

RESEARCH ISSUES IN BIOLOGICAL INSPIRED SENSORS FOR FLYING ROBOTS

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ABSTRACT

Biological inspired robotics is an area experiencing an increasing research and development. In spite of all the recent engineering advances, robots still lack capabilities with respect to agility, adaptability, intelligent sensing, fault-tolerance, stealth, and utilization of in-situ resources for power when compared to biological organisms. The general premise of bio-inspired engineering is to distill the principles incorporated in successful, nature-tested mechanisms of selected features and functional behaviors that can be captured through biomechatronic designs and minimalist operation principles from nature success strategies. Based on these concepts, robotics researchers are interested in gaining an understanding of the sensory aspects that would be required to mimic nature design with engineering solutions. In this paper are analysed developments in this area and the research aspects that have to be further studied are discussed.

KEY WORDS

Biological inspiration, sensors, flying, robots

1. Introduction

The natural world contains some of the most elegant, innovative and robust solution principles and strategies [1]. On the last decades the interest in biological inspired locomotion has rise a lot of interest in the research community [2]. Several robots have been developed that try to mimic the way biological creatures move, adopting legs [3], crawling, and swimming fins and, in the last years, flapping wings [4].

Recently, a large interest emerged in micro air vehicles (MAVs), especially for applications where maneuverability in confined spaces is necessary. Applications for MAVs have been identified including operations in hazardous environments, search-and-rescue and exploration around rubble in collapsed buildings, internal inspection of pipes, reconnaissance and surveillance of indoor environments, etc. [5]. MAV researchers are interested in gaining a deeper understanding about the mobility and sensory aspects that would be required to mimic nature design with engineering solutions [1].

Insect sensors are fascinating for their simplicity in design, efficiency in function, and robustness to variable environments. For instance, the insect mechanoreceptors detect mechanical disturbances such as movement, stress and vibration. Insect mechanoreceptors can be found almost everywhere on the surface of the insect body, which are innervated by one or more sensory neurons that act in response to stretching, bending, compression, vibration, or other mechanical disturbances. However, they may differ in the way they react to stimuli. Four types of mechanoreceptors are *Trichoid sensilla*, *Campaniform sensilla*, *Stretch receptors* and *Chordotonal organs* [6]. These various sensing organs can be seen as the building blocks of sensing mechanisms or sensing systems in which engineers are often more interested. For flight, the sensors of critical importance of the flies are the compound eyes and the mechanical sensors, such as the antennae and the plethora of wind-sensitive hairs, which allow detailed measurements of the airflow.

Many engineering applications can benefit from these features and, therefore, much recent research in biorobotics has focussed on biomimetic sensors. However, human engineering still is very incipient in comparison to nature's capabilities. This area is inherently multidisciplinary requiring the collaboration from biologists, neurologists and engineers [6].

Bearing these facts in mind, the paper is organized as follows. Section two introduces sensors inspired in insect vision and section three introduces sensors based on the fly's *halteres*. Section four presents several biological inspired sensors that mimic the flies and dragonflies *ocelli*, and section five other biological inspired sensor types. Section six introduces some flying robots that use these types of sensors and, finally, section seven outlines the main conclusions.

2. Sensors That Mimic the Fly's Vision

Sensing visual motion gives creature's valuable information about its interactions with the environment. In particular, flies use visual motion information to navigate through turbulent air, avoid obstacles, and land safely.

Insects (for example, honey bees and dragonflies) cope remarkably well with their world, despite possessing a brain that carries less than 0.01% as many neurons as ours does [7]. Although most insects have immobile eyes, fixed focus optics, and lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. The visual acuity of flies is 100–500 times lower than in humans, yet these animals are capable of extraordinary maneuvers as they navigate through a dynamic, unstructured environment. Most of the fly's neural processing is devoted to vision, and its compound eyes are the key to flight control. They not only enable the fly to see static, pixelated patterns, but also the optic flow, that is, the fly's motion relative to its surroundings [8]. Studies of the insects visual behavior found that, when a fly is presented with a leftward (or rightward) moving stimulus, it would turn in the direction of stimulus movement, in order to reduce the image motion on its eyes. Such response is believed to help the fly to maintain a straight course by compensating for undesired deviations during flight [9]. This fact suggests that there is no need for high-resolution imaging cameras for flight control. Instead, coarse-grained arrays of sensors can give good results, provided they are arranged to offer a global view of the environment, able to detect the direction of motion, and endowed with parallel processing to extract the global vector field of motion [5].

