

International Symposium on

Flying Insects and Robots

Monte Verità, Ascona, Switzerland

August 12-17, 2007



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The goal of this symposium is to advance the understanding of the biology, technology, and intelligence of small flying animals and robots by promoting an open discussion at the intersection of neurophysiology, ethology, zoology, micro-engineering, low-Reynolds aerodynamics, and artificial intelligence. Flying insects are marvelous micro-machines that provide sources of inspiration for the realization of intelligent micro-robots capable of autonomous flight.

Organizers

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Symposium Program

Sunday, August 12

15:00 – 21:00

--- Arrivals & registrations ---

19:00 – 19:30

--- Welcome drink ---

19:30 – 21:00

--- Dinner ---

Monday, August 13 – Airframe & Aerodynamics

- 07:00 – 08:45 --- Breakfast ---
- 08:45 – 09:00 Welcome
- 09:00 – 09:45 Ron Fearing – Challenges for 100 Milligram Flapping Flight (p.33)
- 09:45 – 10:15 Roger Quinn – A Small, Biologically-Inspired Vehicle with Hybrid Air-Land Mobility (p.93)
- 10:15 – 10:35 Christian Bermes – Aerodynamic Optimization, Dynamic Modeling and Overall Prototype Design for the muFly Autonomous Micro-helicopter (p.9)
- 10:35 – 11:00 --- Coffee break ---
- 11:00 – 11:30 Kevin Jones – Bio-Inspired Design of Flapping-Wing Vehicles (p.57)
- 11:30 – 11:50 Floris van Breugel – A Flapping Hovering Micro Air Vehicle (p.15)
- 11:50 – 12:10 David Lentink – Novel Micro Aircraft Inspired by Insect Flight (p.67)
- 12:10 – 12:30 Daniel Watman – A System for Controlled Visualisation of Flapping Wings (p.125)
- 12:30 – 14:00 --- Lunch ---
- 14:00 – 14:20 Peter Schützner – High-speed Analysis of Wing and Body Motions in Flying Drosophila Using Fluorescent Markers (p.103)
- 14:20 – 14:40 William Dickson – Inertial and Aerodynamic Mechanisms for Passive Wing Rotation (p.27)
- 14:40 – 15:00 Alain Jaquier – Presentation of Armasuisse, Science and Technology Department
- 15:00 – 15:15 Claudia Lafranchi – A Short Overview of the History of Monte Verità
- 15:15 – 16:00 Poster spotlights:
- Samir Bouabdallah – MuFly Project: The First Steps (p.13)
- Umberto Scarfogliero – Bio-inspired Long-jumping and Gliding Robot for Locomotion in Unstructured Terrains (p.101)
- Mirko Kovac – Towards a Self-Deploying Microglider; Gliding Flight and Bioinspired Wing Folding Mechanism (p.61)
- Tobias Seidl – A Planetary Landing Device Inspired by Gliding Cockroaches (p.105)
- Thierry Jardin – Two-dimensional DNS Study of Asymmetric Motions in Hovering Flapping Flight (p.55)
- Laurent Jacquin – Steady Versus Unsteady Aerodynamics of Flapping Wings in Forward Flight: a 2D Study (p.53)
- Kei Senda – Stability of Flapping-of-Wings Flight of Butterfly (p.107)
- Philippe May – Static and Dynamical Biological Observations of Dragonfly's Wings (p.75)
- 16:00 – 19:30 Coffee // Poster session // Hands-on workshops // Demonstrations // Discussion groups
- 19:30 – 21:00 --- Dinner ---
- 21:00 – 22:30 Hands-on workshops

Tuesday, August 14 – Sensors & Actuators

- 07:00 – 09:00 --- Breakfast ---
- 09:00 – 09:45 Michael Dickinson – Sensory Control of Flight in *Drosophila* (p.25)
- 09:45 – 10:05 Hansjürgen Dahmen – Insect Inspired Odometry by Flow Measurements using Optical Mouse Chips (p.23)
- 10:05 – 10:35 Shih-Chii Liu – aVLSI Motion Detection Circuits (p.73)
- 10:35 – 11:00 --- Coffee break ---
- 11:00 – 11:30 Jacques Duparré – Artificial Compound Eye Imaging Systems by Micro-Optics Technology (p.29)
- 11:30 – 11:50 Christel-Loic Tisse – Hemispherical Depth Perception for Slow-Flyers using Coaxially Aligned Fisheye Cameras (p.123)
- 11:50 – 12:10 Jérôme Casas – Insect Flow Sensors as Templates for MEMS Design (p.19)
- 12:10 – 12:30 Daniel Osmont – Bio-Inspired Structures for the Actuation System of a Flapping Wing Micro Aerial Vehicle (p.85)
- 12:30 – 14:00 --- Lunch ---
- 14:00 – 14:30 Jean-Daniel Nicoud – Flying Paradise: Purgatory for Simulation, Hell for Engineers (p.81)
- 14:30 – 15:00 Robin Wootton – Springy Shells, Pliant Plates and Minimal Motors: Abstracting the Insect Thorax to Drive an MAV (p.129)
- 15:00 – 15:30 Poster spotlights:
- Andrew O. Philippides – Virtual Bee in a Virtual Tunnel: Modelling Angular Speed Detection (p.87)
- Rico Möckel – aVLSI Motion Detection Sensor for Estimation of Optical Flow (p.79)
- Lubin Kerhuel – Yaw Stabilization of an Aerial Robot: Visual Fixation and Ultrafast Vestibulo-ocular Reflex (p.59)
- Andreas Brückner – Compact Color Vision and Increased Sensitivity using Artificial Compound Eyes (p.17)
- Jan Bartussek – A Non-linear Oscillator Model for Control of Flapping Flight (p.7)
- Caroline Soyer – Silicon-based Biomimetic Flying Insect (p.111)
- 15:30 – 19:30 Coffee // Poster session // Hands-on workshops // Demonstrations // Discussion groups
- 19:30 – 21:00 --- Dinner ---
- 21:00 – 22:30 Hands-on workshops

Wednesday, August 15 – Control

- 07:00 – 09:00 --- *Breakfast* ---
- 09:00 – 09:45 Martin Egelhaaf – Active Vision: Strategies and Neuronal Mechanisms of Spatial Orientation Behaviour in Blowflies (p.31)
- 09:45 – 10:15 Steven Fry – Free-flight Control in Fruit Flies – A Systems Analysis Approach (p.39)
- 10:15 – 10:35 Nicola Rohrseitz – Visual Groundspeed Control in Free Flying Fruit Flies (p.99)
- 10:35 – 11:00 --- *Coffee break* ---
- 11:00 – 11:20 Jens Peter Lindemann – Cyberfly: Understanding Fly Flight Behaviour by Closed-loop Simulation (p.71)
- 11:20 – 11:40 Sergi Bermudez i Badia – The Origin and Role of Non-linearities in the Collision Avoidance System of the Locust (p.3)
- 11:40 – 12:00 James Humbert – Bio-Inspired Visuomotor Convergence (p.51)
- 12:00 – 12:30 Mandyam Srinivasan – Visual Guidance of Flight in Flying Insects: An Introductory Review and Summary of Recent Progress (p.113)
- 12:30 – 14:00 --- *Lunch* ---
- 14:00 – 14:20 Geoffrey Portelli – A Bee in the Corridor: Regulating Lateral OF by Side Control (p.91)
- 14:20 – 14:40 Andrew D. Straw – Control of Flight in a Simulated *Drosophila* Model: Successful Centering Depends on Actively Structuring Sensory Input (p.119)
- 14:40 – 15:15 Poster spotlights:
- Sawyer Fuller – Geometric Analysis of Hassenstein-Reichardt Elementary Motion Detectors and Application to Control in a Fruit Fly Simulator and a Robot (p.41)
- Vasco Medici – Principles of Multisensory Flight Control in the Fruit Fly – a Reverse Engineering Approach (p.77)
- Chauncey Graetzel – Analysis of Low-level Motor Control in Tethered Flying *Drosophila* (p.45)
- Emily Baird – A Theory of Ground Height Control in the Honeybee (p.5)
- Antoine Beyeler – Optic-flow-based Altitude and Forward Speed Regulation using Stereotypical Lateral Movements (p.11)
- Hala Rifai – Attitude Stabilization of a Flapping-wing Micro Drone (p.97)
- Finlay Stewart – Modelling Visuomotor Control in Flying *Drosophila* (p.117)
- 15:15 – 18:00 Coffee // Poster session // Hands-on workshops // Demonstrations // Discussion groups
- 19:00 – 20:00 --- *Aperitivo in musica* ---
- Cecilia Baccolo (piano) & Julien Zufferey (violin)*
- 20:00 – 22:30 --- *Social dinner* ---

Thursday, August 16 – Control (continued)

- 07:00 – 09:00 --- *Breakfast* ---
- 09:00 – 09:45 Simon Laughlin – Neuronal Efficiency: a Guiding Principle? (p.63)
- 09:45 – 10:05 Michael Reiser – An Algorithmic Basis for the Visually Mediated Control of Translatory Flight by *Drosophila* (p.95)
- 10:05 – 10:35 Fritz-Olaf Lehmann – The Limits of the Visuo-motor System in Flying Fruit Flies *Drosophila* (p.65)
- 10:35 – 11:00 --- *Coffee break* ---
- 11:00 – 11:20 Bart Baddeley – A Probabilistic Framework for the Study of Active Acquisition of Visual Information in Bees (p.1)
- 11:20 – 11:40 Jochen Zeil – Stealthy Tracking in Satellite Flies (p.131)
- 11:40 – 12:00 Yoon Sik Shim – A Simple Evolutionary Framework for Generating Robust Flight Maneuver in a Physically Simulated Flapping Wing Robot (p.109)
- 12:00 – 12:20 Dario Floreano – Evolutionary Swarms of Flying Robots (p.35)
- 12:20 – 14:00 --- *Lunch* ---
- 14:00 – 14:30 Poster spotlights:
- Rick Cory – On the Controllability of Agile Fixed-Wing Flight (p.21)
- Wolfgang Stuerzl – View-Reconstruction and Visual Homing in Ground-Nesting Wasps (p.121)
- Severin Leven – A Simple and Robust Fixed-Wing Platform for Outdoor Flying Robot Experiments (p.69)
- Sabine Hauert – Pheromone Based Swarming for Positionless MAVs (p.49)
- Allister Furey – Robust Control of Tethered Airfoils Using Evolutionary Robotics (p.43)
- 14:30 – 17:00 Coffee // Poster session // Hands-on workshops // Demonstrations // Discussion groups
- 17:00 – 19:30 Public event: demos brought by the participants and resulting from the hands-on workshops
- 19:30 – 21:00 --- *Dinner* ---

Friday, August 17 – Systems

- 07:00 – 09:00 --- Breakfast ---
- 09:00 – 09:45 Nicolas Franceschini – Insects as Pilots: Optic Flow Regulation for Vertical and Horizontal Guidance (p.37)
- 09:45 – 10:05 William Green – A Hybrid MAV and Biomimetic Sensing for Ingress and Egress of Urban Environments (p.47)
- 10:05 – 10:25 André Noth – Design of Solar Powered MAVs: Scaling Considerations and Realization (p.83)
- 10:25 – 10:50 --- Coffee break ---
- 10:50 – 11:10 Jean-Christophe Zufferey – Insect-inspired Autonomous Microflyer (p.133)
- 11:10 – 11:40 Barbara Webb – An Insect Brain Architecture for Robotics (p.127)
- 11:40 – 12:00 Wrap up
- 12:00 – 13:30 --- Lunch ---
- 13:30 – 17:40 Excursion:
- 13:30 Departure by foot from Monte Verità
 - 14:00 Arrival at the port in Ascona, ticket hand-out and departure by boat
 - 14:30 Arrival at Brissago Islands, guided visit of the botanical garden
 - 15:45 Free time for coffee, shopping etc.
 - 16:35 Departure by boat from the Islands
 - 17:20 Arrival at Ascona port
 - 17:30 Return by mini-bus to Monte Verità
 - 17:40 Arrival at Monte Verità
- 17:40 – ... --- Departures ---
- 19:30 – 21:00 --- Dinner (for those leaving on Saturday) ---

Saturday, August 18

- 07:00 – 09:00 --- Breakfast (for those leaving on Saturday) ---
- 09:00 – 12:00 --- Departures ---

A Probabilistic Framework for the Study of Active Acquisition of Visual Information in Bees

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When bees and wasps leave the nest to forage, they perform orientation or learning flights [1]. This behaviour includes stereotyped flight manoeuvres which could mediate the active acquisition of visual information by, for instance, reducing variation in movement and producing strong motion parallax. Assuming that bees or wasps are attempting to localise themselves in the world with reference to stable visual landmarks, the orientation flight can be modelled as a probabilistic Simultaneous Localisation And Mapping (SLAM) problem [2].

SLAM works by incrementally building a map of environment features using noisy measurements and a stochastic model of the agent-environment interaction. The explicit dependence of localisation performance on movement and sensor models means that SLAM provides an opportunity to explore how the details of the orientation flight affect visual learning. Considering the problem from a bee's perspective, many of the aspects controlling sensor accuracy are fixed. The accuracy of the movement model is not fixed however, and will vary according to the flying conditions and the flight manoeuvres being executed. It is plausible that the stereotypical dynamics of the orientation flight make movements easier to predict, and thus affect the insect's ability to localise itself efficiently.

For our initial investigation we implemented SLAM using a simulated agent with compound eyes (i.e. input from multiple panoramic noisy low acuity sensors) in a simple 3D environment. To investigate the effect of reliable movements we have developed a movement model for orientation flights inspired by the characterisation of orientation flights as a series of arcs at different radial distances centred on the nest [3]. In our simulation the agent flies a fixed distance from the nest before attempting to return to it. A single visual landmark is assumed to be visible whenever the agent is both facing it and it is within a fixed distance. To simulate an orientation flight we include an initial phase where the agent is assumed to fixate the landmark for a number of time steps. We show that reducing the noise in the motor output during the orientation phase (thereby making it easier to predict the sensory consequences) for even a short period, allows the agent to localise itself efficiently relative to a visual landmark and to re-orient whenever the landmark comes back into view (Fig. 1 bottom). In contrast, without this initial grounding the agent is lost (Fig. 1 top). Thus, once the agent learns the relationships between landmarks and nest, the

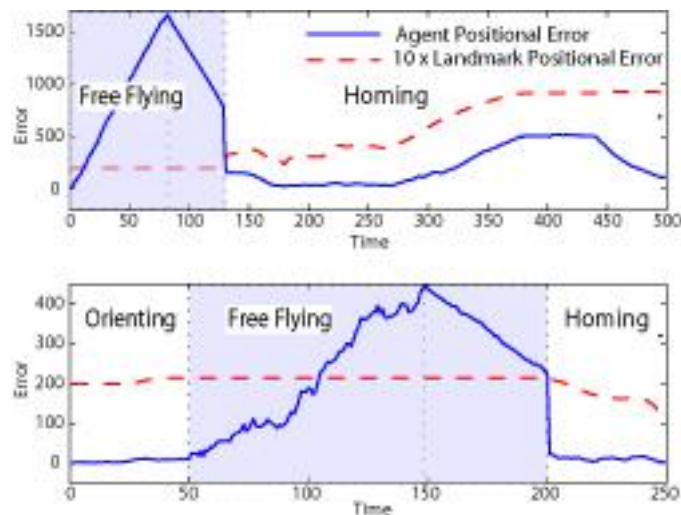


Figure 1. Positional errors of a simulated agent with (bottom) and without (top) an orientation flight

information is fixed and the accuracy of the movement model can be relaxed without uncertainty in the positional estimate rapidly increasing.

Our second investigation applies our framework to the investigation of the structure of real orientation flights. Bees were recorded leaving an inconspicuous nest hole near a conspicuous landmark. As previously reported [e.g. 1], the initial flights consisted of a series of arcs around nest and landmark of increasing distance (Philippides et al., unpublished data). However, it is unclear how the structure of the flight is useful in learning the nest position. To analyse this, we use a simulated agent following the recorded paths. By placing fictive landmarks at various positions throughout the environment, we are able to determine how useful the recorded movements would be in learning about landmarks in each of those positions. Preliminary data show that learning is most effective in the region that contained the real landmark (Fig. 2). This suggests that the orientation flight is structured to extract positional information about landmarks within this region.

We have demonstrated the utility of our approach for investigating orientation flights. Future work is to evolve controllers and employ information theoretic approaches to determine optimal flight paths for comparison with biological data.

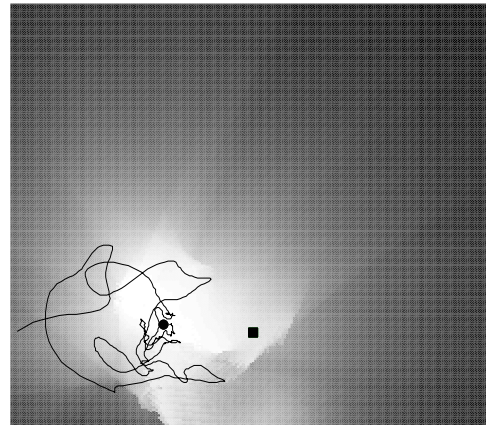


Figure 2. Localisation performance for an agent following the path of a bee performing a learning flight (black line). Filled circle and square indicate the positions of nest and landmark respectively when the orientation flight was recorded. Learning is best (white) in the region around the nest and extending towards the actual position of the landmark.

References

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The Origin and Role of non-Linearities in the Collision Avoidance System of the Locust

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From a theoretical perspective it appears advantageous for single neurons to be able to perform non-linear operations beyond simple thresholding. Indeed, multiplication operations are a key component of several current models of motion processing and stimulus identification in both vertebrates and invertebrates. A particular case in point is the Lobula Giant Movement Detector (LGMD) neuron of the locust, which has recently been reported to locally perform a functional multiplication of its inputs [1]. Here we evaluate an alternative model where the non-linear relationships between input stimuli and neuronal responses [2,3] emerge out of the interactions of many “simple” neurons in a processing structure. A direct empirical validation of this hypothesis is currently, however, impractical since it requires simultaneous measurements from large numbers of neurons. Hence, to assess the validity of the “emergent non-linearity” hypothesis we use a computational approach. We have simulated the processing hierarchy of the locust visual pathway, including its ommatidia, lobula, medulla, LGMD and the Descending Contra-lateral Movement Detector (DCMD) (figure 1).

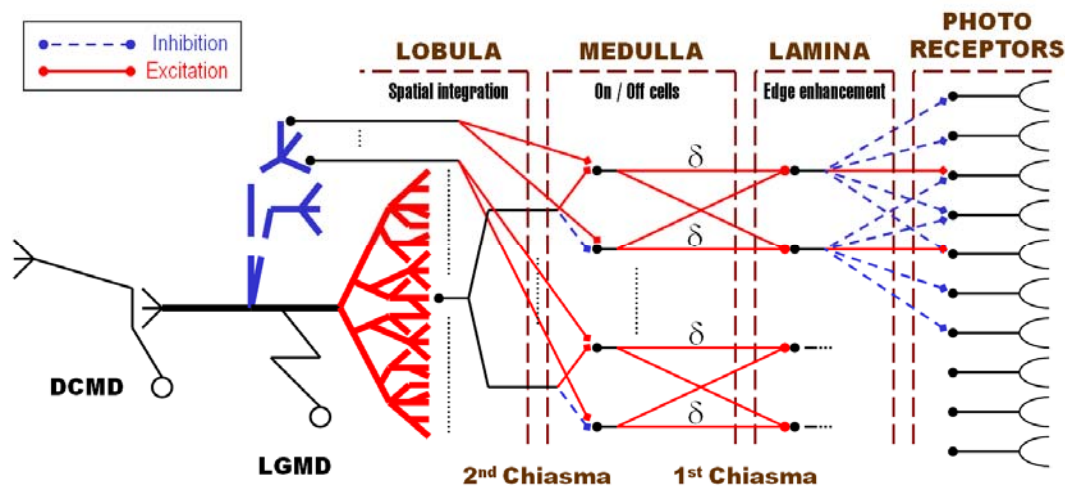


Figure 1. Schema of the LGMD model including the key layers of the locust visual system it models and their functional role. Red: excitation. Blue: inhibition. Delta: delay.

