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Insect inspired autopilots

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Abstract: We address some of the control problems involved in insects’ and robots’ visually guided piloting. We present explicit control schemes that explain how insects may navigate on the basis of optic flow (OF) cues, without requiring any distance and speed measurements. The concept of the optic flow regulator, a feedback control system based on OF sensors, is presented. We tested our control schemes in simulation, and implemented them onboard two types of aerial robots, a helicopter and a hovercraft. Our electronic OF sensors were inspired by the results of our microelectrode studies on motion sensitive neurons in the housefly’s compound eye. The control schemes described do not involve any conventional avionic sensors like rangefinders or speed sensors, and show great potential for the autonomous control of air, underwater and space vehicles.

Index terms: Visuo–motor control, optic flow, Insect, Micro–air vehicles (MAV)

I. INTRODUCTION

Conventional aircraft autopilots require the measurement of state variables such as barometric altitude, groundheight, groundspeed, descent speed, etc. The sensors developed for this purpose - usually emissive sensors such as radar-altimeters, forward-looking infrared sensors, Doppler radars, GPS, etc. - are far too cumbersome for insects or even birds to carry and to power. Natural flyers have developed other systems for controlling their flight and they can teach us some lessons. Flying insects are agile creatures navigating swiftly through most unpredictable environments. Equipped with “only” about one million neurons and only 3000 pixels in each eye, the housefly, for example, achieves 3D navigation at an impressive 700 body-lengths per second. This objectionable creature actually achieves just what is being sought for in the field of aerial robotics: dynamic stabilization, 3D autonomous piloting, ground avoidance, collision avoidance with stationary and nonstationary obstacles, tracking, docking, autonomous takeoff and landing, etc. The last seven decades have provided evidence that flying insects guide themselves through their environments by processing the optic flow (OF) that is generated on their eyes as a consequence of their locomotion. In an animal’s reference frame, the translational OF is the angular speed at which contrasting objects in the environment move past the animal.

This contribution summarizes two recent reviews [2,3], in which we recounted our attempts to model the visuomotor control system that provides flying insects with a means of autonomous piloting at close range. The interested reader is referred to these reviews and original papers for an extensive literature on both insects’ and robots’ vision based autopilots. The aim of these studies was not to produce a detailed neural circuit of the visuomotor control systems, but rather to obtain a more functional overall picture, that is, a picture that abstracts some basic control principles.

Our progress on these lines was achieved by performing simulation experiments and testing our control schemes onboard miniature aircraft. These aerial robots are based on the use of electronic OF sensors inspired by the housefly Elementary Motion Detectors (EMDs), which we had previously analysed in our laboratory.

II. FROM THE FLY COMPOUND EYE TO BIO–INSPIRED OPTIC FLOW SENSORS

Each compound eye consists of an array of ommatidia, the front end of which is a facet lens focussing light on a group of photoreceptor cells (Fig. 1). The fly retina has been described in great details, with the different spectral types of cells, polarization sensitive cells and female tracking cells in the male. There exists a typical division of labour within the retina:

- The two central (tandem) photoreceptor cells, R7-8, display various spectral sensitivities that are randomly scattered across the retinal mosaic, as attested by the characteristic R7 autofluorescence colors (Fig. 1). R7 and R8 are thought to participate in color vision.
- The outer 6 photoreceptor cells (R1-R6) all have the same spectral sensitivity and participate, in particular, in motion detection. In this visual pathway, signal-to-noise ratio is improved by ingenious features:
  (i) a UV sensitizing pigment that enhances the quantum catch, and (ii) an ingenious opto-neural projection called “neural superposition”.