Insects infer distances to potential obstacles and objects of interest from image motion cues that result from their own motion in the environment. The angular motion of texture in images is denoted generally as optic or optical flow. These principles of navigation based on visual cues as deciphered from the honeybee are being implemented electronically by translation of the optic flow algorithms onto embedded hardware [16].

Mobile robots are ideal candidates for using this sensory modality to enhance their performance, but so far have been limited by the computational expense of processing video. Also, the complex structure of natural visual scenes poses an algorithmic challenge for extracting useful information in a robust manner. Researchers are distilling some of these insect-inspired strategies for utilizing optical cues to obtain unique solutions to navigation, hazard avoidance, altitude hold, stable flight, terrain following, and smooth deployment of payload [7]. Several groups have succeeded in building electronic sensors that mimic the fly's vision.

Harrison and Koch addressed these issues by creating a small, low-power visual sensor with integrated analog parallel processing to extract motion in real-time. They constructed a silicon implementation of the Hassenstein-Reichardt motion detector in a standard CMOS VLSI process [8]. The building block of the Reichardt motion sensor is an elementary motion detector (EMD). When a moving image is presented to an EMD, the perceived signal in one receptor is compared to the delayed signal in a

neighboring receptor. If the left signal correlates more strongly to the delayed right signal, then the image is moving from right to left and vice versa. In the EMD implementation, the bandpass filter represents the temporal frequency response of the photoreceptor [9]. Harrison and Koch built an array of photoreceptors with integrated motion processing circuitry on the same chip, resulting in a monolithic visual motion sensor. A lens was mounted over the chip, focusing an image onto the photoreceptors. Motion information was read from the chip as a time-varying current, which was digitized by an external computer. Finally, they show that the developed sensor is suitable for use in the real world, and demonstrate its ability to compensate for an imperfect motor system in the control of a wheeled autonomous robot. The sensor attenuates open-loop rotation by a factor of 31 with less than 1 mW power dissipation [8]. Since their architecture is based on biological motion detectors, they gain the advantages of this highly evolved system – a design that robustly and continuously extracts relevant information from its visual environment. This work was continued by Higgins and Shams that designed fly-vision systems that can extract features from the optic-flow field [10]. These authors implemented in hardware a motion processing architecture, based on modular mixed-signal VLSI building blocks, connected with a high-speed asynchronous digital communications bus, built on three stages. According to the authors, this system allows the real-time processing of visual motion with modest requirements for power, weight, and physical size.

A similar sensor, based on EMDs, was implemented on the Micromechanical Flying Insect (MFI) [9]. Ideally a flow sensor would contain many EMDs whose outputs are summed to eliminate oscillations that are present in the output of a single EMD. However, although some sensors consist of only one EMD (two photodiodes) in either direction of the device, it is experimentally verified that its output exhibits the expected oscillations, induced by objects when the MFI is moving.

In Japan, Kimihiro Nishio of Yonago National College of Technology has designed a fly-vision chip that is used for wheeled robots [11], instead of MAVs.

There are already commercially available sensors of this type. For example, Centeye Inc. sells an insect-inspired optic-flow sensor called LadyBug, designed for MAVs and other types of robots [12].

3. Sensors That Mimic the Fly's *Halteres*

Estimation of angular velocities in aerial vehicles is fundamental for flight stabilization and maneuvering. Although precise microelectromechanical systems (MEMS) gyroscopes are commercially available, their design (package size, power requirements, etc.) are, in general, not suitable for MAVs. On the other hand, piezoelectric vibrating structures were developed and proved to be able

to detect Coriolis force with high accuracy. Therefore, based on the gyroscopic sensing of real flies, a novel design using piezoelectric devices is being considered [13].

