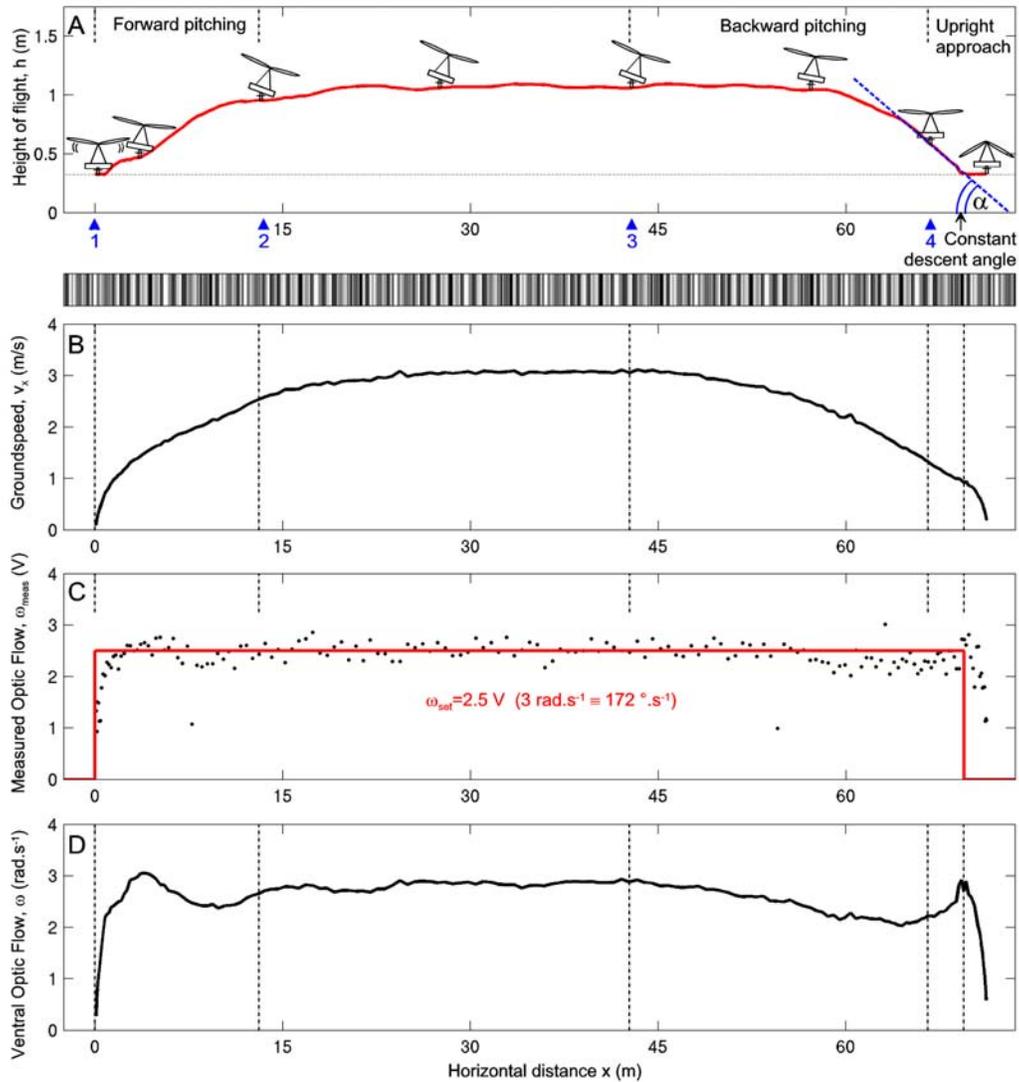


Fig. 9: Flight parameters monitored during a 70-meter flight (consisting of about 6 laps) performed by the robot OCTAVE (Fig. 5b) equipped with the *optic flow regulator* shown in Fig. 8.

(a) Vertical trajectory in the longitudinal plane. Between arrowheads 1 and 2, the operator pitched OCTAVE forward rampwise by an angle $\Delta\theta = +10^\circ$. The ensuing increase in groundspeed (see b) caused the robot to climb and fly level at a groundheight of approximately 1 meter. After flying 42 meters, OCTAVE was pitched backwards rampwise by an opposite angle $\Delta\theta = -10^\circ$ (between arrowheads 3 and 4), and the ensuing deceleration (see b) caused the robot to land smoothly with a constant-descent-angle final approach.

(b) Groundspeed v_x monitored throughout the journey.

(c) Output w_{meas} of the OF sensor showing the relatively small deviation from the OF set-point w_{set} (in red) throughout the journey.

(d) Output (true optic flow ω , calculated as v_x/h) of the feedback loop. It can be seen that the ventral OF resulting from the MH flight pattern was being held virtually - but not perfectly - constant throughout the journey [from 47].