Figure 1: Head of a blowfly with its two panoramic compound eyes, and part of the receptor mosaic observed in vivo after optical neutralization of the cornea. Each micrometer-sized photoreceptor has a distinct autofluorescence color linked to its specific visual pigment (from [3]).
To estimate the OF, insects use motion sensitive neurons. In flies, part of the 3rd optic ganglion called the Lobula Plate (LP) appears as a genuine “visual motion processing center”. It comprises approximately 60 uniquely identifiable neurons, the LP tangential cells (LPTC), that analyze the OF field resulting from the animal’s walking or flying. Some of these neurons transmit their electrical signals via the neck to thoracic interneurons that will drive the wing-, leg-, and head-muscles. Other neurons send their signals to the contralateral eye. The LPTCs are known to be large-field collator neurons that pool the electrical signals from many retinotopic input elements called “Elementary Motion Detectors” (EMDs). Although the cellular details underlying a single EMD are still elusive, we analysed its functioning in the housefly, using microelectrode recording from an identified neuron combined with single photoreceptor stimulation. With a special optical instrument whose main objective was quite simply one facet lenslet (diameter ≃ 25μm, focal length ≃ 50μm), we illuminated two photoreceptors (diameter ≃ 1μm) sequentially within the selected ommatidium. The H1-neuron responded with a vigorous spike discharge to this “apparent motion”, provided the motion was mimicked in the preferred direction, and did not respond to a motion mimicked in the non-preferred (null) direction. From many experiments of this kind, in which various sequences of light steps and/or pulses were applied to selected receptor pairs, we established an EMD block diagram and characterized each block’s dynamics and nonlinearity. While not unveiling the cellular details of the EMD circuit, our analysis allowed the EMD principle to be understood functionally – opening the way to its transcription in electronics.

In the mid 1980’s, we designed an optic flow sensor, the signal processing scheme of which (Fig. 2a) was inspired by lessons taken from the fly EMD. The OF is an angular speed \( \omega \) [rad.s\(^{-1}\)] equal to the inverse of the time \( \Delta t \) taken by a contrasting feature to travel between the visual axes of two adjacent photoreceptors, separated by an angle \( \Delta \phi \). Our OF sensor processes this time lapse \( \Delta t \) so as to generate a response that grows monotonically with the inverse of \( \Delta t \), and hence with the optic flow \( \omega \) (Fig. 2a). A short \( \Delta t \) gives a high voltage output and vice versa. The thresholding makes the response relatively independent of contrast and spatial frequency, unlike the Reichardt “correlator scheme” for motion detection.

### III. “OPTIC FLOW REGULATORS” AS VISION BASED AUTOPILOTS

In Fig. 3A, the ventral OF depends on both the groundspeed \( V_x \) and the groundheight \( h \) and is equal to the ratio between these two variables:

\[
\omega = \frac{V_x}{h} \text{ [rad.s}^{-1}\text{]} \quad (Eq.1)
\]

Flies and bees have been shown to react to the translational OF independently of the spatial texture and contrast, and some of their visual neurons - the “velocity tuned neurons” - may be involved in this reaction because they respond monotonically to \( \omega \) with little dependence on texture and contrast. Neurons facing downwards can therefore act as ventral OF sensors, and thus assess the \( V_x/h \) ratio (Fig. 3).

Sixty years ago, Kennedy put forward an “optomotor theory” of insect flight, according to which flying insects maintain a “preferred retinal velocity” with respect to the ground below. In the meantime, many experiments have confirmed this view: both flies and bees maintain a...
constant OF with respect to the ground while cruising or landing. The big problem is how insects achieve this feat, since there is an infinitely large number of possible combinations of \( V_g \) and \( h \) generating the same \( V_g/h \) ratio. Kennedy’s “theory” therefore called for an explicit control scheme that would clarify: (i) the flight variables really involved, (ii) the sensors really required (iii) the dynamics of the various system components, (iv) the causal and dynamic links between the sensor(s) and the variable(s) to be controlled, (v) the points of application and the effects of the various disturbances that insects may experience (change in relief, headwind, etc.).

In 1999, we established via experimental simulation how a seeing helicopter (or an insect) might manage to follow a terrain and land on the sole basis of OF cues without measuring its groundspeed or groundheight (see Fig. 4.5 in [5]). The landing trajectory obtained in these simulations (Fig. 5 in [5]) resembled the final approach of bees landing on a flat surface. The 840-gram rotorcraft we constructed was able to jump over 1-meter high obstacles (see Fig. 8 in [6]).

We then developed a genuine “OF based autopilot” called OCTAVE (which stands for Optical Control sysTem for Aerial VEhicles), that enables a micro-helicopter to perform challenging tasks ([7, 1]). The idea was to integrate an OF sensor into a feedback loop driving the robot’s lift so as to compensate for any deviations of the OF sensor’s output from a given set-point (figure 4A). This is what we call the OF regulator for ground avoidance. The term “regulator” is used here as in control theory, to denote a feedback control system designed to maintain a variable (here the OF, \( \omega \)) constantly equal to a given reference (the “set-point”).