By exposing this model to the standard LGMD stimulation protocols, we show that all properties of the LGMD neuron that have been seen as resulting from a local non-linear operation, can be explained as emerging from the dynamics of the network. Moreover, we demonstrate that these emergent non-linear operations strongly depend on the details of the synaptic organization of the projections from the on-off cells of the medulla to the LGMD. Using our model we generate a number of predictions that can be validated with standard experimental techniques. , to assess the real-world properties of our model we have applied it to a high-speed mobile robot that approximates the 2-dimensional flight dynamics of the locust (figure 2). We combined our LGMD model with a previously developed insect based course

stabilization model [4], and we show that our model is able to reliably stabilize the movement trajectory of the robot and supports collision avoidance in a manner consistent with the behavior of the locust. These behavioral experiments suggest that the exponential relationship between the angular size of an approaching object and the firing rate observed in the LGMD enhances the system's collision detection acuity.

In summary, our model provides an alternative explanation for the putative local non-linear integration properties of the LGMD that defines them as emerging from the visual processing system as a whole. Moreover, our behavioral experiments show that these emergent non-linear responses are optimally tuned with respect to the collision detection and avoidance behavior of the system.

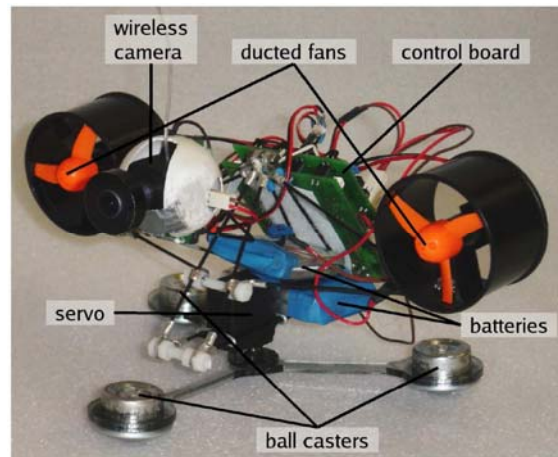


Figure 2. The Strider is about 16 cm, long and it is equipped with three passive wheels. The lift-strength of one ducted fan is 30g, allowing the robot to move at a maximum speed of about 3 m/s. This robot offers an abstraction of a flying robot in terms of inertia and maneuverability, with the advantage of a low deployment cost.

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A Theory of Ground Height Control in the Honeybee

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To achieve stable flight, honeybees must regulate both their ground speed and their ground height in a reliable way. Research shows that insects such as fruit flies and honeybees regulate their ground speed by holding constant the speed at which the image of the environment moves across the eye during flight (optic flow) [1, 2, 3]. In contrast, the mechanisms by which flying insects control their ground height are not well understood. A recent investigation [4] provided the first direct evidence that optic flow cues play an important role in ground height control in the honeybee. However, little is known about how honeybees use these visual cues to obtain information about their height above the ground.

A series of experiments, designed to explore the mechanisms used by honeybees to control ground height, were carried out in both indoor and outdoor flight tunnels, in still air and in wind. The results reveal that ground height control is affected when ventral optic flow cues perpendicular to the mean direction of flight (lateral optic flow cues) are removed from the visual texture. In contrast, the regulation of ground height appears to be unaffected when ventral optic flow cues parallel to the mean direction of flight (axial optic flow cues) are removed. These results suggest that lateral optic flow cues are important for ground height control in the honeybee.

Detailed analyses of flight trajectories under a variety of experimental conditions reveal that honeybees generate uniform changes in the direction of flight that is perpendicular to the mean direction of flight (i.e. lateral position) whilst maintaining

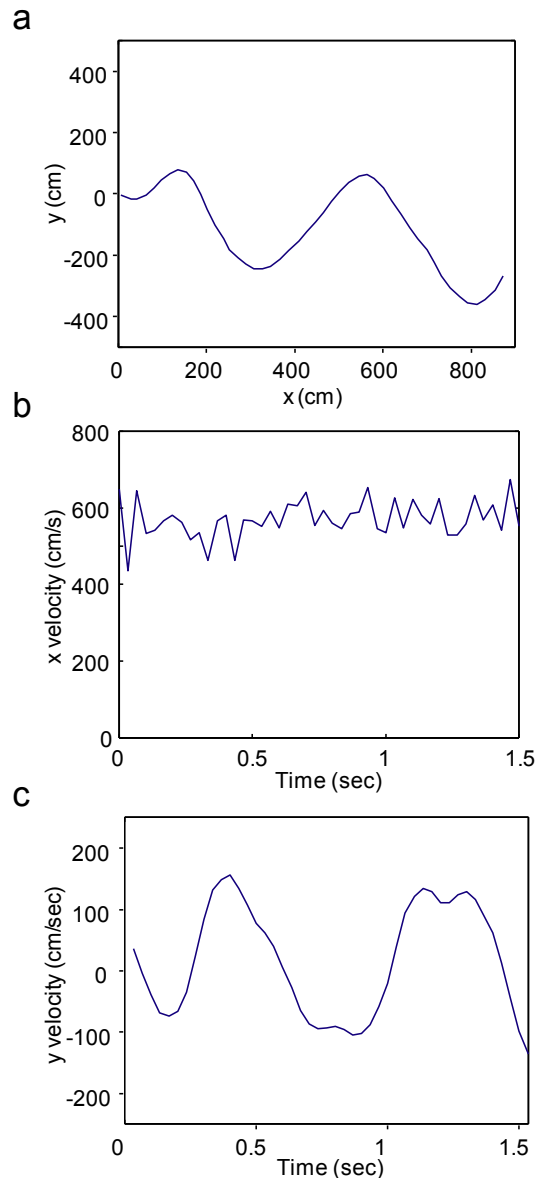


Figure 1. The flight trajectory of a honeybee

- a) The x (direction of forward flight) position and y (lateral) position.
- b) The x (forward) velocity over time
- c) The y (lateral) velocity over time

constant forward speed (for an example, see Figure 1). Analyses of the lateral component of flight indicate that these near sinusoidal oscillations in lateral velocity occur at a consistent frequency and with constant amplitude, despite variations in ground speed and ground height. Moreover, these oscillations appear to be robust to changes in visual texture in both the lateral and ventral visual fields, suggesting that they are being driven by an open-loop motor command which is regulated independently from the visual system.

Regular lateral displacements during flight, such as the ones observed in this study, would generate regular changes in the angular velocity of the lateral component of optic flow in the ventral visual field. Because the angular velocity generated by a surface varies with the distance at which it is being viewed (for a detailed discussion see [5]), a decrease in the overall magnitude of lateral optic flow would therefore indicate an increase in ground height and vice versa, thereby providing information about changes in the distance to the ground. It is hypothesized here that honeybees measure or control the lateral component of optic flow that is generated by regular, non-visually mediated changes in lateral velocity to obtain absolute or relative information about their ground height.

The finding that honeybees control ground height by utilising lateral optic flow cues, in conjunction with the observation that changes in lateral position are consistent and robust to changes in visual texture, indicates that honeybees employ a computationally simple technique of estimating ground height from changes in lateral optic flow in the ventral visual field by changing their lateral position in a regular way. The method of ground height control that is hypothesised here has important implications not only for understanding how a simple brain can extract and apply information from the visual scene for the purposes of flight control, but also for understanding how these tasks can be achieved in autonomous flying vehicles.

References

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A Non-linear Oscillator Model for Control of Flapping Flight

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Flies represent an important model system for the design of flying micro vehicles [1].

The flight muscles of flies are functionally divided into power and control muscles. The stretch-activated power muscles provide flight power from a fast actuation of the wings (~200Hz) [2]. Conversely, the control muscles achieve subtle control of wing motion for flight stabilization and maneuvering, which depends on phase coupled mechosensory input from the halteres and wings. We stimulate the halteres with phase coupled actuation of the fly body [3] and

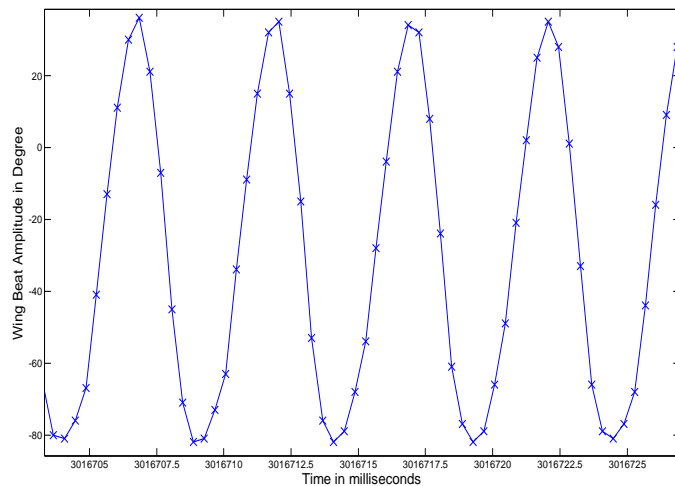


Figure 1. Time resolved wing position raw data

measure the resulting changes in wing movements using a high speed (3kHz), real time vision system. Our setup allows naturalistic stimulation mimicking the Coriolis forces generated during turning maneuvers, as well as artificial stimulus patterns to be delivered. Preliminary results show that mechanosensory feedback may be crucial to maintain phase coherence of the oscillating wings.

Cyclic kinematic patterns can be effectively described with non-linear oscillators [4]. We model the activity of the fly's power muscles as a non-linear oscillator, which is coupled with two linear sub-systems that simulate the wing mechanics [5]. A flight maneuver such as turning is described as a transient desynchronization of the left and right linear subsystems, which is initiated by a perturbation to one (or both) of them done through the control muscles.

References

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- [2] Dickinson, M. (2006) Insect flight, *Curr Biol*, 16: 309-314
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Aerodynamic Optimization, Dynamic Modeling and Overall Prototype Design for the muFly Autonomous Micro-Helicopter

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MuFly is a European framework project comprised of six partners in Europe, one of them being the Autonomous Systems Lab at ETH Zurich. The project has been launched in 2006 and aspires the design and realization of a fully autonomous micro-helicopter comparable to a small bird in size and mass. This corresponds to a mass of approximately 30g and a maximal dimension of 10cm.

The challenges faced in the design of a system in this range of specifications are various [1], the most important are: the low efficiency of the propulsion system due to the low Reynold's number regime; the requirement for too much processing power and high resolution sensors for stabilization and navigation algorithms, the low capacity of current energy storage devices and the lack of powerful methodologies for system level integration. Goal of the ongoing work at ASL is to alleviate the effects of these challenges and find optimal solutions for the restricted target specifications.

In the field of aerodynamics, the goal is to enhance the propeller efficiency by optimization with respect to the tip shape, chord length and blade pitch. Quasi-3D-simulations (using Blade Element Momentum Theory) are performed to predict the thrust force and drag moment of a certain blade design in coaxial rotor arrangement. However the model needs to be validated by experiments to ensure that the optimization based on the simulation model is realistic. Very few experimental data is available from literature [2], thus a test-bench with respective sensors has been designed and built for the testing different blade profiles. With this optimization strategy, the best suited parameter combination will be identified towards a more efficient rotor system at a low Reynold's number.

In parallel to this, a dynamic model of the micro-helicopter has been developed in order to simulate the rigid body dynamics of the system [3]. The special interest within this task lies in the stability behavior of the system with regard to certain design parameters, such as the distance between the two rotors, their position with respect to the center of mass or the dimensioning of the stabilizer bar used on the upper rotor for passive stabilization [4]. Designing the helicopter as a passively stable system is desirable in terms of energy as well as computational efficiency: the less the controller and the respective actuators have to act for keeping the helicopter in a stable pose, the less energy is consumed, which results in higher flight endurance.



Figure 1. Rotor blade test bench.

Finally, a CAD design model for the first prototype of muFly is proposed. Despite the fact, that a coaxial rotor setup is used, utilization of a gearbox and concentric drive shafts can be avoided. This is due to the fact that the motors with the respective propellers are mounted on a cage-like structure, at opposite ends. As a result system mass and mechanical complexity can be reduced, while the cage serves as a structural component as well as a mean of protection for and from the propellers. For directional authority, center of mass displacement systems similar to [5] and [6] were considered, but eventually discarded in favor of a conventional swash plate mechanism engaged by piezoelectric linear actuators. As can be seen in the design, all necessary sensors as well as energy supply and main processing board are accommodated in a pod structure attached under the cage. With this design, the objective of a compact and lightweight helicopter having the required sensor and processing capabilities for fully autonomous flight on board is achieved.

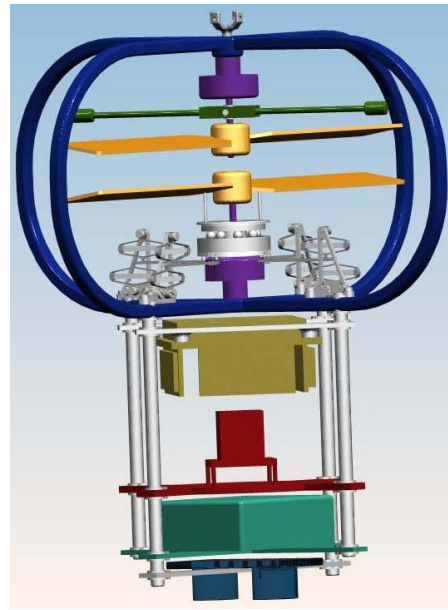


Figure 2. Prototype 1 design of muFly.

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Optic-flow-based Altitude and Forward Speed Regulation using Stereotypical Lateral Movements

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Biologists have shown that navigation in flying insects is based primarily on optic flow cues [1, 2]. This strategy has inspired control mechanisms of several flying robots, in particular for forward speed regulation and altitude control [3-6].

The flight control strategy thought to be used by insects and commonly implemented in robots is based on the longitudinal ventral optic flow (i.e. the component of optic flow perceived below the agent that is parallel to the general direction of flight, see figure 1) [5-7]. It has been shown that holding this component of optic flow constant allows sustained flight and ground obstacle avoidance [6]. However, this strategy does not allow

independent regulation of altitude and forward flight speed. Since longitudinal optic flow cues are proportional to forward speed and inversely proportional to altitude, any perturbation (e.g. wind) on one component of flight will translate into a change in the other.

We propose here a novel flight control strategy (illustrated in figure 1) to cope with the ambiguity of altitude and forward speed regulation. This is achieved using a stereotyped lateral oscillation that generates transversal ventral optic flow (i.e. component of ventral optic flow perpendicular to the general direction of flight), which can be used to regulate altitude independently from forward speed. Specifically, the amplitude of *transversal* ventral optic flow is held constant by controlling thrust, to regulate altitude, while *longitudinal* ventral optic flow is maintained constant by controlling pitch, to regulate forward speed.

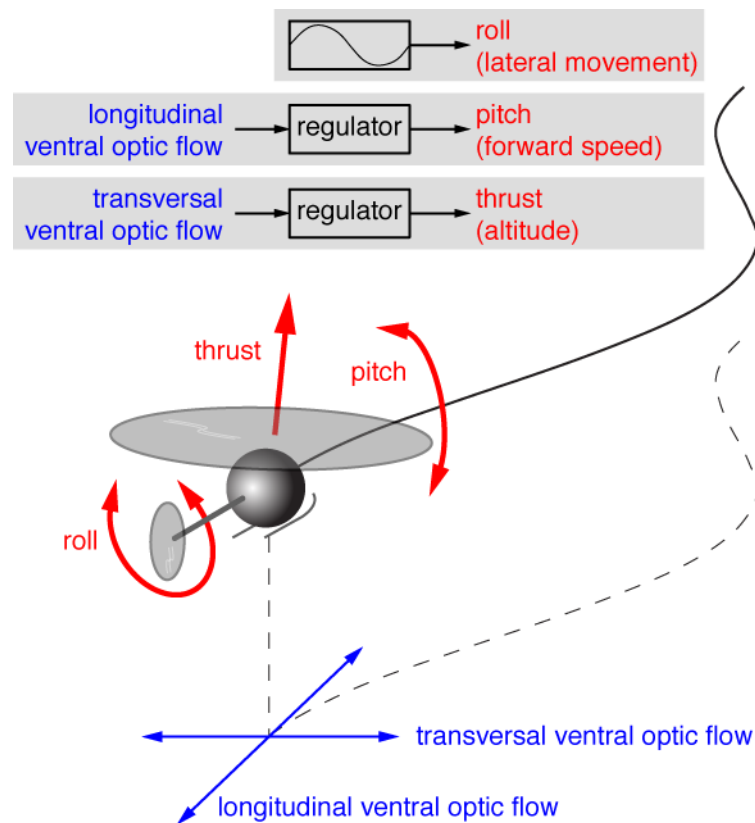


Figure 1. Illustration of the flight controller for the flying agent. Stereotyped roll control induces oscillatory lateral movements that generate transversal ventral optic flow, which is in turn used to control thrust (altitude regulation). Longitudinal ventral optic flow is used to control pitch (forward speed regulation). Note that the direction of thrust is fixed with respect to the body of the agent.

We assess this new control scheme using a simulated agent with dynamics similar to that of insects and helicopters [8, 9] and show that altitude and forward speed can effectively be regulated independently. Furthermore, by modulating the stereotypical lateral behaviour using transversal ventral optic flow, we show that roll perturbations can be rejected, effectively achieving roll stabilisation.

Interestingly, the final behaviour shares many similarities with honeybees – especially in term of oscillating trajectories – as recently recorded by Baird and Boeddeker (at the Australian National University, unpublished data). Therefore, this result paves the way toward both novel approaches in flying robot control and formulation of biological hypotheses about the mechanisms underlying insect flight.

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MuFly Project: The First Steps

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Flying objects have always exerted a great fascination on man encouraging all kinds of research and development. Despite all the impressive progress in micro/nano and information technology, and all the interest of the scientific community in the Micro Aerial Vehicles (MAV), fully autonomous micro-helicopters of the size of a small bird are still not available.

Nevertheless, few research groups have tackled this problem. The Mesicopter group at Stanford University [1] studied the feasibility of a centimeter scale quadrotor. The group of Prof. Nonami at Chiba University [2] achieved a 13g semi-autonomous coaxial helicopter able to fly three minutes. Unfortunately, none of these developments combines reasonable endurance and autonomous navigation in narrow environments.



Figure 1. Artist's view of the muFly helicopter.

The European project muFly [3] was born in this context in July 2006; it targets the development and implementation of a fully autonomous micro-helicopter, with a span of 10cm and a mass of 30g. The consortium is composed of six partners; each one will provide a subsystem of the entire helicopter. The project shall demonstrate innovative approaches and technologies in: (1) system level design and optimization, (2) design of miniature inertial units and omnidirectional vision sensors, (3) miniaturized fuel-cells, (4) micro piezoelectric actuators and (5) low processing power control and navigation algorithms. The final system is expected to find applications in rescue missions and surveillance of buildings.

The configuration selection for muFly became clear after a comparative study. The evaluation of 11 criteria with different weights showed that the coaxial rotor concept is the most suited for this project. This configuration is not only compact, but also easier to design and control [6].

The requirements of the steering and stabilization functions strongly limit the possible solutions, which furthermore have to be compatible with the technologies available in the consortium. Nevertheless, the first design of muFly comprises a stabilizer bar on the upper rotor and a simplified swash plate on the lower one based on an innovative piezoelectric linear actuator. The idea is to have a hybrid, passive/active attitude stabilization system. This solution is not only attractive for its endurance to energy-consumption ratio, but also interesting as a dynamics and control problem.

The muFly helicopter will have an ultrasonic altitude sensor, an Inertial Measurement Unit and an Omnicam with a polar-radial arrangement of pixels. The latter is combined with a four laser lines generator and used as a 360° laser range finder. This will reduce drastically the processing power needed for navigation and obstacle avoidance, while increasing the perception reliability. The two cores of the muFly

processor will provide enough processing power for range data extraction, sensor fusion, control, obstacle avoidance and navigation at low power (400mW@ 2000 MMACs). All the power supply will be provided by a Lithium-Polymer battery for the first prototype, while a micro fuel cell is in preparation for the second one.