In order to maintain stable flight flies also have special organs, unique among insects, for sensing their own rotation, called *halteres*, to detect body rotational velocities via gyroscopic forces. The *halteres* of a fly are drumstick-shaped protrusions on the fly's thorax, evolved from hindwings (are the remnants of a second pair of wings) and are hidden in the space between thorax and abdomen, so that air current has negligible effect on them (Figure 1) [5]. The *halteres* of a fly resemble small balls at the end of thin sticks (Figure 2). There are about 400 *sensilla* embedded in the flexible exoskeleton at the *haltere* base. These mechanoreceptors function as strain gauges to detect the Coriolis force exerted on the *halteres*. During flight, the *halteres* beat up and down just like wings in vertical planes through an average angle of nearly 180° anti-phase to the wings at the wing beat frequency, but they do not generate any lift. Instead, sensors in the sockets of the *halteres* detect their position, which in turn helps the insect stabilization. Without the *halteres* insect is not able to fly. In fact, when the fly's *halteres* are removed or immobilized, it quickly falls to the ground. In addition, the two *halteres* of a fly are noncoplanar and each one is tilted backward from the transverse plane by about 30° (Figure 3). This noncoplanarity of the two *halteres* is essential for a fly to detect rotations about all three turning axes [13]. In fact, a fly with one *haltere* removed is unable to detect rotations about an axis perpendicular to the stroke plane of the remaining *haltere* [14].

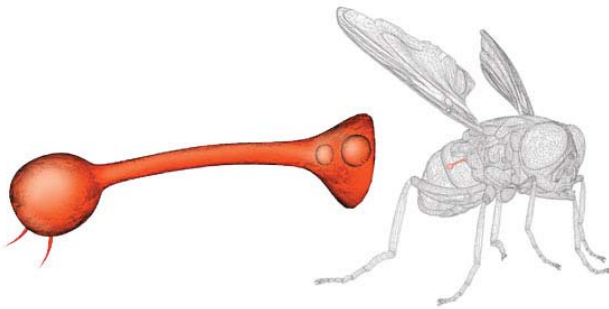


Figure 1. To sense its own rotation, the fly uses *halteres*, drumstick-like protrusions on its thorax that vibrate with each wing beat and help stabilize the insect [5]

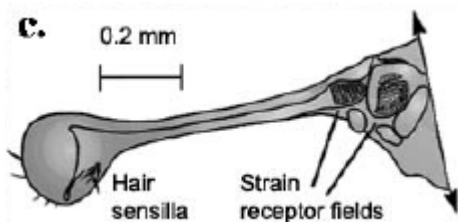


Figure 2 A blowfly *Calliphora* left *haltere* from above. Most of the mass of the *haltere* is in the knob (left). The base houses more than 300 strain receptors [6]

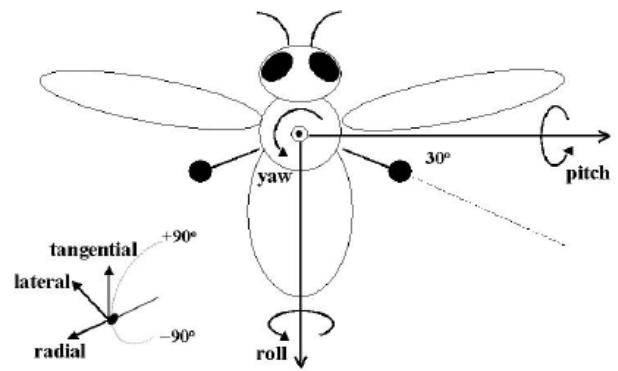


Figure 3. Schematic of enlarged *halteres* of a fly [13]

Wu *et al.* developed an artificial *haltere* for detecting rotation and applied it to MFI [9]. Since a *haltere* must have only one sensing degree of freedom (*i.e.* the direction orthogonal to the *haltere* beating plane), the design of a mechanical *haltere* must allow for high stiffness in the tangential direction and compliance in the lateral direction. The best mechanically design for this is a flat beam with the wide face in the plane of the *haltere* beating and the end of the beam is twisted to allow a high compliant section for rotation. To detect the Coriolis forces, two strain gauges are placed, on each side of the beam, close to the point of rotation, such that one would be in compression while the other is in tension [9]. Two types of biomimetic gyroscopes have been constructed using foils of stainless steel. Both devices are driven by piezoelectric actuators and detect the Coriolis force using strain gages. The mechanism by which the *halteres* detect angular velocities and the proposed demodulation method were tested [9]. Using the characteristics (frequency, modulation, and phase) of these force signals on the left and right *halteres*, a demodulation scheme was proposed to decipher roll, pitch, and yaw rotations [14]. The angular velocities of an insect under hovering condition are generated by the virtual insect flight simulator (VIFS), a software testbed that is used to simulate the dynamics of the MFI and evaluate control algorithms [15], and it is concluded that it works according to expected. Afterward, the experimental results shown successful measurements of angular velocities and these devices have the benefits of low power and high sensitivity [13].