The OF sensor produces a signal \( \omega_{\text{meas}} \) (figures 3B) that is compared with the OF set-point \( \omega_{\text{Set}} \) (Fig. 4A). The error signal \( \epsilon = \omega_{\text{meas}} - \omega_{\text{Set}} \) drives a controller adjusting the lift \( L \), and hence the groundheight \( h \), so as to minimize \( \epsilon \) (Fig. 4A). All the operator does is to set the pitch angle \( \Theta \), and hence the airspeed: the OF regulator does the rest, holding the \( V_g/h \) ratio – i.e., the ventral OF - constant. In the steady state (i.e., at \( t = \infty \)), \( \omega_{\text{meas}} \approx \omega_{\text{Set}} \) and the groundheight \( h \) becomes proportional to the groundspeed \( V_x \) (Eq. 2):

\[
h = K \cdot V_x, \quad \text{with} \quad K = 1/\omega_{\text{SET}} = \text{constant}
\]

Figure 4: (A) The OCTAVE autopilot consists of a feedback control system, called the optic flow regulator (bottom part) that controls the vertical lift, and hence the groundheight, so as to maintain the ventral OF, \( \omega \), constant and equal to the set-point \( \omega_{\text{SET}} \), whatever the groundspeed \( V_g \). (B) Like flies and bees, our micro-helicopter (MH) gains speed by having its flight force vector \( F \) pitched forward at an angle \( \Theta \) with respect to the vertical. Controlling \( F \) (via the rotor rpm) amounts to mainly controlling \( L \) because \( \Theta \) always remains small (\( \Theta_{\text{max}} < 10^\circ \) for \( V_g = 3 \text{m/s} \)) (from [1]).

To test the robustness of this OF regulator scheme, we implemented it on a micro-helicopter (MH) equipped with a two-pixel ventral eye driving a single EMD (Fig. 5A). The MH is tethered to the tip of a flight mill (Fig. 5B) equipped with ground-truth azimuthal and elevation sensors, with which the position and speed of the MH can be monitored accurately. Any increase in the rotor rpm causes the MH to lift and rise, and the slightest (operator mediated) forward pitching induces the MH to gain speed. The feedback reacts to this increase in forward speed \( V_x \) by increasing the vertical lift \( L \) - and hence, the groundheight \( h \) - so as to hold the \( V_x/h \) ratio constant.

![Figure 5: (a) 100-gram Micro-helicopter (MH) equipped with a ventral OF sensor (Fig. 2) and an OF regulator (Fig. 4A) that acts upon the lift by altering the rotor rpm. (b) Tethered to the tip of the (pantographic) arm of the flight mill, the MH is remotely commanded to pitch forward at an angle \( \Theta \). It makes successive laps over the arena (diameter 4.5m), the ground texture of which is randomly distributed in terms of both the spatial frequency and the contrast \( m \) (0.04<\( m \)<0.3) (from [7]).](image)

OCTAVE’s OF regulator scheme (Fig. 4A) results in the behavioral patterns shown in Fig. 6, which gives the MH flight variables monitored during a 70-meter flight over a flat terrain [1]. In Fig. 6A (left), the operator simply commanded the MH to pitch forward rampwise by an angle \( \Delta \Theta = +10^\circ \) (between arrowheads 1 and 2). The ensuing increase in groundspeed \( V_x \) (which reached 3m/s, see B) automatically made the MH take off, since the feedback loop consistently increased \( h \) proportionally to \( V_x \) to comply with Eq 2.
The MH eventually flew level at a groundheight $h$ of approximately 1 meter - the value imposed by the OF set-point $ω_{set} = 172°/s$ (Fig. 6C). After covering 42 meters, the MH was commanded to pitch backwards rampwise by an opposite angle $Δ\Theta = −10°$ (between arrowheads 3 and 4), and the ensuing deceleration (see B) automatically induced a gradual descent. The final approach (starting at arrowhead 4, Fig. 6A) was made at a constant descent angle $\alpha$, as actually observed in landing bees [10] and predicted by the OF regulator scheme [1].