The low Reynolds number regime is one of the main challenges facing the development of mission level MAVs [4]. Thus, for muFly an important effort is invested in enhancing the propellers' efficiency and thus getting maximum lift out of the injected power. For this, a simulation tool based on blade element momentum theory was developed and is under validation on a dedicated test-bench. The aim is to optimize parameters of the propeller, like shape, angle and twist and analyze aspects like surface state, tip shape and leading edge sharpness by CFD simulation [5].

In the field of modeling and control, a full dynamic model is in preparation. It includes the models of the sensors, actuators, propellers, stabilizer bar and battery. This model is foreseen for stability analysis, multidisciplinary design optimization and control design.

The next steps are clearly defined as continuing the design of the first prototype, finishing the dynamic modeling, validating the first control algorithms on a dedicated vehicle test-bench and only after that, release the bird for a first flight.

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A Flapping Hovering Micro Air Vehicle

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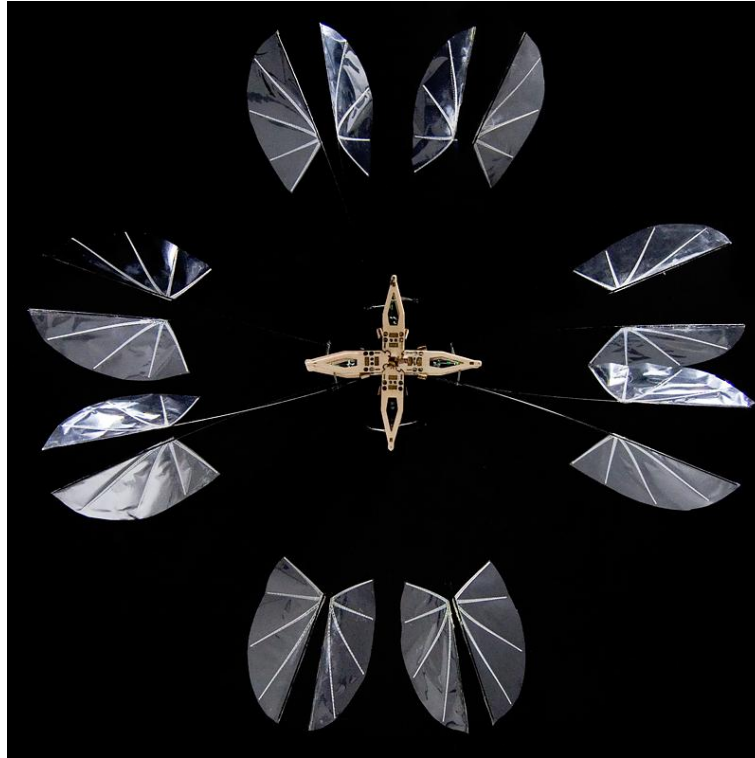


Figure 1. Strobe image of flapping hovering micro air vehicle. For each pair of wings two stages of the stroke are shown, the clap (outer pair), and the fling (inner pair). Wing pitch is passively controlled by aeroelastic effects.

Many insects and some birds can hover in place using flapping wing motion. Although this ability is key to making small scale aircraft, flapping hovering behavior has been difficult to reproduce artificially due to the challenging stability, power, and aeroelastic phenomena involved. Although a number of ornithopters have been demonstrated [1],[2],[3] (some even as toys [4],[5],[6]), these designs cannot hover in place because lift is maintained through airfoils that require forward motion. Following Delaurie et al. [7] seminal demonstration of a ~400g hoverer, a key challenge [8],[9] is to demonstrate untethered flapping hovering ability at a weight and power approximating that of insects and birds where flapping hovering flight is observed in nature[10].

In this talk we will demonstrate a passively-stable 18g machine capable of sustained flapping hovering flight at a Reynolds number similar to insects ($Re=8 \times 10^3$). The device uses the clap-fling effect observed in many insects [11],[12],[13][14], in addition to wing beam resonance to maximize lift. Using four pairs of wings, running at 6V and 20Hz, it can generate sufficient lift for an 8g (>50%) payload. The need for secondary actuators to control wing pitch are eliminated through the use of passive

aeroelastic wing bending (figure 1). Stable flight is achieved through a passive stabilization system comprised of two sails and a lowered center of mass. Stability was verified throughout all launch angles, including upside-down, zero velocity initial conditions.

The reduction of over an order of magnitude in weight and power was achieved by eliminating the need for active stabilization and by exploiting natural resonant frequency of the wings. This architecture may help in the design of insect-sized hovering vehicles, and shed light on the aeroelastic dynamic principles underlying insect flight.

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Compact Color Vision and Increased Sensitivity using Artificial Compound Eyes

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Advances of ultra-thin cameras inspired by the neural superposition eye

The investigation of the principles of insect vision has recently led to the fabrication of artificial compound eye cameras which allow a further miniaturization of imaging systems compared to those using single aperture objectives [1]. Artificial apposition compound eyes combine the potential for a large field-of-view (FOV) with a small volume and low weight which is crucial e.g. for flying robots. Unfortunately, they exhibit a low spatial resolution and a sensitivity that is inversely related to the same [2].

As the same physics apply to the natural archetype, we might ask: Why have the smallest known optical sensors been evolutionary successful for about 350 million years in nature? One answer to this question is found in the first synaptic layers of the eye of a fly. Cross-linking of receptors in such a neural superposition eye is a way to information pooling and parallel signal processing which enables an effectively higher resolution for motion or optical flow, contrast enhancement or increased sensitivity [3,4,5].

Inspired by the neural superposition eye of insects, we demonstrate some advanced features of ultra-thin camera devices which increase the attractiveness for specific applications in fields like object tracking, surveillance as well as autonomous and machine vision.

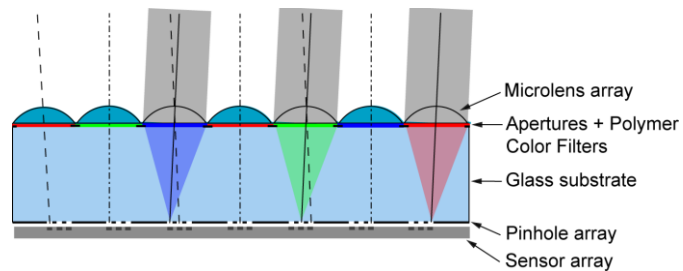


Figure 1. Layout of the artificial neural superposition eye with additional polymer color filters to acquire color images. Each direction is imaged through a blue, green and red color filter in different channels.

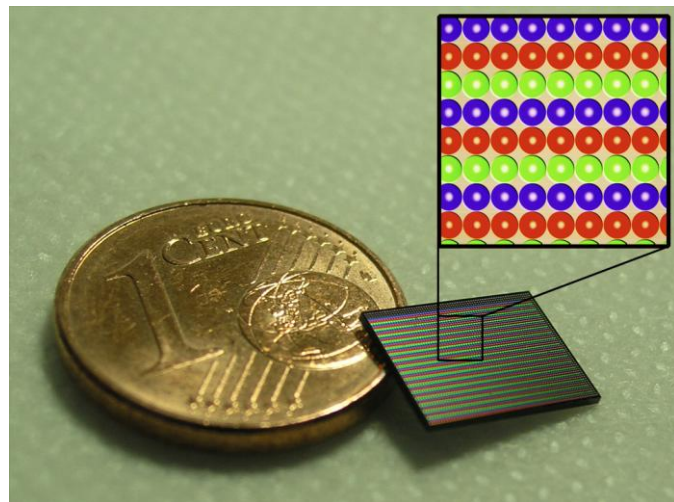


Figure 2. The artificial neural superposition eye objective (large view) with color filter array integrated in the microlens array (black box).

We propose an optical setup according to Figure 1 where multiple pixels are extracted in each channel.

The optical axes of certain pixels are parallel so that one

object point can be sampled by several channels. This multiple sampling enables spatially resolved polarization or color imaging using filter arrays (shown in Figure 1).

Without filters it can be used to increase the sensitivity and also the signal-to-noise ratio of the image.

The optical design, micro-optical fabrication techniques (Figure 2) and performance characteristics of example systems are demonstrated (Figure 3).



Figure 3. Images acquired with the ultra-thin color camera. From left to right: color chart, the principle author, "Image Processing Lena", color mixing circle. The image resolution is 52x43 pixels.

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Insect Flow Sensors as Templates for MEMS Design

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Crickets, as many other insects, possess some of the most exquisite hairs to sense the air flow produced by approaching predators [1]. In this talk, we first describe the functioning of the real and the bionic hairs (Figure 1) [2]. In order to gain some understanding of the flow experienced by hairs, we describe longitudinal and transversal flows around the cerci, two appendages at the rear of the animal and bearing the hairs. We compare the observed flow using PIV with existing theories [3]. The question of hydrodynamical hair to hair interaction becomes central to the biomimetic design of MEMS arrangements on an artificial cercus. We therefore go back to the crickets to analyze the hair positions on cerci [4]. We end up the talk with our latest results on micro PIV for characterizing flow around single bionic hairs.

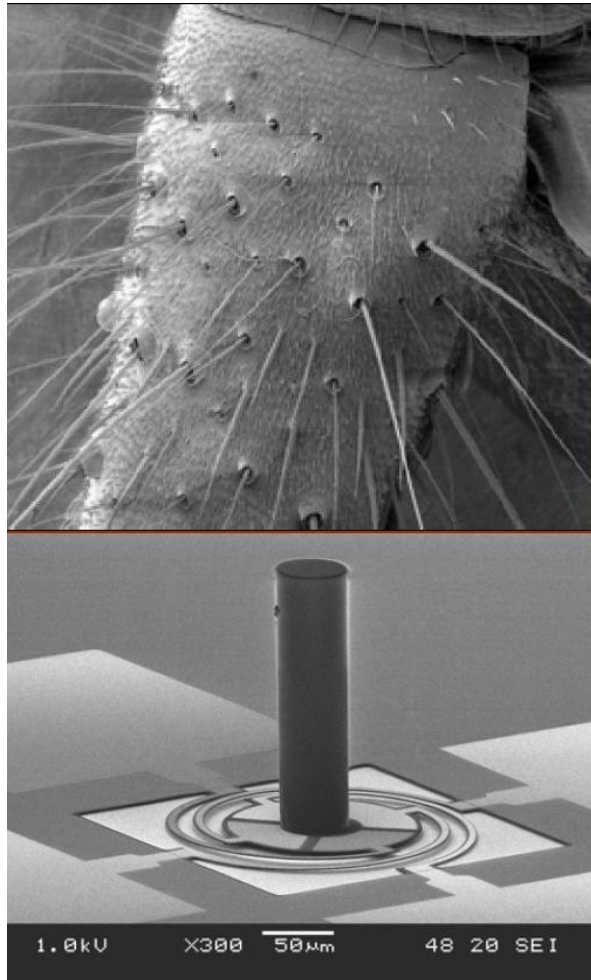


Figure 1. Cricket hairs on a cercus and a bionic hair.

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On the Controllability of Agile Fixed-Wing Flight

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Introduction

Over the past few years, there have been a number of impressive demonstrations of UAV aerobatic flight (e.g. [1]). However, the maneuverability of these UAVs is no match for a human piloted aircraft, where the pilot is capable of executing extreme aerobatic maneuvers and quick recoveries in spite of turbulent airflows. We believe that maneuverable flight can be characterized by the need to maintain energy-efficient and time-dependent interactions with the surrounding airflow, a characteristic we believe can be formulated as an optimal control problem. To this end, we have begun an intensive research project in system identification, controllability analysis, and optimal control for a fixed-wing hovering aircraft (Fig 1). This abstract describes preliminary results on a practical implementation of a linear controller on a real aircraft and extensions to optimal control for a learned linear dynamic model in simulation.



Figure 1.

Autonomous Hover

Stabilizing a Hovering UAV

We have begun with an investigation into the controllability of our plane in a Vicon MX motion capture environment during vertical hover. The motion capture environment provides real-time sub-millimeter tracking of the plane along with its control surface deflections and has provided a convenient and non-obtrusive way of collecting flight data for system identification. Our initial task was to regulate the orientation of the aircraft to a vertical hovering state. Orientation control is trivial, and can be regulated through simple P.D. control on the orientation error. We were interested in testing the basin of attraction of this simple controller and performed a

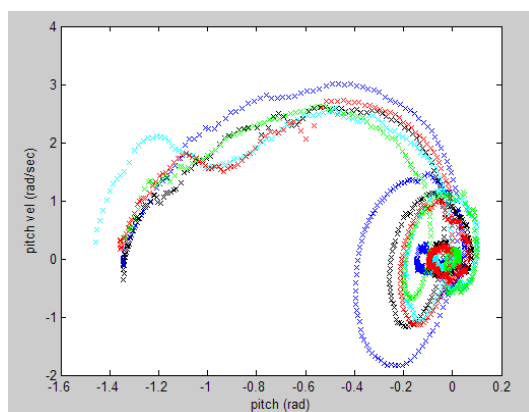


Figure 1.

Samples of pitch basin of attraction

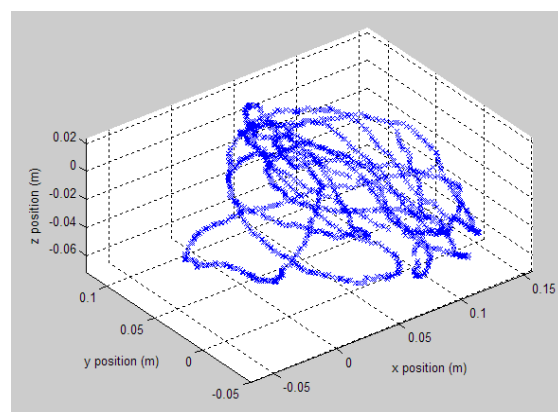


Figure 2.

P.D. control position trajectory

few trials of the plane starting from horizontal (i.e. normal flight orientation) and were surprised to find the robustness of this simple controller away from the linearization point. Fig. 1 shows five samples of the basin of attraction (for pitch) starting from horizontal. However, as shown in Fig. 2, the noisy environment in combination with

suboptimal gains makes the plane drift away from its initial state in (x,y) coordinates during hover. The regulation of these state variables becomes non-trivial due to the fact that we are completely underactuated in these degrees of freedom. Our goal is then to learn a dynamic model of the plane such that we can control all state variables using linear optimal control.

Controllability Analysis and Optimal Control

Since we are simultaneously trying to regulate orientation as well as absolute position, the task becomes non-trivial. Namely, for a given desired orientation and position (e.g. in an aerobatic maneuver), the required control surface deflections will differ and will depend on the aircraft's control derivatives. We fit a linear state-space model of our aircraft by logging motion capture data of the orientations, positions, and control surface deflections (Fig. 3). Using the learned model, we computed an optimal linear controller for the regulation task (LQR). The task was to regulate all states to zero from an arbitrarily chosen state ($x=1, y=1, z=1$, roll=.1, pitch=.1, yaw=.1 ; units in meters and radians).

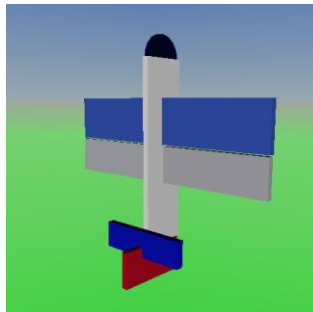


Figure 3.

Simulator using learned dynamics

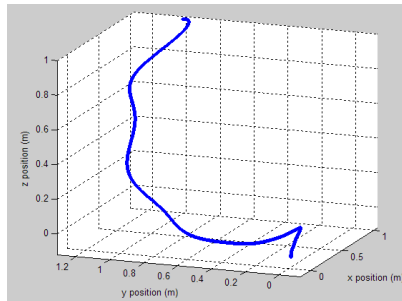


Figure 4.

LQR position trajectory

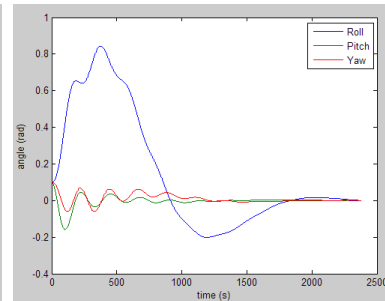


Figure 5.

LQR orientation trajectory

Fig. 4 shows the position path and Fig. 5 shows the Euler angle orientation trajectories. Currently, we are performing statistical tests for error bounding our dynamic model. A controllability analysis on our currently learned model shows that it is full-state controllable. Once this analysis is complete and we are confident in our model, we will transfer our control system to the real plane.

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Insect Inspired Odometry by Flow Measurements using Optical Mouse Chips

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Introduction

Inspired by research on the waterstrider visual system we investigated precision limits for the estimation of self motion parameters from optic flow [1]. The result was that ego motion parameters can be extracted from flow to a surprisingly high precision if flow can be observed in image patches of opposite visual angle distributed over a large solid angle. Under these conditions only a few properly combined flow observations are necessary.

Since optical mouse chips are available we have cheap (2.5 €), light (0.5 g) and fast (response < 1msec) flow detectors at our hands. Here we present a hardware realization of an odometer driven solely by flow measurements in a few directions in space.

The device

The device (Figure. 1) contains eight optical mouse sensors (ADNS-2620, Avago) each provided with an adjustable plastic collimator lens (CAY045 Philips) of $f = 4.6$ mm focal length which images the environment onto the light sensitive area of the sensor. The mouse sensors sample the light intensity on their 1x1 mm array of 18x18 light sensitive diodes about 1500 times/sec. The focal length of the lens and the size of the diode array determine the angular size of the visual field of the sensors ($12.4^\circ \times 12.4^\circ$). A fast on-chip digital signal processor (DSP) correlates the patterns of two consecutive samplings and evaluates the displacement between them. In order to avoid too large displacements between two images the maximum allowed speed of the pattern on the chip's light sensitive surface is specified to 30 cm/sec. This limits the maximum rotation speed of the sensors to $(300 \times 180 / \pi) / f$ [°/sec] (i.e. 3737 [°/sec]). When the viewing distance to ground is D [cm] the maximum translational speed is $(300/f) \times D = 65.22 D$ [cm/sec] (i.e. about 980 [cm/sec] for our odometer model ($D \approx 15$ cm)).

Via two serial lines to each sensor a microprocessor (MP) (CY7C68013A-56P, Cypress) reads information continuously from all sensors in parallel. The information consists of three bytes : dY, dX, SQ in that order. dY, dX are the pattern displacements along each sensor's Y/X axis since the last reading, SQ is a 'quality' byte which indicates the 'number of features' detected in the sensor image while correlating. If SQ undergoes a selectable threshold dY, dX may be discarded. The MP is connected via USB to a PC. Reading the information from all sensors (strictly in parallel), transferring them via an USB bulk transfer to the PC costs less than 2 msecs.

The odometer

We consider first the simple case of the odometer on a robot moving on flat contrasted ground. Motion is restricted to two degrees of freedom : rotation about the high axis (yaw) and translation along the long axis (but also sideways translation can easily be included). For each small time interval motion can be decomposed into yaw and translation. The response of all sensors to yaw was calibrated by performing a well defined pure rotation about the yaw axis and reading all sensors' response. The same was done for a pure forwards (sideways) translation. The 'response

patterns' for yaw and translation depend on the arrangement of the sensors and the properties of the environment. In our case eight sensors with horizontal X-axis and the optical axis (Z-axis) oriented at 45° azimuth with respect to each other look down at 45° onto a flat ground with an irregular contrasted pattern. If we monitor motion combined of any yaw with any translation it is easy to extract each component from the accompanied ensemble of sensor responses. We simply calculate a best fit of the actual response to a linear combination of yaw and translation unit sensor responses. Monitoring the SQ byte allows to exclude sensors with poor contrast from ego motion estimates.

A more general ego motion estimate (more degrees of freedom, uneven ground etc.) with a device with 16 sensors is currently under research.

We would like to bring a prototype with us and show a hardware demonstration of our odometer at the conference.