There are several advantages for the MFI in using *halteres*, instead of gyroscopes based on MEMS technology, as angular rate sensors. First, the *haltere* consumes far less power since it does not use active actuation. Second, the *haltere* has a large dynamical range [9, 13, 14]. Finally, when the wings of the MFI are flapping, the wing inertia causes the MFI body to oscillate, as a result of the wing inertia, along an axis parallel to the wing-stroke direction. Since the forces orthogonal to the *haltere*'s beating plane (*i.e.*, lateral forces) are sensed, it is possible to avoid the error caused by this common-mode body oscillation by phase locking the *halteres* to the wings in the stroke plane [13, 14].

4. Sensors That Mimic the Flies and Dragonflies *Ocelli*

Ocelli are light-sensitive organs present in most flying insects. They are small eyes on the dorsal and forward regions of the heads of many insects. The *ocelli* are distinct from the compound eyes that are most commonly associated with insect vision. In many insects, the *ocelli* are little more than single-point detectors of short-wavelength light and the behavioral responses to the *ocelli* stimuli are hard to observe. The notable exception is found in dragonflies, where flight control is notably degraded by any interference with the *ocellar* system [7]. This system consists of three wide-angle photoreceptors placed on the head of the insect (Figure 4). They are oriented in such a way that they collect light from different regions of the sky. However, the photoreceptors have poor image resolution. Although the exact physiology and contribution of *ocelli*, and their purpose in insect flight, are still not completely understood it is believed that they play a fundamental role in the insect attitude stabilization, in particular, in the horizon stabilization [9]. Biologists believe that insects estimate their orientation relative to the sky by comparing the intensity of light measured by the different photoreceptors in their *ocelli* [14]. Chahl *et al.* state that the *ocelli* are a dedicated horizon sensor, with substantial optical processing, and multiple spectral sensitivity [7].

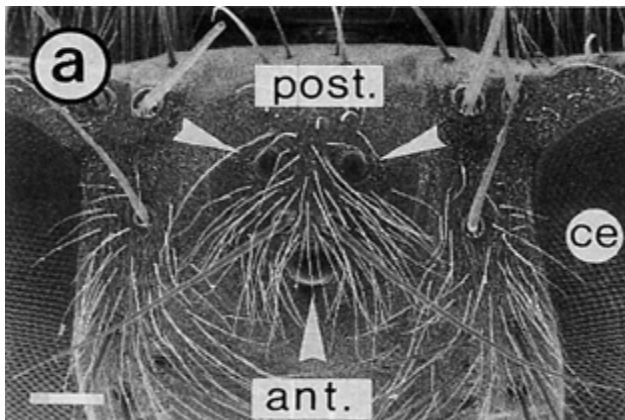


Figure 4 Dorsal view of part of the head of a female *Caliphora*; arrows: *ocelli*; ce, compound eye; ant., anterior; post., posterior; scale bar, 200 μm . [19]

Experimental results of experiments performed on some insect species suggest that *ocelli* collaborate synergistically with compound eyes to minimize the delay of visual processing, and to augment visual responsiveness, when no sharp horizontal border is present. When an insect is presented with a moving artificial horizon, it first tries to rotate its head in order to fixate the horizon on the retina. Only afterwards does it change its wing pattern to realign its abdomen with its head. Taylor observed that cauterization of the *ocelli* doubles the latency between the horizon motion and the compensatory head movement. Moreover, in dimly lit environments, ablated *ocelli* also reduced the insect sensitivity to horizon motions, resulting in smaller

mean amplitude of head motion responses. Therefore, it can be stated that *ocelli* are important for the stabilization of the retinal image of the compound eyes during flight, where disturbances are sudden and frequent. *Ocelli* seem to be designed for high sensitivity and speed of response at the expense of acuity [14].