The MH flight pattern shows how an airborne vehicle can take off, navigate and even land on flat terrain without having to measure any groundheights or groundspeeds, provided it is equipped with an OF sensor facing the ground and an OF regulator servoing the OF to a reference value. The OF regulator concept and the robot’s performances were found to account for a series of puzzling, seemingly unconnected flying abilities observed during the last 70 years in various species (fruitflies, honeybees, moths, mosquitoes, dung-beetles, migrating locusts and butterflies).

In line with the OCTAVE autopilot, we designed the LORA III autopilot (LORA III stands for Lateral Optic flow Regulator Autopilot, Mark III) [8]. LORA III is a dual OF regulator that is able to control both the forward speed $V_x$ of an aerial robot and its lateral distance to the right wall $D_r$ or left wall $D_l$ in a corridor (Fig. 7).

We showed the feasibility of this scheme in simulation experiments where a miniature seeing hovercraft navigates in a straight or tapered corridor [8]. Our hovercraft is equipped with two additional lateral thrusters that make it fully actuated. It is therefore capable of independent side-slip and forward slip. LORA III is based on only two OF sensors (one looking to the right, one to the left). The groundspeed is constrained by the environment, as observed on bees navigating in straight or tapered corridors [10]. The groundspeed $V_x$ is controlled by the error signal $ε_{Fwd}$ between the forward OF set point $ω_{setFwd}$ and the sum of the two OFs (right and left). The clearance from the walls is constrained by the environment too: the lateral distance from one wall is controlled by the error signal $ε_{Side}$ between the sideways OF set-point $ω_{setSide}$ and the larger of the two lateral OFs (right or left).

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The advantage of this control scheme is that it determines both the forward speed and the distance from the walls on the sole basis of two constants - two OF set-points - without any needs for measuring forward speed, lateral distances and corridor width, that is, without any needs for onboard velocimeters and rangefinders whatsoever. Extensive simulations experiments were presented, showing how the robot copes with major OF perturbations brought about by, e.g., an opening in one wall, a moving wall or a tapered corridor [8].

The LORA III dual OF regulator accounts particularly well for two types of behavior observed on bees flying freely in a corridor: the “centering behavior” [4, 10] and the “wall-following behavior” [9]. We showed that a “centering behavior” will simply ensue from a more general “wall-following behavior” whenever the values of the OF set-points $\omega_{setFwd}$ and $\omega_{setSide}$ meet particular conditions with respect to each other [8].

IV. CONCLUSION

OCTAVE and LORA III autopilots consist of feedback control loops called “optic flow regulators”: the block diagrams of which (Fig. 4, 7) show which variables are measured, which ones are controlled, which ones are regulated (i.e., maintained constant), while giving the causal and dynamical relationships between these variables. In contrast with conventional aircraft’ autopilots, OCTAVE and LORA III control loops do not aim to achieve any “speed holding” or “distance holding” abilities. They aim instead to modulate the behavior by an “OF hold” process that does without any measurements of speed and range. This OF regulator process consistently tunes the animal behavior so as to make the OFs deviate little from the OF set-points, and therefore greatly reduces the dynamic range constraints imposed upon the OF sensors themselves [1].

- From a biological viewpoint, these explicit control schemes are interesting working hypotheses because they account for a number of puzzling, seemingly unconnected flight behaviors observed in many insect species over the last 70 years - including terrain following, sensible reactions to headwind, flight over mirror-smooth water, flight along tapered corridors, and landing at a constant slope on flat surfaces, as discussed in details in [1, 3]. Our novel finding that bees do not center systematically in a corridor and tend to follow a wall [9] cannot be accounted for by the “optic flow balance hypothesis” [4,10] but is well accounted for by the LORA III model, where “centering behavior” arises as a particular case of “wall-following behavior” [8]. It should be added that the neural implementation of an OF regulator is undemanding since it requires only a few linear operations (such as adding, subtracting an applying various filters) and nonlinear operations (such as minimum and maximum detections).

- From an engineering viewpoint too, these OF regulation schemes are undemanding and attractive since they do not rely on any rangefinders or velocimeters and can therefore do without the bulky and power-hungry emissive sensors of conventional avionics, such as Radars, Ladars or Flirs that equip many aircraft and spacecraft. Once engineered beyond the state of the minimalistic demonstrators presented here, OCTAVE and LORA III principles could potentially be harnessed to provide micro aerial, underwater and space vehicles with a certain degree of autonomy when they are to navigate in uncertain closed quarters or through complex terrains such as mountainous canyons.

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