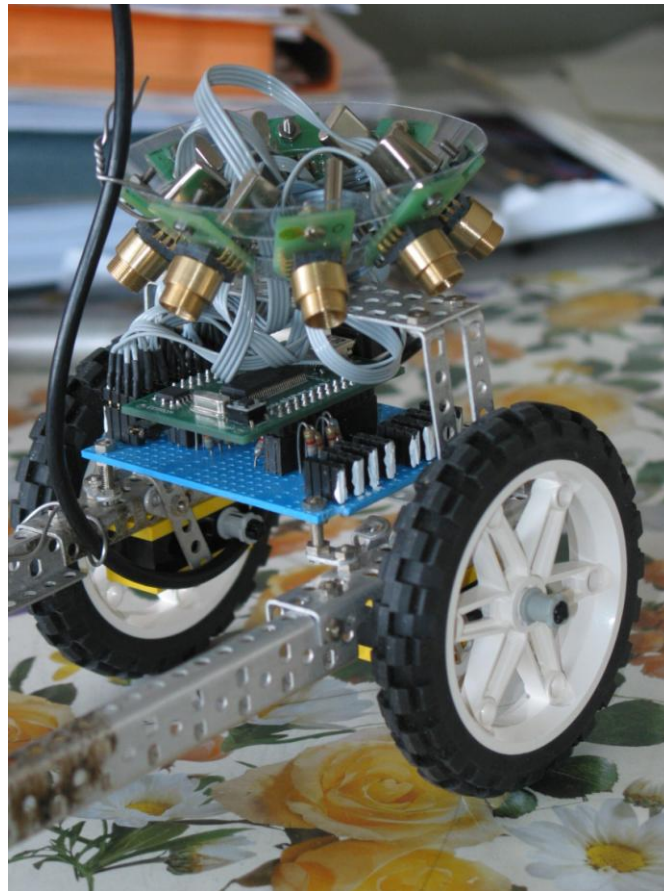


Figure 1. The odometer mounted on a two wheel chariot about 11cm above the contrasted flat ground. Five of the eight sensors looking down to the floor can be seen. Above the blue board there is the Cypress CY7C68013A-56P microprocessor installed.

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Sensory Control of Flight in *Drosophila*

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Like all forms of locomotion, flight results from a complex set of interactions among neurons, muscles, skeletal elements, and physical process within the external world. Most of an insect's nervous system is dedicated to sensory processing, however, the brain must combine information from many different modalities to generate a motor code that plays out through a small but complicated set of muscles. The animal's motion through space alters the stream of information that runs through the array of visual, chemical, and mechanical sensors, which collectively provide feedback to stabilize flight and orient the animal towards specific targets. Using the fruit fly, *Drosophila*, as a model system, the goal of the research in my lab is to 'reverse engineer' an insect's flight control system, and thus determine the means by which the nervous system controls the animal's trajectory through space.

Drosophila, like many flies, search and explore their environment using a series of straight flight segments interspersed with stereotyped changes in heading termed saccades. My talk will focus on both components of this algorithm – flying straight and rapidly turning. *Drosophila* fly straight in part by orienting towards long vertical edges in their visual field, a behavior termed fixation [1]. In contrast, flies reflexively avoid small objects. Steering towards long vertical objects and away from small blobs might represent a simple, but robust algorithm for distinguishing perches from predators. Although this behavior does not require object expansion, flies do possess a strong expansion avoidance behavior that may be analogous to the centering response of bees [2]. This reflex is so strong that both experiments and modeling suggest that a fly would robustly steer towards a pole of visual contraction, and thus always fly backwards! The solution to this paradox is in the observation that sensory stimuli that elicit forward flight, including head wind and object fixation, can override the expansion avoidance.

Although *Drosophila* are capable of gentle banked turns, most changes in course involve rapid saccades. Using a combination of tethered and free flight methods, my lab has investigated both the sensory signals that trigger and terminate these rapid turns as well as the aerodynamic means by which the animals produce the required torque. The results suggest that some saccades represent a collision avoidance reflex initiated by the visual system. Once triggered, hard wired sensory-motor circuitry executes a rapid all-or-none program that directs a saccade either to the left or to the right. High speed analysis of saccades indicates that flies must generate torque to start the turn, and counter-torque to stop. Further, whereas the visual system triggers the saccade, the signal to initiate the counter-turn that terminates the maneuver arises from the mechanosensory halteres, which are more sensitive than the eyes to rapid rotation.

Collectively, this research illustrates how processes within the physical world function with neural and mechanical features of an organism's design function to generate a complex behavior.

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Inertial and Aerodynamic Mechanisms for Passive Wing Rotation

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Background

For many insects wing rotation plays an important aerodynamic role during flight [1]. Rapid rotation of the wings allows for lift generation during both upstroke and downstroke by maintaining a positive angle of attack. Depending on when it occurs within the stroke cycle, wing rotation can either increase or decrease the aerodynamic forces produced by the wings [2]. The current degree to which insects employ passive vs. active mechanisms to rotate their wings during flight is not at present well understood. We examine possible aerodynamic and inertial mechanisms for passive wing rotation. In addition we consider the application of passive wing rotation to a small flying vehicle.

Aerodynamic and inertial mechanisms

Previous studies have shown that inertial effects may play an important role in wing rotation [3]. We developed a dynamic model of a flapping wing, which includes both inertial effects and aerodynamic forces, to help understand the primary factors influencing the timing and magnitude of passive wing rotation. For simplicity the wing is considered to be a rigid-body. An empirically derived quasi-steady model is used to predict the aerodynamic forces and moments acting on the wing. In particular, the model enables us to examine the effects of mass distribution, wing shape, rotational axis location, and driving function. In addition both active and passive actuation schemes can be introduced through the addition of torques acting about the rotational axis of the wing, for example a spring or damping force.

Mechanical models

Two mechanical models are used to examine the physics of passive wing rotation and to provide experimental validation of the dynamic model. The first mechanical model consists of a robotic wing flapping in a tank filled with mineral oil (Fig. 1). The wing is free to rotate about its long axis and is equipped with a shaft encoder to measure the time varying rotation angle of the wing. The effect of axis location, wing shape and mass distribution are examined at two Reynolds numbers, 200 and 1500. The second mechanical model consists of a small 4" model wing flapping in air at frequencies of up to 80 Hz. As with the first mechanism the wing is free to rotate about its long axis. The resulting motion of the wing is recorded using calibrated high-speed video cameras and from the high-speed video sequences the kinematics of wing rotation are determined.

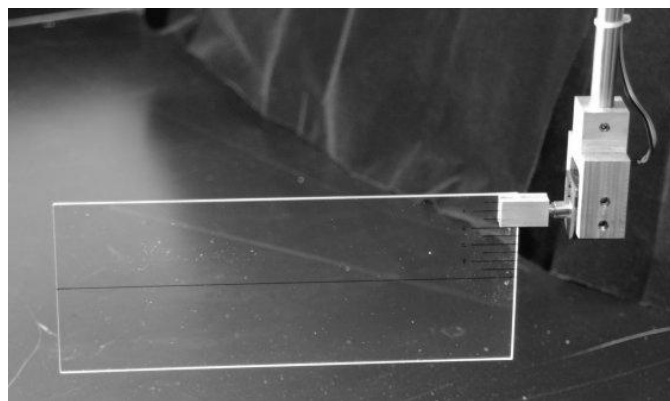


Figure 1. Robotic wing equipped with a shaft encoder to study the passive wing rotation in oil tank experiments.

Applications

Finally, we consider the application of passive wing rotation to the propulsion system of small flying robotic vehicle (Fig. 2). The use of passive wing rotation enables considerable simplification of the linkage mechanism driving the motion of the wings. The time course of rotation angle can be tuned to optimize efficiency by adjusting the axis location and mass distribution of the wing as well as through the introduction of stops.

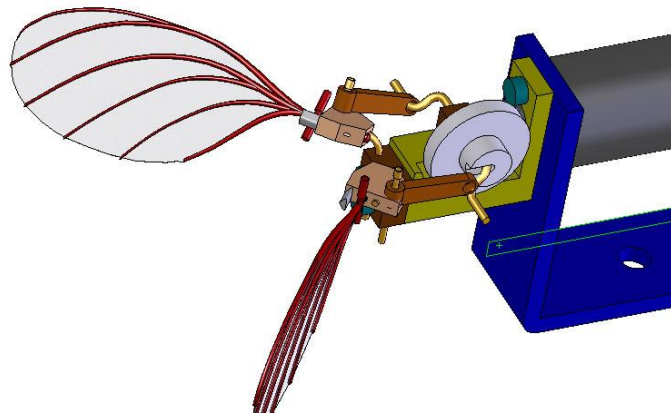


Figure 2. Prototype propulsion system utilizing passive wing rotation developed for a flying robotic model.
(Designed by David A. Cylinder)

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Artificial Compound Eye Imaging Systems by Micro-Optics Technology

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Natural Compound Eyes – Perfect Archetype for Compact Vision Systems

Natural compound eyes combine small eye volumes with a large field of view, at the cost of comparatively low spatial resolution. For small invertebrates as for instance flies or moths the compound eyes are the perfectly adapted solution to obtain sufficient visual information about their environment without overloading their brain with the necessary image processing. Microoptics technology enables the generation of highly precise and uniform microlens arrays with small lens sags and their accurate alignment to the subsequent optics-, spacing- and optoelectronics structures [1,2] (figure 1). The result are thin, simple and monolithic imaging devices with the high accuracy of photo lithography (figure 2). Artificial compound eyes promise to lead to a completely new class of imaging systems. Due to their compactness, high FOV and large depths of focus artificial compound eyes can find applications, usual objectives will never find their way in. Compound eye cameras could for instance fit into tight spaces in automotive engineering, credit cards, stickers, sheets or displays, be used for security and surveillance, medical technology and anywhere else, where the imaging system shall not be recognized as such. They especially would be suitable for the application as vision system in light-weight MAVs (micro air vehicles) which also sometimes have their archetype in insect-principles. The obtainable resolution is sufficient for many machine vision applications (figure 3).

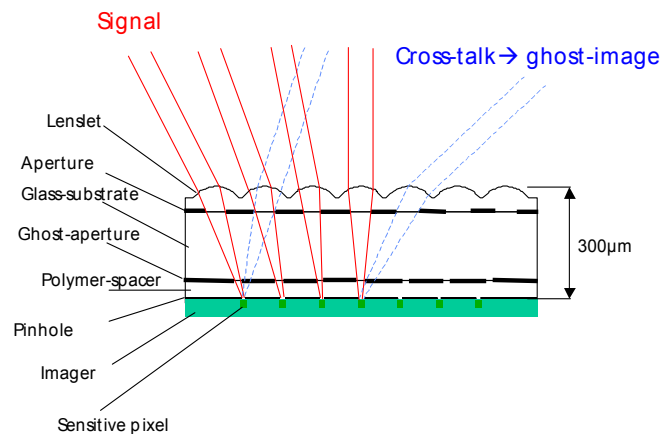


Figure 1. Principle of artificial apposition compound eye with included ghost image suppression.

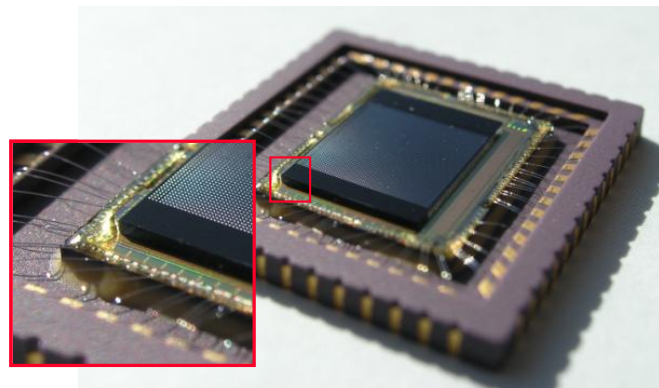


Figure 2. Compound eye objective directly attached to CMOS image sensor makes up the ultra-thin camera.

Compound eye cameras could for instance fit into tight spaces in automotive engineering, credit cards, stickers, sheets or displays, be used for security and surveillance, medical technology and anywhere else, where the imaging system shall not be recognized as such. They especially would be suitable for the application as vision system in light-weight MAVs (micro air vehicles) which also sometimes have their archetype in insect-principles. The obtainable resolution is sufficient for many machine vision applications (figure 3).

Furthermore, the desired low optical fill factor in image plane of an artificial compound eye objective allows to integrate near-to-the pixel analog signal processing directly on the imaging chip such as for instance the calculation of the optical flow for flight stabilization and navigation of MAVs.

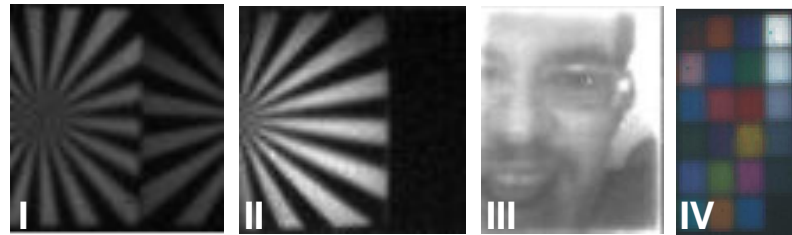


Figure 3. Images captured with the artificial apposition compound eye camera (from left to right). I: System without additional aperture layer for ghost suppression. Radial star pattern moved partly outside the FOV - ghost image appears from the other side. II-IV: Ghost suppression layer included. II: Same radial star pattern as in I, but ghost image is suppressed. III: Duparré in front of bright background. IV: Imaging of color objects is possible by means of extracting several pixels per channel and implementing color filters.

Recent Advances

We present our latest results of research and development on:

- The artificial apposition compound eye, directly integrated with the CMOS-imager, improved resolution and field of view and blocking of ghost images by an additional internal aperture array layer.
- Hyperacuity of an artificial apposition compound eye for position-detection of point sources or edges with an accuracy far beyond the resolution limit of the compound eye with respect to bar targets [3].
- Applying more than one pixel per channel in the artificial apposition compound eye for improved sensitivity (neural superposition) or colour vision without loss of resolution.
- The rotating artificial apposition compound eye column for distortion-free 360° panoramic vision by a highly compact stick-like device.
- The artificial apposition compound eye on a curved basis by a special type of laser beam writer [4].
- The microoptical telescope compound eye, which is providing a regular image of higher resolution due to the upright transfer of parts of the overall field of view by each channel [1].
- The ultra-short, large object-size microscope by a unity-magnifying array of microlens telescopes directly attached to an image sensor.

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Active Vision: Strategies and Neuronal Mechanisms of Spatial Orientation Behaviour in Blowflies

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Saccadic flight and gaze strategy to facilitate processing of optic flow

It may appear plausible to assume that the control of complex behaviour requires a correspondingly complex brain. Our studies on blowfly visually guided orientation behaviour show that this assumption is generally not justified. We investigate by behavioural, neuronal and modelling analysis which brain mechanisms enable blowflies to move in their environments without colliding with obstacles. The fly is an excellent model system to analyse how this vital task can be solved. With its miniature brain, the fly is able to control highly aerobic flight manoeuvres and, in this regard, outperforms any man-made autonomous system. To accomplish this extraordinary performance, flies employ a clever trick: they shape actively by the specific properties of their own movements the dynamics of the image sequences on their eyes ('optic flow'), an activity which results in visual information that can be processed by the brain with relatively little computational effort.

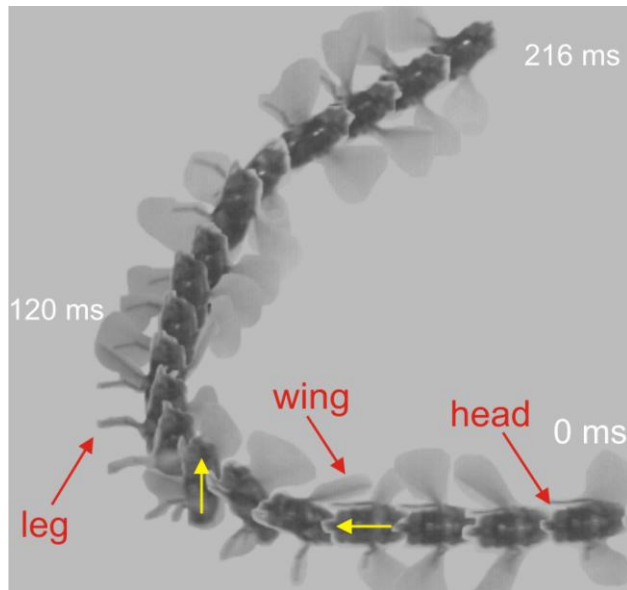


Figure 1. Saccadic flight and gaze strategy of a blowfly.

This is accomplished by shifting the gaze by saccadic turns of body and head and by keeping the gaze fixed between saccades (Fig.1) [1].

Representation of spatial information by population of motion sensitive neurons

We could show by using a novel visual stimulation setup which allows us to present naturalistic optic flow to the animals in electrophysiological experiments (Fig.2) [2] that, by utilising the intervals of stable vision between saccades, an ensemble of motion sensitive neurons in the blowfly visual system is able to extract information about different aspects of the spatial layout of the environment from the optic flow. This extraction is possible because the retinal image flow evoked by translation, containing information about object distances, is confined to low frequencies and the residual intersaccadic head rotations are small and encoded at higher frequencies. Information about the spatial layout of the environment can thus be extracted by in a computationally parsimonious way [3-7]. The detectability of environmental objects is even enhanced by adaptation mechanisms in the visual motion pathway.

Cyberfly to test performance biological mechanisms

The consistency of our experimentally established hypotheses are tested by modelling the motion vision system [8] and using this model to control the locomotion of a 'Cyberfly' moving in virtual environments. Our experimental and modelling results on neuronal function based on naturalistic, behaviourally generated optic flow are in stark contrast to conclusions based on conventional visual stimuli.

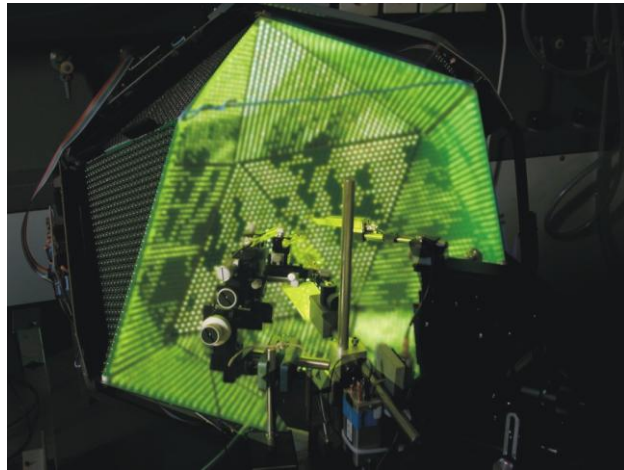


Figure 2. FlyMax, a panoramic visual stimulation device made of more than 7000 LEDs for presentation of naturalistic optic flow at 370 frames/s.

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Challenges for 100 Milligram Flapping Flight

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The goal of this project is to create a 100 milligram micromechanical flying insect (MFI) which uses similar wing stroke kinematics as flies or bees (Figure 1). Key challenges have been thorax mechanics, thorax dynamics, and obtaining high power-to-weight ratio actuators [1]. Careful attention to mechanical design of the thorax and wing structures, using ultra high modulus carbon fiber components [2,3] has increased wing drive frequency from 150 to 270 Hz. At resonance, active control of a 2 degree of freedom wing stroke requires precise matching of all components [4]. Using oversized actuators, a bench top structure has demonstrated lift greater than 1000 microNewtons from a single wing (Figure 2) [5]. Dynamometer characterization of piezoelectric actuators under resonant load conditions has been used to measure real power delivery capability [6]. With currently available materials, adequate power delivery remains a key challenge, but at high wing frequencies, we estimate that greater than 400 W/kg is available from PZT bimorph actuators. Neglecting electrical drive losses, a typical 35% actuator mass fraction with 90% drive efficiency would yield greater than 100 W/kg wing shaft power.

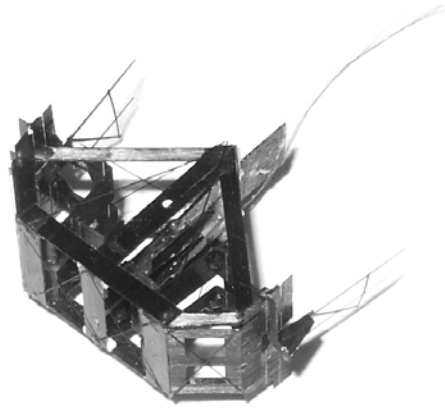


Figure 1. Micromechanical Flying Insect integrated prototype with off board power and control. Mass 120 milligrams.