Two additional findings deserve mentioning. The first is that, in case of ablated compound eyes and intact *ocelli*, an inverted horizon corresponding to upside-down insect orientation caused no head motion unless the two lateral *ocelli* were unequally illuminated, unlike insects with intact compound eyes. This is consistent with the mathematical modeling of *ocelli* developed by Schenato *et al.*, which predicts an unstable equilibrium configuration for the upside-down orientation. The second finding is that the insect head, with compound eyes disconnected and intact *ocelli*, quickly responded to sudden horizon displacements, but then soon relaxed toward the rest position even when the horizon remained displaced. In other cases, animals with intact compound eyes maintained a rotated head. This observation suggests that the *ocelli* behave similarly to a high-pass filter. This could be motivated by the fact that the light distribution can change substantially during the course of a day due to sun motion, atmospheric variations, or simply because the insect can traverse shady trees or urban environments during its flight. Nonetheless, these variations have a long timescale relative to the insect motion timescale, and can be compensated for by the compound eyes. From an engineering perspective, insects combine low-bandwidth compound eyes with high-bandwidth *ocelli*, to obtain an accurate horizon sensor for attitude stabilization over a large frequency domain [14].

Chahl *et al.* describe a biomorphic hardware *ocellus*, based on distilling the principles from the dragonfly *ocelli*, to obtain horizon sensing for attitude reference and, thereby, to attain stable flight/mobility to navigate through hard terrain [7]. The significant observation from the dragonfly *ocellus* is that it does not react to changes in light level on one side or the other independently; the change must be correlated (reduction on one side, increase on the other) and the *ocellus* reacts to keep the light balanced across the two sides. The elementary motion detectors in the system described are designed as Reichardt correlators, to detect properly correlated motion, and gate the reflex depending on the degree of correlation [7]. The performance of the biomorphic *ocelli* was tested by embedding it in a small aircraft to obtain the essential lowest level of autonomy in an aircraft using biomorphic means. The *ocelli* were embedded on a 1 kg delta wing flyer platform and are shown to reliably stabilize the biomorphic flyer, while largely rejecting the biasing effects of the sun [7]. Figure 5 shows a Bioinspired Engineering of Exploration Systems (BEES) flyer, incorporating such a set of *ocelli* on it, which was successfully flight tested. According to these authors, this was the first demonstrated use of a biomorphic *ocellus* as a flight stabilization system.



Figure 5. BEES flyer with the *ocelli* mounted on the nose

The advantage of the *ocelli* over a similarly sized system of rate gyroscopes is that both attitude control and rate damping can be implemented in one device. As a stand-alone unit, stability augmentation may be provided to an autopilot at low cost in terms of space, power, and mass. Furthermore, the sensor is about 40-times lighter than a comparable inertial attitude reference system [7, 16].

The MFI also has *ocelli*. Although real insects have three *ocelli*, these authors adopt a four-receptor configuration because the design is simplified and the results are intuitive. According to Schenato *et al.*, although all the results in their work can be extended to the three-photoreceptor *ocelli*, they prefer to present them relative to a four-photoreceptor configuration, as the proofs are more elegant and intuitive [14]. Furthermore, these authors state that the output from the *ocelli* can be used as an estimate of the orientation of the *ocelli* reference frame relative to the light source. Thus, the *ocelli* can be used to align its reference frame with the light source as described in detail in [14]. This proposition indicates that the *ocelli* still give an approximate orientation of the light source, regardless of the exact orientation of the photoreceptors relative to the insect body, and regardless of the specific light intensity distribution, as long as it is monotonic [14]. This means that the *ocelli* outputs not only estimate the direction of the light source, but also calculate its distance in terms of the latitude [14].

One problem with this implementation of the *ocelli* is that, in the outdoor settings, the vector field points to the position of the apparent light source. However, the apparent light source does not coincide with the azimuth of the sky sphere, as in the indoor setting. As a consequence, the insect would rotate accordingly to *ocelli* output, its body would be tilted, and would not be parallel to the ground plane. However, the orientation could be biased to move the apparent light source position to the ground axis, by adding an offset to the *ocelli* output. This could be possible only if another sensor would estimate correctly the ground azimuthal axis. Once the *ocelli* are biased, it would still respond to sudden changes in attitude due to external disturbances. This attitude estimation strategy is consistent with the observation that the *ocelli* behave like a high-pass filter. To this goal, Schenato *et al.* are currently exploring the manufacturing of a simple electromechanical gravity sensor to be used in order to provide the correct bias for the *ocelli* [14].