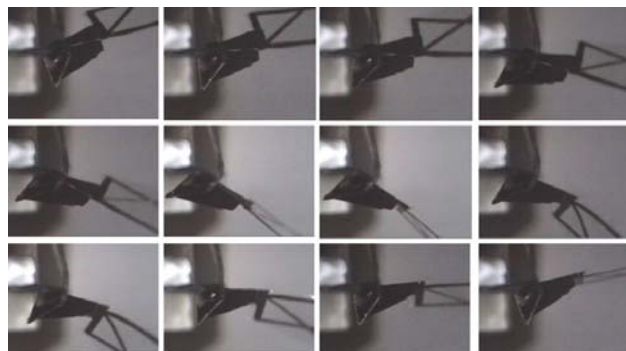


Figure 2. 270 Hz wing stroke for 11 mm wing generating greater than 1 mN of lift.

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Evolutionary Swarms of Flying Robots

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In case of a wide-area catastrophic event, rescuers often need a dedicated communication system allowing them to exchange information with a base station and with other rescuers. In this project, we are developing a swarm of small and light-weight flying robots that will autonomously locate the rescuers and establish a communication network with the base station (figure 1). The swarm of robots should be able to operate in various lighting conditions, including at night, and maintain the communication link if rescuers move around the area or if some robot fails.

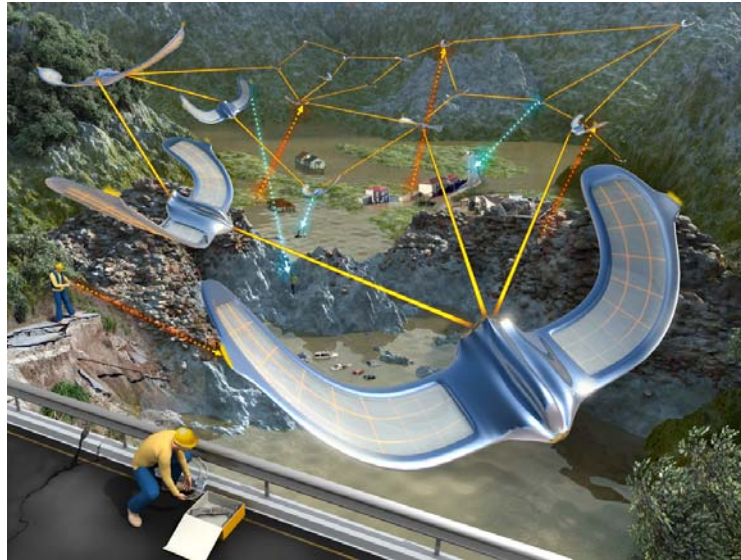


Figure 1. Artist's view of a deployable swarm of autonomous robots for ad hoc communication networks in case of catastrophic events.

The robot consists of a flying wing equipped with a pressure altimeter, a speed sensor, a magnetic compass, two rate gyros, a wireless radio-link, and a Linux onboard computer for handling control and communication (the detailed description and demonstration of the robot can be found in another poster presentation [1]). For this project, the robot does not use vision and GPS. However, we are designing the robotic platform in such a way that it can be easily customized with several sensors and easily programmed by other researchers in the biological and engineering communities.

In a preliminary scenario, a swarm of 20 robots are manually launched from a box, search for one rescuer within a distance of 550 m, and reconfigure so to establish a reliable communication link between the rescuer and the launching location where the base station is supposed to be. Robots cannot rely on GPS and vision to know their own position and that of other robots. All a robot knows, is whether there is another robot within a surrounding area with a radius of 100 m, and how many robots away (hop count) it is from the base station and from the rescuer (if one has been found).

Hand-coding a suitable set of control systems for the swarm is difficult because, since the behaviors of the robots are locally and mutually dependent and cannot use an absolute referential system, small behavioral variations can have large and hard-to-predict consequences in the swarm dynamics. Therefore, we resorted to a process of artificial evolution to generate control systems that collectively achieve the goal scenario. Once a satisfactory control system was found, we reverse engineered the evolved controller into a control program that could be easily understood and

modified according to the scenario constraints. (The use of a different, non-evolutionary, strategy based on ants is described in another poster presentation [2]).

Artificial evolution of collective control systems however is not yet well understood and, in particular, it is not clear how swarm fitness should be distributed among swarm members and how similar or different should the control system of swarm members be. We thoroughly investigated these two questions with the help of a swarm of wheeled robots and obtained guidelines for evolving swarms of individuals that must cooperate to achieve a collective task [3].

These guidelines were then applied to the swarm of flying robots in this scenario. We carried out all evolutionary experiments in simulation. The control systems of the robots consisted of a feed-forward neural network that was equal for all robots. The fitness function was the percentage of time a reliable communication was maintained by the swarm. Strategies found through evolution (figure 2), allowed for the establishment and maintenance of a communication link between the base station and rescuer.

The trajectories of evolved control systems were analyzed and translated into two simple control principles. These rules were then implemented in the simulated swarm and its performance measured under various conditions. Given these promising results, some functionalities of the hardware, such as the turning radius of the robot, have been matched to the evolved control rules in order to ensure their porting from simulation to the physical robots.

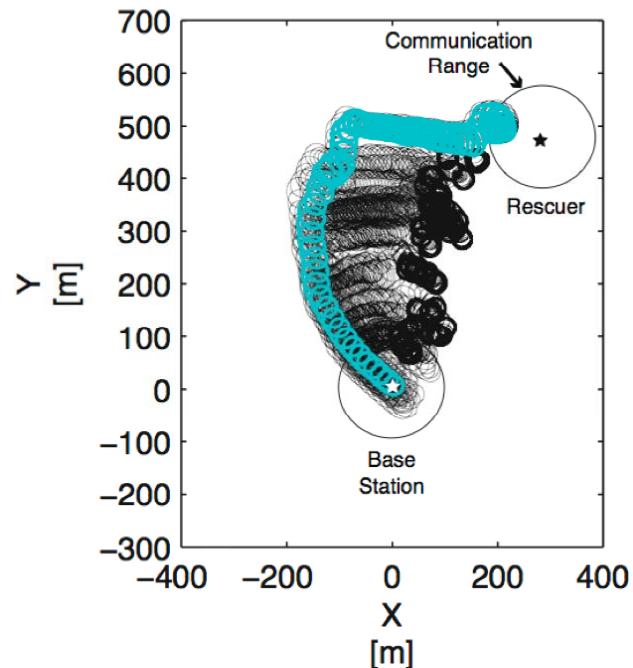


Figure 2. Flight trajectories of an evolved swarm that found a rescuer and established a communication link with the base station.

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Insects as Pilots: Optic Flow Regulation for Vertical and Horizontal Guidance

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When insects are flying forward, the image of the ground sweeps backward across their ventral viewfield and forms an 'optic flow' (OF) that depends on both the groundspeed and the groundheight. Ever since Kennedy has put forward the hypothesis that insects have a 'preferred' retinal velocity with respect to the ground below [1], several studies have shown that insects are able to maintain a constant OF with regard to their surroundings while cruising and landing, without having to measure their groundspeed and groundheight. Our recent research attempted to establish an explicit flight control scheme that can allow insects to behave in this way [2].

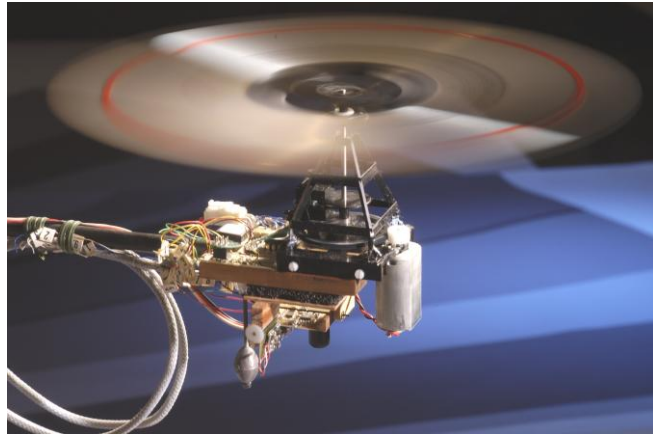


Figure 1. The robot OCTAVE equipped with a ventral OF sensor and an *OF regulator* mimics insect behaviour in the vertical plane

We put forward the concept of *optic flow regulator* that may account for both insects' ground avoidance and lateral obstacle avoidance, while offering interesting solutions to MAV's automatic guidance systems based on vision [3,4]. The word 'regulator' is used here in the strict sense to describe a feedback control system that strives to maintain a variable at a fixed set-point. The variable measured is, however, neither the groundspeed nor the distance but the groundspeed:distance ratio - in other words the *optic flow* - which the insect can access directly via motion detecting neurons. In the vertical plane, the insect will alter its vertical lift, and thus its groundheight, to maintain a set-point of ventral OF at all times. Once reaching a given groundspeed, the insect is bound to maintain a constant height above varying terrain and therefore to 'follow' the terrain. If the insect increases its forward speed, it will automatically increase its groundheight. If its groundspeed decreases for whatever reason - whether the insect plans to land or faces a headwind - the *OF regulator* will force it to descend to hold again the groundspeed: groundheight ratio at the OF set-point. Strong headwind will lead to forced - but smooth - landing. The *OF regulator* concept accounts for a number of seemingly disparate insect behaviours that were reported over the last decades. Most reports are qualitative, but recent quantitative findings made on honeybees' landing [5] can also be explained on the basis of this simple control system, including the constant descent angle observed in the bee's final approach [6].

In a similar vein, a honeybee trained to fly in a corridor [5] may rely on a *dual OF regulator* to adjust both its forward speed and its clearance to the walls, by controlling its forward and side thrusts, respectively, without ever measuring its forward speed and distance to the walls [7,8].

Our thinking along these lines was aided not only by simulation experiments but also by physical implementation of *OF regulators* onboard two kinds of MAVs: a robotic helicopter for ground avoidance (Fig.1) and a robotic hovercraft for lateral obstacle avoidance and speed control. In both cases, the electronic OF sensor [9,10] was derived from the housefly Elementary Motion Detector (EMD), which we had previously analysed using single neuron recording combined with optical microstimulation of two photoreceptor cells within a single ommatidium [11].

The block diagram of the *optic flow regulator* describes not only the *causal* but also the *dynamical* relationships between measured and controlled variables, while pinpointing the specific loci of the various disturbances that may affect the control system behavior.

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Free-flight Control in Fruit Flies – A Systems Analysis Approach

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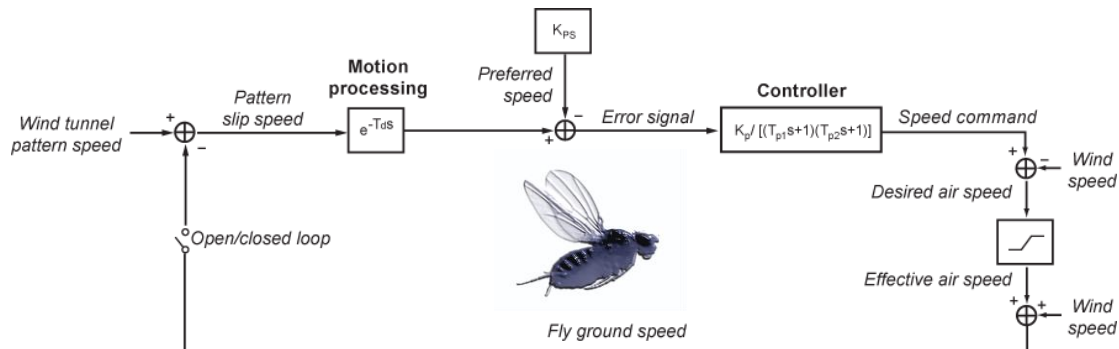


Figure 1. Experimentally derived control diagram of the fruit fly's visual ground speed response.

The highly sophisticated flight control system of the fruit flies offers itself as a model for the design of biomimetic microrobots. While increasingly detailed knowledge about the fly's basic neuromotor control circuits is available, their functional relevance for free-flight control under realistic behavioral conditions is not well understood. This functional understanding of the free-flight control mechanisms is crucial for a meaningful interpretation of the biological data, as well as the implementation of biomimetic control principles.

A rigorous control systems analysis of relevant free-flight behaviors can serve an improved functional understanding and furthermore provide a common conceptual framework for the analysis of biological control systems and robotic engineering design. This approach is experimentally challenging, as it requires precise sensory stimulation and a detailed measurement of the behavioral reactions under realistic free-flight conditions.

To this end, we explored the visual requirements for translational flight control using 'FlyTrack', a wind tunnel equipped with virtual reality display technology. We induced speed responses in presence of a precisely defined step input of retinal optic flow ('virtual open-loop' stimulation) and measured the fly's response by sampling its 3D position at 50 Hz. Based on these data, we performed a systems analysis of the fly's speed control reflex. The resulting control model explains transient and steady-state response properties measured under open-loop conditions, as well as under realistic closed-loop conditions in presence of natural image stimuli.

We extended this approach to analyze the control of body pitch during visually elicited speed response maneuvers. In this case, we induced flies to accelerate forward, while their body motion was measured using a side mounted high speed (~1 kHz) camera. Knowledge of the visual (retinal optic flow) and mechanical inputs (Coriolis forces sensed by the halteres), as well as the output (body pitch and flight velocity) allowed a detailed analysis of the underlying control circuits.

Geometric Analysis of Hassenstein-Reichardt Elementary Motion Detectors and Application to Control in a Fruit Fly Simulator and a Robot

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HR-EMD's are thought to estimate velocity of image flow in insects by performing a time-lag and correlate operation. The steady-state HR-EMD response to pair of visual "pixels" separated on the retina by angle $\Delta\phi$ reading a moving zero-mean sinusoidal luminance signal is $R = \frac{C^2}{2\pi\tau} \cdot \frac{f_s v}{(f_s v)^2 + 1/(2\pi\tau)^2} \sin(2\pi f_s \Delta\phi)$, [1] where C is the amplitude of the signal, f_s is its spatial frequency in cycles/radian around the retina, v is its velocity in radians/sec, and τ is the time lag of the EMD.

Here we consider a fly moving forward at velocity \dot{x} m/sec over a sinusoid-stripped floor of infinite extent (as in Figure 1 (left), but without the walls) with spatial frequency F_s cycles/m at height z with the pitch angle θ held at zero. We show that when the imagery is projected onto the retina during this motion, the EMD response becomes

$$R(\gamma, \varphi) = \frac{C^2}{2\pi\tau} \exp\left(-2 \frac{\left(\frac{2\pi F_s z}{\sin^2 \gamma \cos \varphi}\right)^2 \Delta\rho^2}{16 \log 2}\right) \frac{\dot{x} F_s}{(\dot{x} F_s)^2 + \frac{1}{(2\pi\tau)^2}} \sin\left(\frac{2\pi F_s z}{\sin^2 \gamma \cos \varphi} \Delta\phi\right) \quad (1)$$

where $\gamma \in (0, \pi)$ is the angle measured downward from the body-centered horizon, $\varphi \in (-\pi/2, \pi/2)$ is the angle in the roll direction away from vertical downward, and $\Delta\rho$ is the acceptance angle of the Gaussian spatial blurring of the light sensors. An intermediate step in the derivation shows the temporal frequency $f_s v$ of the luminance signal is simply $f_s v = \dot{x} F_s$ cycles/sec. This suggests that \dot{x} could be estimated by measuring the temporal frequency $f_s v$ and knowing only F_s , irrespective of z or γ .

Alternately, correlating the vector $\mathbf{e}(t)$ of EMD responses with a "matched filter" \mathbf{m} can give velocity estimates. For example, the \dot{x} velocity estimate is $\hat{\dot{x}} = \alpha \mathbf{e}(t) \cdot \mathbf{m}_x$, where (\cdot) is the vector dot product and \mathbf{m}_x is the mean EMD response to moving forward at nominal velocity and height over a striped floor (α is an appropriate scaling factor). The equivalent analytic estimate is $\hat{\dot{x}} = \alpha \int_0^\pi d\gamma \int_{-\pi/2}^{\pi/2} d\varphi R_{nom}(\gamma, \varphi) R(\gamma, \varphi)$ where R_{nom} is equivalent to the matched filter. The analytic result was compared to the response measured by the "Grand Unified Fly" [2] simulator of insect sensory systems and flight mechanics (Figure 1) and shows reasonable agreement. Integrations over γ and φ were performed numerically.

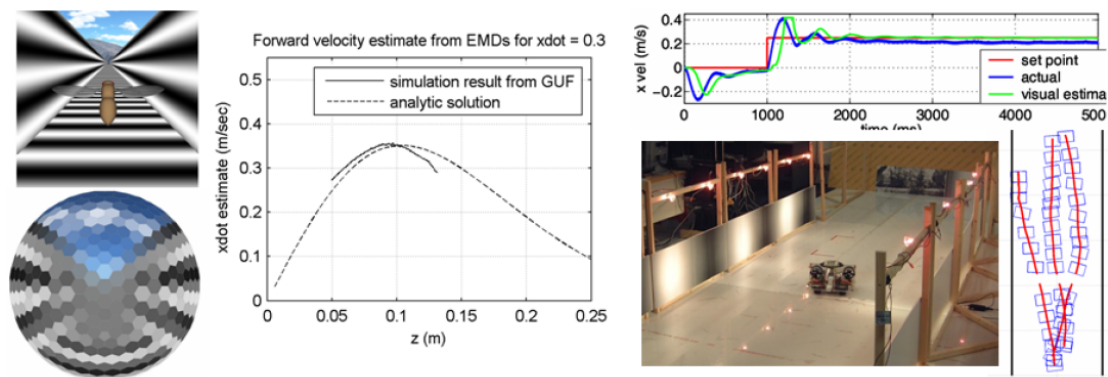


Figure 1: Left: rendering of GUF virtual world. Middle: a comparison of analytic and simulated forward velocity estimates as z is varied. Upper right: step response of forward flight controller in GUF. Lower right: a robot using EMD's for corridor navigation (left) and trajectories (right).

A controller was designed that could regulate longitudinal forward flight by controlling pitch, forward velocity, and vertical velocity in a corridor environment by modulating wingbeat magnitude and mean stroke position in GUF (Figure 1, top right).[3] And a fan-actuated robot and controller were built that used an array of light sensors and sinusoid-textured walls to navigate a corridor (Figure 1, bottom right).

We report three results. First, the analytic model approximates EMD behavior in the full GUF simulator. Differences can be attributed to a difference in spatial frequencies observed by the two sensors constituting the EMD, as well as the discreteness of the EMD's. The velocity estimate increases as the fly descends and then eventually saturates. This is consistent with the "grazing landings" reported for bees. We expect that refinements to EMD's to operate on broadband textures reported elsewhere[1] can be incorporated into this analysis. Secondly, we observe that velocity may be estimated by measuring temporal frequency alone, regardless of z or measurement angle γ by knowing the texture frequency *a priori*. For instance, it can be expected an animal would know the length scale of a leaf on the ground. Third, we present two robot controllers that operate stably near nominal conditions. We expect the analytic work will lead to improved performance.

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Robust Control of Tethered Airfoils using Evolutionary Robotics

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Introduction

Novel tethered airfoil (kite) energy generation systems promise far higher efficiencies and reduced costs compared to traditional wind turbine systems [1]. Both electricity generation and marine propulsion kite applications transfer the aerodynamic forces generated at the kite via the lines in order to perform useful work at ground level. To maximize the forces transferred through the lines most effectively, the kite must be actively steered through the airspace near perpendicular to the wind, in order to maximize the apparent wind velocity. Ideally, controllers should be able to fly the kite in predictable repeated trajectories producing consistently high line tensions in the widest possible range of wind conditions. We take an evolutionary robotics (ER) approach to this problem and selectively evolve neurocontrollers in simulation, as a foundation for a future hardware implementation.

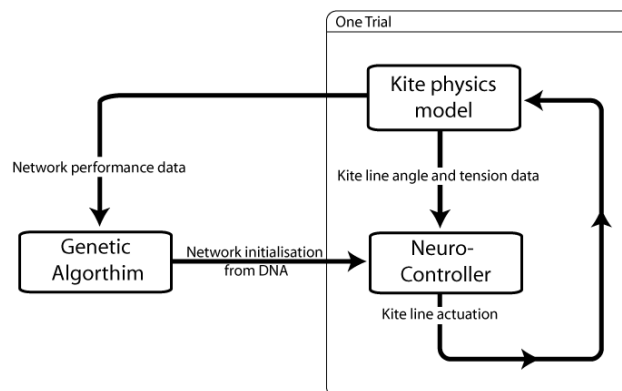


Figure 1. Simple schematic of information flow between components.

Evolution of neural networks has a successful track record of flight control both in simulation and hardware [3,4]. Neural networks can be sufficiently adaptive and robust to noise to maintain coherent behaviours across a range of wind conditions and therefore constitute an appropriate control substrate. Although in this simple initial formulation it is possible to hand-code a neural network to perform the task, a genetic algorithm (GA) is chosen here as future work will require both line reel-out and retraction phases and multiple kites in the same airspace. GAs also allow the possibility of optimising for a certain set of conditions i.e. those of a certain real world site and when deployed in hardware could potentially exploit quirks of aerodynamics that are difficult to model, vortex creation and manipulation for example.

Methodology

Recurrent neural network controllers are tested using a simplified aerodynamic simulation of a four-line kite, steered by altering the relative lengths of the rear lines. In order to resemble commercially available 'Leading Edge Inflatable' kites, the leading edge is more rigid than the trailing edge, allowing the kite canopy to flex asymmetrically. Within each trial the kite is subjected to random gusts and lulls of the wind. We use a microbial GA to evolve neurocontrollers that generate either the highest aerodynamic forces at the kite, or maximise the component of the aerodynamic forces that is in line with the flying lines.

Key Findings

We show that neurocontrollers evolved using an evolutionary robotics methodology steer the kite repeatedly in a figure eight trajectory (Figure 2), that has been shown previously to be an optimal trajectory for the generation of line tension [2]. Controllers are robust, maintaining the evolved trajectory in wind gusts and lulls up to 40% of the background wind speed. Interestingly, during fast onset gusts and lulls the controller deviates to a figure eight trajectory more perpendicular to the wind and then returns to its original trajectory on the resumption of more consistent wind speeds. The best performing networks are those evolved to maximise the component of the aerodynamic forces that is in line with the flying lines.

Contrary to other work [2], the evolved trajectories are often rotated 45° from a 'lying eight' position and are not centred directly downwind of the tether point. Additionally, the evolved trajectories all use a greater arc of downwind airspace than in previous work [1,2]. Specific aspects of our implementation are potentially the cause of these differences, which will be investigated in future work.

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Analysis of Low-level Motor Control in Tethered Flying *Drosophila*

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Introduction

Despite limited neural resources, insects achieve an awe-inspiring active control of mechanically unstable flapping flight [1]. A better understanding of the underlying neuromotor control can provide biomimetic design principles for micro-aerial vehicles.

We analyze flight in a reverse-engineering approach, where biological flight is studied from a control systems' perspective. To perform this analysis, we have developed novel tools that allow the measurements of the instantaneous kinematics and forces generated by tethered fruit flies.

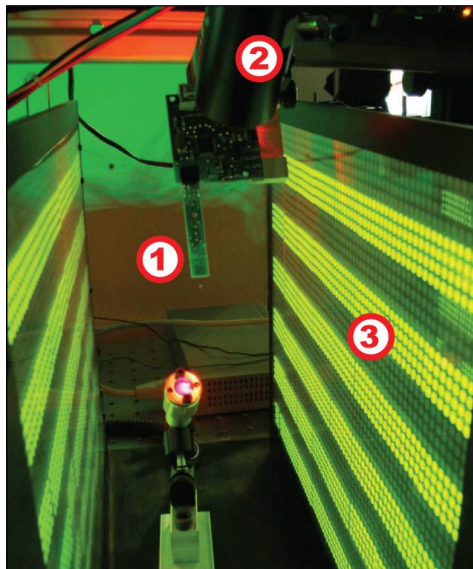


Figure 1. Experimental setup. 1) MEMS force sensor 2) Digital wing beat analyzer 3) LED flight arena

1) MEMS force sensors

We have developed multi-degree-of-freedom capacitive micro-force sensors (figure 2) to characterize the flight forces of tethered fruit flies [2]. The sensors have a sub micro Newton resolution and a bandwidth of over 8kHz, making them particularly well-suited to measure the fast-varying micro Newton scale combination of inertial and aerodynamic forces generated by fruit flies.

2) Digital wing beat analyzer

We have developed a high speed computer vision system to extract instantaneous wing kinematics at 2x3kHz (figure 3, [3]).

3) Visual flight simulator

The real time measurements are used to drive a visual feedback loop in a flight simulator (figure 1) [4]. The LED flight arena is based on a design by Dickinson *et al.* (www.dickinson.caltech.edu).

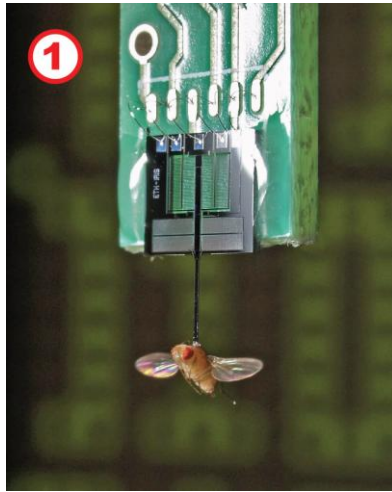


Figure 2. Fruit fly tethered to a 2 DOF MEMS force sensor



Figure 3. Real time extraction of kinematic parameters at 2x3kHz.

Experiments

Our goal is to identify low-level flight control strategies. In a current experiment, we explore the dynamics and neuromotor control strategies underlying lift control. Lift reactions are induced from vertically-moving patterns and the wing motions and lift forces are measured simultaneously. The responses are characterized using classic tools from control systems' analysis.

Combining our novel measurement tools with a rigorous systems' level approach allow a better characterization of the neural and biomechanical flight control principles of fruit flies, providing insights for biomimetic control of micro robots.

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A Hybrid MAV and Biomimetic Sensing for Ingress and Egress of Urban Environments

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Small Unmanned Air Vehicles (UAVs) such as AeroVironment's Puma, are designed for military support at the tactical level. These miniature UAVs can be rapidly deployed via a hand or bungee launch. Most commercial unmanned aircraft currently in service are autonomous in the sense that they can be programmed to follow GPS waypoint routes and can be updated in mid-flight. Typical missions include surveillance, reconnaissance, bomb damage assessment, and search and rescue. Although most missions are carried out at extremely low altitudes (e.g. 20–100 meters), the UAV flight control systems do not have collision avoidance capabilities. Furthermore, flight in these low altitude or near-Earth environments, such as urban areas and mountainous terrain, often degrade GPS signals.

Autonomous flight in near-Earth environments requires a system with high maneuverability, endurance, slow cruise velocity, and novel sensing and collision avoidance techniques. Some groups are investigating flight in indoor or cluttered areas [3] [4] and others are focusing on the outskirts of urban environments [1] [2]. The focus of this research is to bridge the gap between the two communities and develop a system capable of flying in both domains. This adds an additional design constraint in that the aircraft must be small enough to fit through narrow openings and passageways such as doorways.

A Closed Quarter Aerial Robot (CQAR) was prototyped with a fixed wing configuration for maneuverability and endurance. It was estimated that a weight of 40-50 grams was enough to sustain flight outdoors in moderate wind conditions (i.e. 2-4 m/s) while still allowing a low wing loading (e.g. 2.5 N/m²) for slow flight indoors. The CQAR prototype was capable of flying at 2 m/s, giving a control system 5 seconds to detect and avoid walls when flying in a 10m x 10m room. For inspiration towards autonomous navigation of this aircraft in and around buildings, the authors looked to flying insects. Flying insects, such as honeybees and fruit flies, use optic flow to navigate in complex and dynamic environments. By mimicking insect behaviors, the authors were able to demonstrate tasks such as collision avoidance and landing inside an urban structure. However, the limitations of such a lightweight aircraft were soon realized. For example, the payload capacity was quickly exhausted after adding a flight control system and a single sensor. Furthermore, flying at such slow speeds enabled the aircraft to avoid most obstacles; however, flight in more densely populated obstacle fields demands a vehicle that is capable of hovering

To address these limitations, a secondary flight mode was incorporated into a fixed-wing aircraft to preserve its endurance and maneuverability while adding the capability of hovering. This novel MAV platform is well suited for flight in near-Earth environments as the hovering flight mode can be used to navigate in and around urban environments (see Fig. 1). Autonomous control of the secondary flight mode and the transition into it is achieved using a quaternion feedback controller. Quaternions are not vulnerable to singularities at ± 90 degrees and thus can be used to control the aircraft in its high-alpha flight mode. Finally, biomimetic sensing is currently being applied to detect doorways and implement reactive path planning to traverse them autonomously. Entering a dangerous environment to gather

intelligence autonomously is the ultimate goal of this research and will provide an invaluable resource to any command and control team.



Figure 1. A fixed-wing MAV transitions to hovering mode to maneuver through a small opening of an urban structure. *Inset:* A surveillance image from the onboard wireless camera is also shown.

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Pheromone Based Swarming for Positionless MAVs

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Swarming without positioning

Application oriented swarm systems as presented in [1] currently rely heavily on global or relative positioning information concerning themselves and their direct neighbors ([2,3,4,5]). However, such information is not always available in real-life applications because of hardware and environmental constraints.

To render a more realistic and achievable system, it was chosen to investigate in 2D simulation the development of swarming algorithms, which are not based on positioning information.

This endeavor is motivated by an application whereby twenty fixed-wing Micro Air Vehicles (MAVs) must organize autonomously to establish a robust multi-hop communication network between two users located on ground. Rather than positioning, MAVs rely only on their own heading information and local communication with neighbors (situated communication [6]).

In-air virtual pheromone

Inspiration for our MAV controllers is taken from army ants, which are capable of optimally deploying to search for and maintain paths leading to food sources in nature ([7][8]). Ants modify their environment by depositing pheromone and navigate by sensing it (stigmergy). Pheromone based MAV deployments were investigated in [9,10] with MAVs maintaining a virtual map of the pheromone, which is only possible with positioning information.

Instead, the approach proposed here consists in separating the MAVs into two categories 1) node-MAVs and 2) ant-MAVs. Node-MAV constitute the environment on which pheromone can be deposited and read from. Ant-MAVs are capable of navigating through a "grid" of node-MAVs while depositing virtual pheromone through

Swarming MAVs for Communication Relay

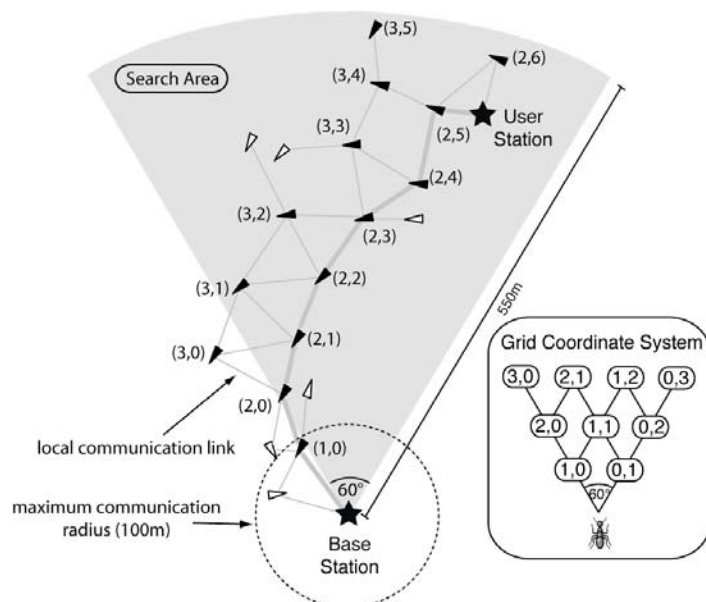


Figure 1. 2D simulation of a deployed swarm of 20 MAVs which must establish and maintain a communication link between a base station and user station. Ant-MAVs (white triangles) navigate through a dynamic grid composed of node-MAVs (black triangles) using pheromone based rules inspired from army ant foraging. Pheromone is virtually deposited and sensed by ant-MAVs using local communication with the node-MAVs. Based on pheromone information and a virtual coordinate system (bottom right corner), ant-MAVs choose between navigating towards the left or the right

the use of local wireless communication. MAVs can reactively change between categories to render a highly dynamic network.

Results

Results show that despite the high dynamics of the system (MAVs must be constantly in movement unlike hovering platforms), the swarm is capable of efficiently finding more than 99% of the user stations positioned in the search area shown in figure 1. The connection between the base and user station is then maintained in a stable and robust manner throughout the 30 minutes trial duration.

In the future, we intend to extend such algorithms to systems with multiple or dynamic user stations while increasing the realism of the simulations (3D environment, wind). Also, currently collision avoidance is assumed unnecessary and will have to be implemented through altitude differentiation in the 3D version.

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Bio-Inspired Visuomotor Convergence

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The insect retina can be thought of as a map of the patterns of luminance of the environment. As an insect moves, these patterns become time dependent and hence are a function of the kinematics of motion and the spatial distribution of objects in the environment. The speed and direction of these local image shifts, taken

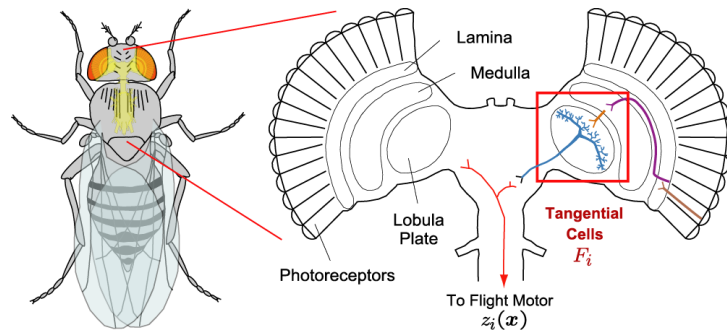


Figure 1. Tangential cells in the lobula plate parse complex optical flow by comparing neural images from local motion estimators with pre-determined motion pattern sensitivities, effecting behavioral responses.

over the entire visual space, form what is known as the *optical flow field* [1]. Insects compute local estimates of optical flow and pass this information to wide-field motion-sensitive neurons (tangential cells) in the lobula plate [2]. Information extraction occurs at the level of tangential cells (Figure 1), which serve to spatially decompose complicated motion fields into feedback signals useful for navigation and flight control [3],[4].

This talk will address the question of how tangential cell processing (WFI, or wide-field integration) can be used in closed loop feedback to regulate the spatial structure of optic flow. The approach is based on a novel premise: tangential cells are used not to estimate kinematics of a vehicle or flying organism directly as in traditional implementations. Instead, complicated patterns of optic flow can be quickly decomposed into feedback signals with “mechanical” significance, such as stiffness and damping necessary for stable evasive behavior (obstacle avoidance, terrain following, and speed regulation). By performing specially weighted integrals (simple summations) of the optical flow field, where the weightings correspond to tangential cell receptive fields (Figure 2A), WFI techniques result in feedbacks *with respect to the surrounding environment*, for instance to maintain a safe distance from buildings in the immediate flight path. The advantage of this approach is that it does not require state estimation, feature detection, extraction, or classification. Useful local information for guidance and navigation is obtained by computing a handful of inner products of optical flow – a very efficient process.

A rigorous characterization of the information available from this visuomotor convergence technique for motion within environments exhibiting non-homogeneous spatial distributions will be presented, which establishes the connection between retinal motion sensitivity shape and closed loop behavior. The proposed output feedback methodology (Figure 2B) is shown to be sufficient to give rise to experimentally observed insect navigational heuristics,

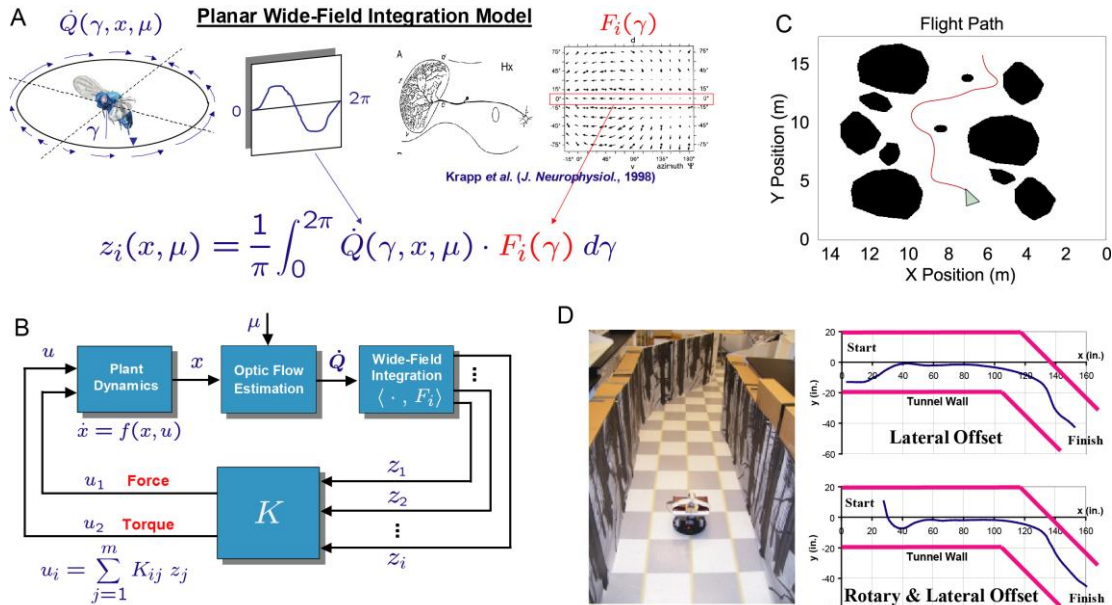


Figure 2. WFI Concept. Optical flow over a wide FOV (e.g., tangential to the horizontal plane) is analyzed with a weighted integral; weighting determines the information derived. (A) Planar LPTC processing model, (B) Wide-field integration based static output feedback, (C) Cluttered obstacle avoidance response, (D) Experimental demonstration of the centering response.

including forward speed regulation, obstacle avoidance, hovering, and terrain following behaviors [5],[6],[7]. Examples of autonomous guidance and navigation from recent simulations (Figure 2C) and experiments (Figure 2D) in the Autonomous Vehicle Laboratory at the University of Maryland will be presented.

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Steady Versus Unsteady Aerodynamics of Flapping Wings in Forward Flight: a 2D Study

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2D DNS simulations of a heaving and pitching airfoil NACA 0012 at $Re=1000$ (see e.g. in figure 1) are used to characterize the transition from a quasi steady regime to a pure unsteady regime for the flow around flapping wings. The frequency is characterized by $St_c = f c / U_0$ where f denotes the frequency, c is the chord of the airfoil and U_0 , the mean forward velocity. Four basic aerodynamic mechanisms which may contribute to the aerodynamic efforts are scrutinized. These are (see [1],[2]) : (i) a circulatory force due to flow separation and formation of the leading edge vortex, (ii) the added mass reaction (iii) the "wake capture" phenomenon, (iv) the rotational force. We quantify and discuss the respective contribution of these mechanisms when the frequency changes. This analysis allows us to define three regimes.

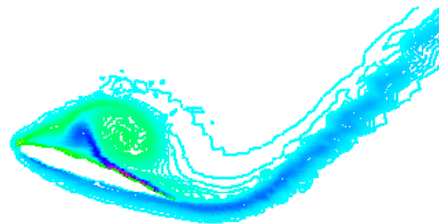


Fig1. Heaving and pitching motion : iso-vorticity contours at the end of a downstroke at $Re = 1000$

- $St_c < 0.1$: the quasi steady regime

Considering a pure heaving motion, lift is mainly generated by circulatory forces due to mechanism (i). Those forces remain large even for high incidences. Lift is governed by the effective incidence of the airfoil during the stroke and a quasi steady model is sufficient to represent the instantaneous forces (lift and drag). The unsteadiness of the vortex during its shedding poorly modifies this quasi steady estimation.

- $0.1 < St_c < 0.5$: the transitional regime

Above $St_c = 0.1$, the rotational force (mechanism (iv)) starts to contribute for the pitching motion and it leads to a reduction of the quasi steady drag. Considering the heaving motion, we also observe that from $St_c \approx 0.2$ the added mass

reaction becomes of the same order than the circulatory forces and induces high transient efforts during the acceleration and deceleration phases of the airfoil. For $St_c > 0.25$, a value corresponding to the frequency of the Von Kármán street in the static case, we observe that the size of the leading edge vortex decreases. At $St_c = 0.4$, the vortex interacts positively with the airfoil during the upstroke and the mean lift reaches its maximum.