5. Other Sensor Types

Campaniform sensilla work as biological strain gauges through strains on the wing base. For instance, these *sensilla* permit the insect to feel the wing position and orientation by encoding the cuticle deformations [6]. Wood and Fearing [17] discussed the use of strain gauges for flight force measurement for the MFI. They also analyzed the placement of the gauges on different body parts.

On Earth, bees, crickets, and ants use sky polarization patterns in the ultraviolet/blue part of the spectrum as a direction reference relative to the position of the Sun. A robotic direction-finding technique based on this concept is more robust in comparison to a simple Sun compass, because the polarization pattern is distributed across the entire sky on Earth and is redundant. Heading direction can be extrapolated from a small region of clear sky in an otherwise cloudy sky that hides the Sun [16]. The BEES flyer system adopts another dragonfly-inspired sensor, namely the UV/green spectral opponency circuit. Spectral sensitivity is largest at those wavelengths in which the contrast between sky and ground is a positive maximum, that is, in the near UV at daytime and in the green at twilight on Earth [7].

6. Flying Robots Adopting Biological Inspired Sensors

The BEES and the MFI projects have developed flying robots, the first one based on flapping wing flight, and the second on fixed wing flight, that use several biological inspired sensors.

The intent of BEES is to distill the principles found in successful, nature-tested mechanisms of specific crucial functions that are hard to accomplish by conventional methods, but accomplished rather deftly in nature by biological organisms [7]. The objective is to develop a novel approach to low-mass yet highly capable Mars flyers based in adapting principles proven successful in nature to achieve stable flight control and navigation [2]. For the above reasons, these vehicles were also called biomorphic flyers [16]. Flight-control and navigation systems inspired by the structure and function of the visual system and brain of insects are adopted to form the BEES flyers [16].

These authors describe the results of successful flight tests of biomorphic flyers (Figure 5) that incorporate bio-inspired sensors including a dragonfly *ocellus*-based horizon sensor, for attitude reference, a honey-bee based optic flow sensor, for altitude control, and hazard avoidance, and insect inspired sun/polarization compassing [16]. To meet and overcome these challenges, Thakoor *et al.* [2, 7, 16] are adapting for Mars exploration principles proven successful in nature to achieve stable flight control and navigation. *Halteres* of the group of flying insects known as *Diptera* are a good example of such systems [6].

The MFI project, at the University of California at Berkeley, aims to create a biologically inspired, autonomous, flapping-wing micro aerial vehicle robot, approximately 25 mm in size (wingtip to wingtip), that will be capable of sustained autonomous flight [9, 14], and complex behaviors, mimicking a blowfly *Calliphora* [18] (Figure 6). Schenato *et al.* combine the outputs from the *ocelli* and the *halteres* to obtain stabilizing control laws to align the axis of the body frame with the axis of the fixed frame. They verify that a simple proportional control law, based on *ocelli* and *halteres* outputs, can reorient the insect toward the light source without knowing the exact light intensity function or the *ocelli* latitude. Moreover, the set of stabilizing gains is quite large, and can be optimized relative to some performance indices, such as settling time or minimal input torque. In particular, the *ocelli* output can be linearized for getting a stable equilibrium [14].

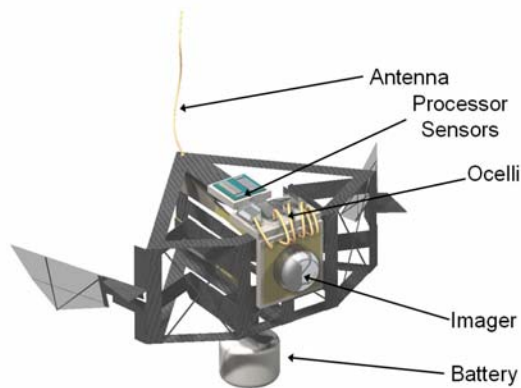


Figure 6. Artist's drawing of future autonomous MFI

7. Conclusion

This paper presented a series of research issues that are under study in order to allow the development of true autonomous flapping wings flying robots. Although not being exhaustive, we believe that it was demonstrated that, in order to achieve autonomy for a flapping vehicle, there is the need to promote further developments in the sensors to provide measurements of both internal and external parameters. However, the sensor-rich feedback control architecture does not depend on a specific type of instrument, that is, there is not the need to exactly replicate the fly's compound eye or *haltere* to achieve the same results. All that is needed is a biomimetic approximation, in other words, a sensor that collects the relevant information, with the required speed and accuracy.

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