- **$St_c > 0.5$: the added mass and rotational force regime**

The rotational force and the added mass reaction, proportional to $\omega = 2\pi f$ and ω^2 , respectively, become dominant and induce large variations in the aerodynamic efforts during the stroke. For the pitching motion a thrust is obtained for $St_c > 0.5$.

This classification is summarized in the diagram of figure 2. We deduce from biological data [3] that those three regimes correspond respectively to birds, large insects and small insects. These are elements which may contribute to understand the flight strategy, the stability and the manoeuvrability of the different living species regarding their frequency [4]. They could also provide useful indications for designing future flapping MAVs models [5].

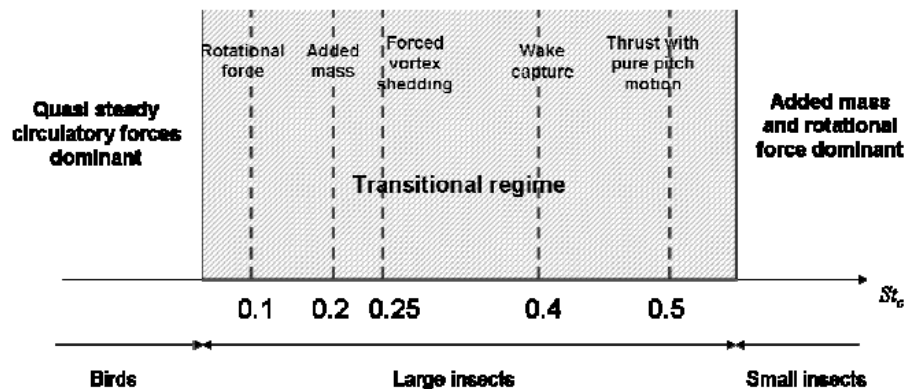


Fig2. Frequency diagram of unsteady mechanisms

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Two-dimensional DNS Study of Asymmetric Motions in Hovering Flapping Flight

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Introduction

The aerodynamic particularity of flapping flight resides in the highly vortical flowfield resulting from the unsteady wing kinematics as well as the characteristic low Reynolds number. The major phenomena are principally the presence of a Leading Edge Vortex [1] or dynamic stall mechanism, the Kramer effect [2,3] due to wing rotation, the Wagner effect [4] and the wing-wake interactions [5].

These phenomena have been widely studied in the case of symmetric hovering (or “normal hovering”) [6], known as the most common hovering configuration in the world of insects. The present work focuses on an alternative configuration; the asymmetric hovering which combines both lift and drag in order to obtain maximum vertical aerodynamic force [7]. Its main characteristic is a change of angle of attack between downstroke and upstroke, leading to a non-horizontal stroke plane in order to maintain zero mean horizontal aerodynamic force. A parametrical study is here performed for a wide range of downstroke/upstroke angles of attack ($30^\circ/5^\circ$ to 60°) and for varying upstroke velocities.

Numerical methods

Two-dimensional first order DNS simulations are performed on a NACA0012 profile. The computational domain is made of a rectangular region close to the profile, surrounded by O-type grids. The domain diameter is 15 chords. The flapping motion (figure 1) is implemented through the use of subroutines by moving the computational domain.

The flow solver returns the time-dependent aerodynamic force coefficients together with vorticity flowfields. The study relies on the investigation of drag C_D , vertical force C_y , pseudo-glide parameter C_y/C_D and power CP coefficients.

Results and discussion

The asymmetric hovering is characterized by the difference between downstroke and upstroke angles of attack. When this difference increases, the stroke plane angle for which the mean horizontal force over a flapping period is null increases, hence leading to a larger contribution of drag to vertical force. Thus, during downstroke, the asymmetric motion generates a stronger vertical force than the symmetric motion, for a quasi-similar drag production. On the other hand, although the upstroke angle is fixed to a low value in order to minimize drag production during upstroke, the corresponding vertical force is weak, reaching a negative value in some configurations.

Moreover, a direct consequence of the difference between downstroke and upstroke angles of attack is the wing rotation velocity at both ends of downstroke and upstroke (supination & pronation). High rotation velocity, which coincides with a low upstroke angle of attack, implies high rotation effects which are harmful to lift production but beneficial to drag decrease. Besides, it greatly affects the dimensions of the Leading Edge Vortex (LEV) and Trailing Edge Vortex (TEV) and consequently the resulting dipole shed into the wake, whose influence on aerodynamic forces is important as

the airfoil interacts with it at the beginning of a stroke [8]. Figure 2 shows how both "normal hovering" and asymmetric hovering dipoles contrast. The resulting jet engenders a wider and stronger overpressure on the airfoil surface in the "normal hovering" case.

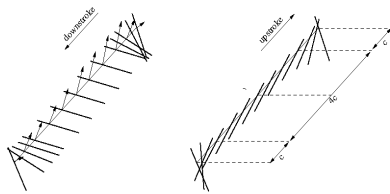


Figure 1. Example of asymmetric wing kinematics

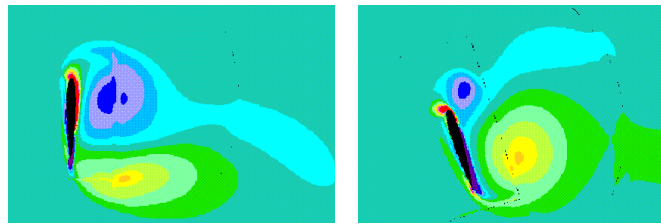


Figure 2. "Normal hovering" (left) and asymmetric hovering (right) vortices' dipole at stroke reversal

As a consequence to these physical phenomena, an asymmetric flapping motion generates weaker average aerodynamic forces than a symmetric flapping motion. On the other hand, the asymmetric hovering case appears as more efficient than the "normal hovering" case, revealing a higher pseudo-glide parameter in most configurations. This remark is accurately verified for downstroke angles of attack above 30° . In parallel, the energy consumption decreases strongly.

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Bio-Inspired Design of Flapping-Wing Vehicles

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Research on the production of thrust from flapping wings [1], and the use of flapping wings to affect boundary layer development [2] led to the design of the flapping-wing propelled Micro Air Vehicle shown in Fig. 1 [3]. The unconventional platform uses a large fixed wing to develop most of the vehicle lift, followed by a bi-plane pair of wings flapping in counterphase to produce thrust. However, the really interesting aerodynamics comes about through the interaction between these three wings. The symmetry of the flapping wings emulates a single wing flapping in ground effect, producing better performance, while providing an aerodynamically and mechanically balanced system. The Figure of Merit (ratio of grams lifted over mechanical power required) is some 60 percent better than conventional rotary-wing designs for producing static thrust [4]. The downstream placement of the flapping wings helps prevent flow separation over the main wing, allowing the aircraft to fly efficiently at very low speeds with high angles of attack without stall. Wind tunnel experiments document the flow reattachment phenomenon. As with most birds and insects, the model depends on aeroelastic deformations to provide additional degrees of freedom. The full manuscript will discuss several newer developments in control, hovering flight and diverse application of the design.

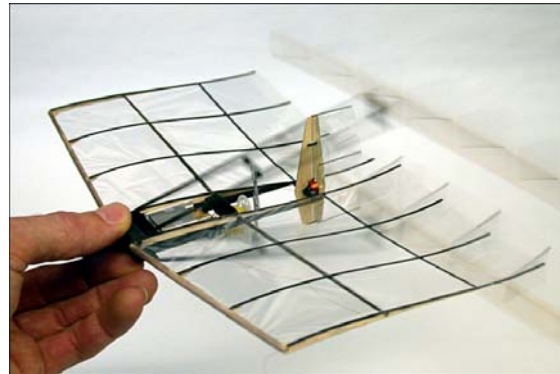


Figure 1. NPS 25cm-span bio-inspired flapping wing micro air vehicle.

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Yaw Stabilization of an Aerial Robot: Visual Fixation and Ultrafast Vestibulo-ocular Reflex

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Autonomous guidance of Micro Aerial Vehicles (MAVs) in unknown environments is a challenging task because these artificial creatures have small aeromechanical time constants, which make them prone to be disturbed by gusts of wind. Flying insects are subject to quite similar kinds of disturbances, yet they navigate swiftly and deftly. Gaze locking in vertebrates and invertebrates seems to play a major role during locomotion. Most of the time, gaze control systems involve the fusion between inertial (inner ear, halteres...) and visual modalities [1].

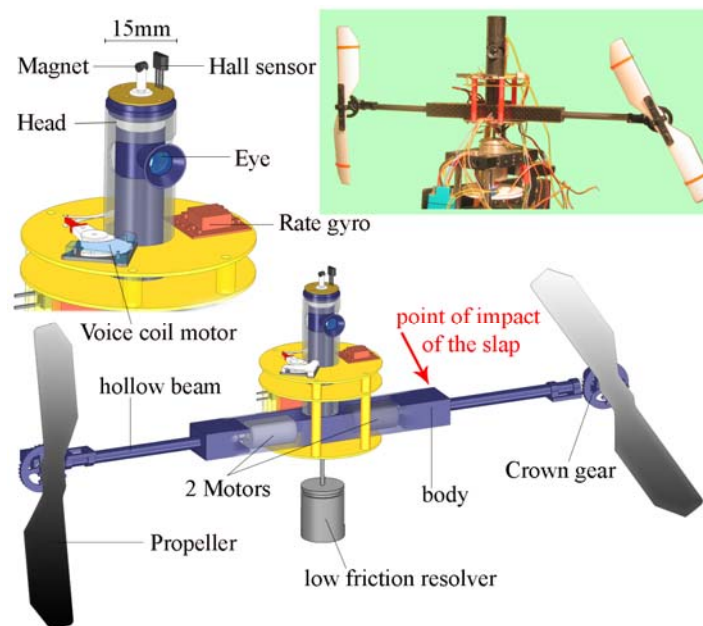


Figure 1. CAD scheme of the OSCAR II robot. By driving its two propellers differentially on the basis of what it sees, the robot can control its angular orientation about the vertical (yaw) axis. The eye of OSCAR II is mechanically uncoupled from the head. This mechanical arrangement, combined with a VOR reflex, allows the robot to stabilize its gaze despite severe disturbances (vibrations, gusts of wind, slaps) that may affect its yaw orientation (heading).

In a previous design, the robot (OSCAR I) was able to lock its heading accurately onto a contrasting target during long fixation periods [2] and track a target with high accuracy [3]. The Achilles' heel of OSCAR I lied however in its sensitivity to aerial disturbances such as gusts of wind.

Natural oculomotor systems teach us that a solution to this weakness may reside in the ability to have the eye's and head's orientation controlled independently (e.g.[4]). The novel OSCAR II aerial robot presented here, exhibits manifold improvements compared to its former version. A major improvement concerns the mechanical decoupling of the eye from the head (cf. figure 1). As a consequence, the heading is controlled via the orientation of the eye itself. As the eye is capable to rotate 10 times faster than the head, it keeps the robot fixating the contrasting target despite, for

example, a nasty thump that we deliberately gave to its body with a custom-made “slapping machine”.

Another major improvement concerns the choice of the eye's actuator. It is a 2.4-gram voice coil motor, acting as an “extra-ocular muscle” (EOM) that is able to rotate the eye with a rise time as small as 12ms regardless of the saccade size (i.e., twice as fast as the fly [5]). This very fast EOM endows the robot with a high performance “vestibulo ocular reflex” that keeps the gaze locked onto the target whatever perturbations in yaw affect the robot's body. Whenever the robot is perturbed (by a slap applied onto its body), the gaze keeps fixating the target, while being the reference to which the robot's heading is servoed. It then takes the robot only 0.6s to realign its heading with its gaze.

This study puts the stress on the necessity to stabilize the gaze for controlling and thus stabilizing the attitude of an aerial robot. In this work, the high performances of a robot's heading control system are directly related to the high performances of the gaze control system.

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Towards a Self-Deploying Microglider; Gliding Flight and Bioinspired Wing Folding Mechanism

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Gliding flight is very powerful to overcome obstacles and to travel from one point to another. We claim that it can be applied in miniature robotics as an easy to use and energy efficient mode of locomotion. In the animal kingdom, many small animals are able to get into the air by jumping, fast running or dropping down from trees. Once airborne, they recover, stabilize (passively and/or actively) and perform goal directed aerial descent [1][2] (e.g. gliding frogs, flying geckos, gliding lizards, locusts, crickets, flying squirrels, gliding snakes, gliding fish, gliding ants, etc.).

In this project, we aim at developing a fully autonomous palm sized microglider of around 10g that possesses the ability to self-deploy from ground or walls, to then open its wings, recover from any position in mid-air and subsequently perform goal directed gliding and attachment to walls.

We present our first two steps towards this completely autonomous self deploying microglider and put it in perspective to further intentions.

The first step in our exploration of gliding as a biologically inspired and complementary locomotion method in the domain of miniature robotics, we developed a 22cm long microglider [3] (figure 1) weighing a mere 1.5g and flying at about 1.5m/s. It is equipped with sensors and electronics to achieve phototaxis, which can be seen as a minimal level of control autonomy. A novel 0.2g Shape Memory Alloy (SMA) actuator for steering control has been specifically designed and integrated in order to keep the overall weight as low as possible.

The second step that has been accomplished is the realizations of a 4.5g wing folding mechanism (figure 2) that uses the same principle as bats to fold its wings [4]. This design has been chosen because of its conceptual simplicity, compactness and structural stability when open. A novel SMA based releasing mechanism has been developed and integrated that allows a very quick unfolding of the wings (less than 50ms). This light weight wing folding mechanism is an important milestone in order to allow the microglider to deploy itself as far as possible with folded wings and then open its wings and perform stable gliding.

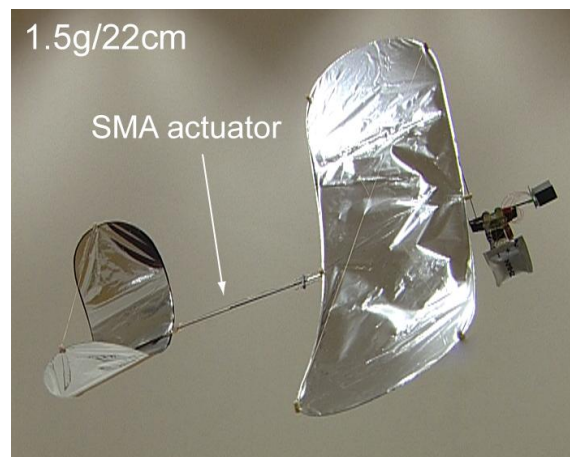


Figure 1. 1.5g Shape Memory Alloy-actuated microglider capable of autonomous phototaxis.



Figure 2. Novel bioinspired 4.5g bat-like wing folding mechanism

Further critical issues on the path towards the realization of our self-deploying microglider are (i) the trade-off between passive stability, maneuverability and maximal gliding ratio [5] (ii) the low Reynolds number ($<10^4$) that leads to increased influence of boundary layer effects and renders the applicability of the conventional and well known large scale aerodynamics impossible and (iii) the control of the unsteady dynamics during recovery and flight. The work in progress addresses these aspects. Embedded mechanisms for autonomous self-deployment from ground or walls into the air will be considered at the next stage.

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Neuronal Efficiency: a Guiding Principle?

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Efficiency, the ratio between performance and cost, is a useful quantity in physiology because its analysis forces us to define valid measures of function and identify constraints, and encourages us to consider how systems are assembled and designed to operate effectively. Ramon y Cajal's observation that nervous systems are wired up to maximize efficiency has been verified repeatedly [1], and the proposition by Horace Barlow, that neuronal coding is organized to neatly package information within a neurons' limited representational capacity, accounts for a variety of sensory processes [2]. The explanatory power of "neat packaging" was first demonstrated in blowfly [3], suggesting that neuronal efficiency is important for the control system of this high performance insect.



Figure 1. Blowfly flight demands an efficient control system, in which neurons are used advantageously (photo: M Parsons).

I review how fly visual systems are organized to operate efficiently by starting from first principles. Some universal properties of neurons (membrane capacitance, the use of ions to generate potentials and conduct charge, and membrane bound receptors and ion channels) limit representational capacity by constraining bandwidth, response range, signal to noise ratio and energy efficiency. The effects of these constraints are demonstrated both theoretically and experimentally. Stochastic and deterministic models of neural membranes show how channel noise limits energy efficiency and demonstrate that efficiency can be improved by using voltage-gated channels to match the gain and frequency response of photoreceptor membranes to signal quality. Comparative studies of fly photoreceptors show that, because metabolic costs rise non-linearly with performance, it is critical to match investment in sensory performance to behavioural requirements [4]. This match can explain the large differences in photoreceptor size observed among insects.

The photoreceptor studies show that neurons use their strengths (flexibility through variations in structure and molecular composition, short and long term adaptation to changing demands) to offset their weaknesses (low representational capacity). Efficiency could also be improved by combining analogue and pulsatile signaling, by exploiting neurons' capacities for making widespread connections, and by using distributed codes. I consider these factors within the context of recent work on lobula plate tangential neurons

and conclude that efficiency illuminates both the gathering of sensory information, and its downstream processing and distribution.

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The Limits of the Visuo-motor System in Flying

Fruit Flies *Drosophila*

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Flight behavior in flies is shaped by the limits of both (i) the sensory system that encodes information coming from the antennae, the compound eyes, the ocelli and mechanoreceptors, and (ii) the motor system that precisely controls aerodynamic forces by subtle changes in wing motion. There is a continuing debate on the role of each of these components for flight stabilization, visual orientation and aerial maneuverability in insects. This lecture thus highlights some of the features of the *Drosophila*'s flight motor and evaluates the significance of the interplay between sensory information processing and motor control for aerial performance.

Fruit flies possess two different major mechanisms for stabilizing flight: the visual system and the gyroscopic halteres. When flown under tethered conditions, the animals typically exhibit optomotor and object fixation behaviors in response to moving visual stimuli. Findings from freely flying flies, however, suggest that image speed on the retina often exceeds the threshold of the visual system and flies should thus predominantly rely on haltere feedback control. To explicitly test this assumption and thus the limits of visual flight control in *Drosophila*, we scored tethered flies flying in a flight simulator on their ability to visually track moving objects. For this purpose, we employed a novel physics engine for feedback simulation that mimics free flight conditions based on analytical modeling. The model predicts and our behavioral data show that in *Drosophila* body friction dominates flight, not body inertia, which contradicts previous findings derived from freely flying animals. Our data are consistent with the suggested role of the halteres for flight stabilization during saccadic flight because visual tracking performance of the flies collapses near the physical conditions estimated for freely flying animals. The kinematic analyses, however, suggest that this measured loss of flight control might be in part due to a limited fine control in the fly's steering muscles below a threshold of approximately 1° wing stroke amplitude rather than being the consequence of the limits of visual motion detection by the fly's compound eyes. Consequently, in freely flying animals the precision of yaw torque control might be enhanced by other kinematic parameters such as the wing's rotational timing and flip duration at the end of each halfstroke.

Despite of the suggested role of the halteres for flight stabilization, freely flying fruit flies change their flight behavior to compensate for the retinal slip on their complex eyes. We showed this by scoring freely flying *Drosophila* on their ability to compensate the rotational motion of a random dot visual environment. In these experiments, we measured horizontal, angular and vertical velocities of single flies using high-speed video analysis and estimated gaze to evaluate retinal slip compensation in response to the rotating visual panorama. In a stationary visual environment, flight is characterized by straight flight sequences and low angular velocities that are more frequent than angular velocities typical for flight saccades. During optomotor stimulation, *Drosophila* compensates for retinal slip by increasing both angular and horizontal velocity that results in a continuous turning behavior. With increasing stimulus strength, the radius of the circular flight paths increases likewise supposedly due to an increase in centrifugal forces acting on the animal's body. The fly may achieve retinal slip compensation at stimulus velocities of up to 500° s^{-1} at which the animal achieves maximum horizontal and angular velocities at approximately 485 mm s^{-1} and 612° s^{-1} , respectively.

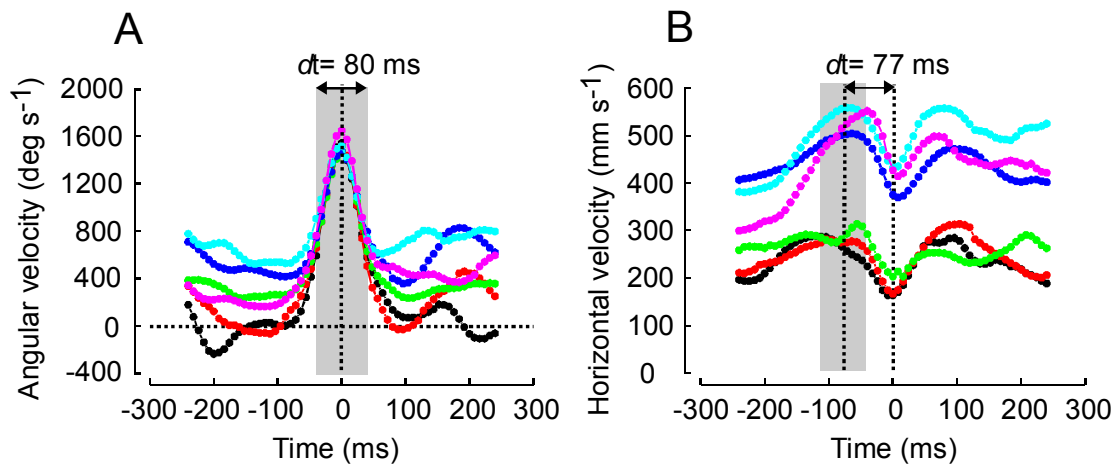


Figure 1. Angular and forward velocity of fruit flies during flight saccades. Data show that the fly increases velocity before initiating the turn. Forward speed decreases during turn due to the production of centripetal forces.

To approach the limits of this behavior, we developed an analytical model based on force balance that allows predictions of flight path curvature at various combinations of horizontal and angular velocity. The model fairly matches the experimental data assuming maximum short burst flight performance of approximately 2.7 times body mass that appears close to values reported previously for this insect. Interestingly, at maximum forward speed *Drosophila* spends approximately 50% of its maximum total aerodynamic force on the compensation of centrifugal forces during turning. In many insects centrifugal force may be compensated by banking the insect body towards the inner side of the turn. The data in Fig. 1 show that banking behavior during flight saccades results in a temporally transient decrease in forward velocity of the fruit fly of approximately 150 mm s⁻¹. In sum, the presented findings contribute to our understanding of how the different sensory and motor pathways in an animal exactly interact during flight and to what degree those pathways might be redundant for both, the sensory encoding of feedback signals and the precision with which the animal controls aerodynamic forces and moments.

Novel Micro Aircraft Inspired by Insect Flight

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From insect flight to flapping micro robots

Recent advancements in micro-electronics and machining allow our society to start the prototyping of biologically inspired robots that fly like insects. Such new flight vehicles provide unprecedented surveillance opportunities with on-board optical, chemical and acoustical sensors. As an example I will present a recently developed flapping micro airplane 'Delfly' (figure 1) that can detect targets with an on-board camera system (co-developed by the TU Delft, Wageningen University and Ruisink Dynamic Engineering, [1]). One of the key challenges for developing such micro-mechanical insects is to simplify the flight system such that they are easy to design, produce and operate. Here I propose to not copy nature's flapping wings directly but to utilize recently gained insight into the aerodynamics of insects to simplify the design along the principle 'less is more'.



Figure 1. Delfly; a fully functional flapping micro plane inspired by insect flight.

Development of simple micro airplanes

The remarkable flight performance of insects is largely due to a stably attached leading edge vortex (LEV) on top of their wings [2,3]. The question emerges, however, if we need to flap a wing as complex as an insect does to obtain the flight performance of insects. As they flap back and forth, insect wings revolve around the hinge at their base, as propellers do around their shaft. Although both insect wings and propellers based on insect wings can generate stable LEVs and corresponding high lift under certain conditions, LEVs are always unstable when generated by two-dimensional wings that flap in a translational fashion. The mechanism that accounts for the stability of LEVs on revolving wings under some conditions and their shedding on translating two-dimensional wings is not fully understood.

Mastering the trick of insects: stabilize a LEV

Based on a recently study in collaboration with Michael Dickinson (Caltech) I show that LEVs on revolving wings are stabilized by centripetal and Coriolis accelerations provided that the Rossby number, a dimensionless number that measures the relative importance of these rotational accelerations, is of order one. This implies that the key kinematic feature necessary for LEV-based aerodynamic force in insect flight is not the back and forth flapping of the wing but rather its propeller-like revolution. Experiments show that this mechanism operates within a Reynolds number range of at least 110 to 14,000 and that even LEVs that have undergone spiral bursting

remain coherent and continue to generate elevated aerodynamic force. These findings are analogous to observations on propellers and wind turbines at Reynolds numbers above 1,000,000, which suggests that this mechanism extends across an even larger range of scales, well beyond the realm of flying insects.

Such a large range of scales provides unprecedented inspiration for the development of novel micro aircraft. By stabilizing LEVs with a revolving, insect-like wing our future vehicles will be able to generate up to twice as high forces compared to conventional micro air vehicles, at an efficiency that is significantly larger than that of insects. For this the revolving wing should operate at a low enough Rossby number. Experiments show that a Rossby number close to 3 in hovering flight is sufficient to stabilize LEVs effectively. This value is similar to the average value found for insects, bats and birds during take off and landing, and in some cases hover flight. Hence the required drive system can be significantly simplified, from insect to propeller-like, provided that the Rossby number of the wing is kept low enough. This finding can accelerate the development of bio-inspired aircraft that range from large Unmanned Air Vehicles to future Nano Air Vehicles.

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A Simple and Robust Fixed-Wing Platform for Outdoor Flying Robot Experiments

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In the last decades, the development of flying robots has made much progress. However, a flying platform for outdoor robot experiments, in particular research in collective systems, which fulfills the main criteria of safeness, ease of use, robustness and simplicity does not exist yet. Rather, current systems (e.g. the ones used in [1], [2] and [3]) tend to be dangerous in case of crash, are difficult to operate (requiring a technical staff and expert safety pilot) and expensive especially because they rely on complex sensors such as GPS, inertial measurement units (IMU), active range finders or complex vision processing.

Motivated by the so-called Swarming MAV project, currently under development in our laboratory (<http://lis.epfl.ch/smavs>), we are in need of a simple, cheap and robust aerial robotic platform, capable of completely autonomous flight. In the project, a swarm of flying robots will establish a communication network in the air: MAVs will interact and communicate with airborne fellows and ground stations. Being able to hover is not required, neither is the ability of absolute position detection. In order to develop a suitable aerial platform, we propose a concept that is different from the conventional approach: In terms of sensory modalities and flight control, instead of using an IMU and GPS, we aim at a system with a minimum number of sensors and simple, Braitenberg-like control laws based on direct input from the sensors. In this paper, we show the viability of such an approach.

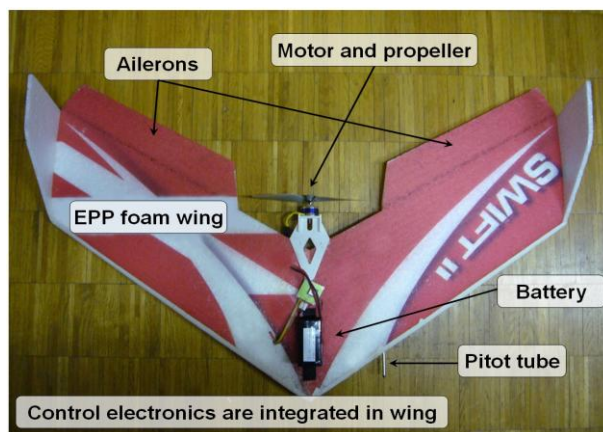


Figure 1. A simple and robust fixed-wing platform for robotic experiments (80 cm wing span, 350g weight - fully equipped -, 30min endurance)

In terms of platform hardware, and at the current stage of development, the chosen airframe is a very low-cost, commercially available flying wing made of expanded polypropylene (EPP) foam (Fig. 1). It has been chosen for its resistivity to crash, good flight behavior in windy conditions, and reasonably low weight (max. 350g). The platform's control electronics consist of a tiny microcontroller (dsPIC) and no more than 4 sensors: a differential and an absolute pressure sensor permit to determine airspeed and altitude, 2 rate gyros measure the plane's rotational speed around the yaw and pitch axes. The basic flight

control strategy uses the raw sensor values and is able to robustly steer the plane to autonomously take off, reach a predetermined altitude, circle with a constant turning rate, and land after a given time or when triggered. An example of an autonomous flight is depicted in Figs 2a and 2b.

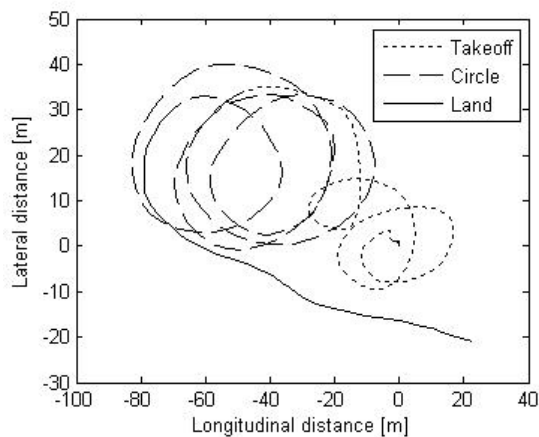


Figure 2a. Top-view of the trajectory for 3 autonomous flight phases. Switching between phases is done manually.

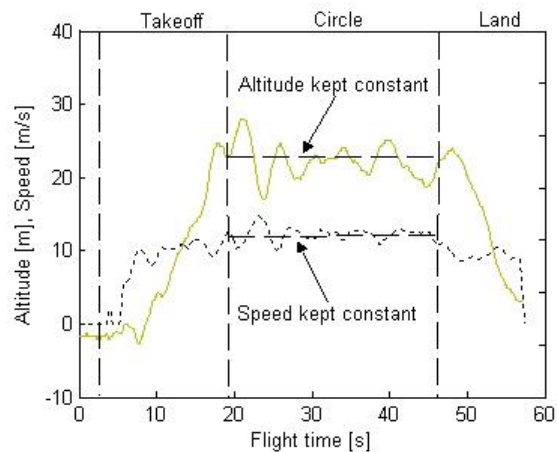


Figure 2b. Altitude and flight speed measured with the absolute and differential pressure sensors.

The main properties of this platform, i.e., ease of use, simplicity and robustness, make it ideal for real-world experiments in outdoor aerial robotics. Apart from its first application with the Swarming MAV project, it will particularly help to promote research in bio-inspired, collective and swarm aerial robotics.

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Cyberfly: Understanding Fly Flight Behaviour by Closed-loop Simulation

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Flies serve as a model animal for the investigation of visual motion analysis and visually guided behaviour for many years. The sensory physiology of the motion vision system of these animals is known in great detail. Quantitative models can accurately predict the responses of large-field motion sensitive neurons to natural images moving with dynamics recorded in free flight [1, 3]. Much less is known about the circuits evaluating the signals of these motion sensitive visual interneurons and eventually controlling flight behaviour of the animals. In closed-loop simulation experiments coupling the quantitative sensory model to movements of a virtual animal with motion dynamics close to the dynamics observed in blowfly free flight, we tested a hypothetical sensory-motor interface for its ability to avoid the walls of a cylindrical flight arena.

The model

The sensory model consists of correlation-type elementary motion detectors (EMDs) detecting horizontal image movements in a cylindrical projection of the simulated 3D environment. The responses of the EMDs are nonlinearly spatially pooled by simulating the electrical equivalent circuit of a one-compartment passive neuronal membrane. This pooling reduces the dense optic flow field to a low dimensional time-dependent neuronal activity known to carry information on the egomotion of the visual system [2]. This signal is fed into a sensory-motor interface mimicking the saccadic flight strategy of flies by generating pure translatory movements intermitted by fast short turns, where the amplitude and timing of the turns is determined by a simple feed-forward evaluation of the activity of the sensory neurons. The velocity profile of the turns was matched to the saccadic turns of freely flying flies. An example for the trajectories generated by this model is shown in figure 1.

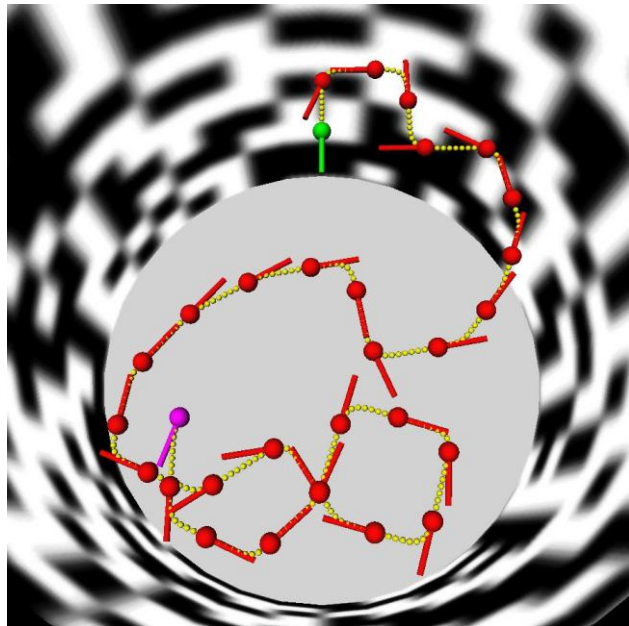


Figure 1. Trajectory generated by the closed-loop simulation. The wall of the cylindrical environment is avoided based on visual motion information.

Results

By the closed-loop simulation of this simple model of the fly flight control system we could show that the information coded in the signals of identified motion sensitive visual interneurons can be exploited to generate obstacle avoidance behaviour. Furthermore, the simulations add evidence to the hypothesis that the saccadic flight

strategy of blowflies serves to separate rotational and translational components of the optic flow and thereby makes available information on the relative distance to obstacles in the responses of wide-field motion sensitive neurons.

The system presented here is not meant to be an exhaustive model of the blowfly flight control. Nevertheless the results are encouraging for the approach to understand the evaluation of sensory neuronal signals by sensory-motor interfaces under closed loop conditions in simulation experiments.

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aVLSI Motion Detection Circuits

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We are developing motion aVLSI circuits [1,4,5] that capture the various principles used in the motion processing circuits of the fly. These circuits (Figure 1) include front-end photoreceptor circuits that adapt to the background intensity thus allowing the sensors to code motion over a wide range of background values. There are many benefits to using these chips on a robotic platform for measuring image motion. These benefits – *low-power consumption, parallel, collective computation, light weight* – make them attractive for mobile, battery-powered platforms, especially for autonomous micro-flying devices [2, 3,6]. The model on which this chip is based provides for motion outputs that are invariant to a range of spatial and temporal frequencies in the image.

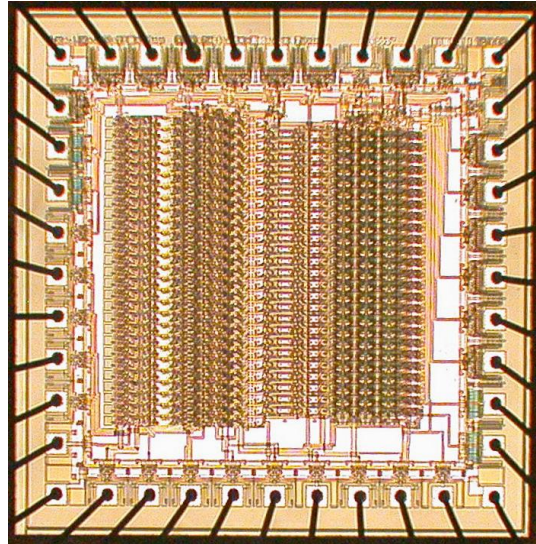


Figure 1. Microphotograph of a prototype one-dimensional motion chip.

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Static and Dynamical Biological Observations of Dragonfly's Wings

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In order to increase our knowledge of the aerodynamic behaviour of the insect flight and then of flight control, we started to focus our biological observations on the structural specificity of the dragonfly's wings [1]. This study was done in the LMCE with young dragonflies (*Aeshna cyanea*, *Anax imperator* and *Orthetrum cancellatum*). We developed methods for maintaining and conducting in the LMCE a breeding of dragonflies from larva to adult so that we can conduct these observations. First, the static aspect of the wings was analysed by using optic microscopy in association with the scanning electron microscopy (SEM). These observations enabled to collect useful informations concerning the structure aspect [2-3] such as veins network. The next point of this static stage was to confirm and study the circulation of the haemolymph described before [4].

The dynamical biological observations were done in both LMCE and the nature by using a high speed motion capture videocamera^b at a level of 3000 pictures per second.

The first movie that will be presented during the symposium will describe the takeoff of an anisoptera dragonfly (*Aeshna cyanea*, wingspan: 14 cm). The second movie concerns the takeoff of a zygoptera dragonfly (*Platycnemis pennipes*, wingspan: 7 cm). The comparison of these two movies reveals a first major difference in the wing's deformation which can be explained with the difference of wing's mass and rigidity. However much more details can be collected by those simple observations such as the independent control of each wing previously suggested by the neuroanatomy [5-6]. The visual analysis of the dynamical wings deformation revealed also inertial effects on wing's structure and suggested us, indirectly, useful aerodynamic informations. We will describe these informations during the symposium.

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Principles of Multisensory Flight Control in the Fruit Fly – a Reverse Engineering Approach

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Introduction

The fruit fly *Drosophila* achieves impressive flight control despite its tiny size, and hence limited neural resources. Its straightforward ‘helicopter-like’ control strategy involves the precise control of body posture from subtle changes in wing motion [1], which consequently lead to the desired changes in flight velocity.

While visual input often provides the external stimulus to elicit flight maneuvers, the control of body posture also requires reafferent feedback from mechanosensory systems, such as the halteres, which function analogously to a helicopter’s gyroscope [2]. To fully understand the fruit fly’s flight control strategies, therefore, the interactions between multimodal sensory inputs [3] need to be explored under realistic flight conditions.

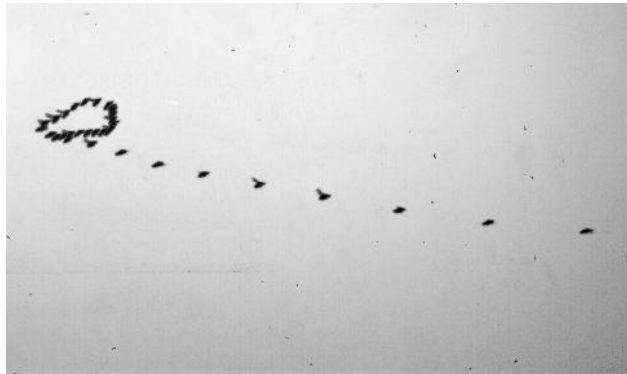


Figure 1. Flight sequence captured from the side using a high-speed camera.

Experimental approach

We explored the principles of multimodal neuromotor control based on the fruit fly’s groundspeed response, which depends on visual input as an external control input, as well as proprioceptive mechanical stimuli for the control of body pitch. This well defined and amenable behavioral paradigm allows relevant components of the underlying neuromotor control system to be measured and the control principles to be identified. Precise stimulus control and behavioral read-out was achieved using ‘FlyTrack’, a wind tunnel equipped with ‘virtual reality’ technology [4].

Results

Speed responses were elicited by stimulating individual flies visually in ‘virtual open-loop’, with a step increase of retinal slip speed (see Rohrseitz et al.), while the body pitch angle and position of the fly were measured using a high-speed computer vision system. We then performed a control systems analysis of body pitch control based on the known visual input and the angular velocity encoded by the halteres [5]. A more detailed model of the encoding of mechanical stimulation by the halteres provides the basis for a robust feedback control model based on mechanosensory reafference.

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aVLSI Motion Detection Sensor for Estimation of Optical Flow

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Neuromorphic analog Very-Large-Scale-Integrated (aVLSI) motion sensors which output optical flow information are ideal for robotic platforms and microflyers. The implemented models range from motion energy, token-based, correlation-based, and optical flow algorithms [1-6] which model the motion processing circuits in biological systems like insects. Many of these chips include front-end photoreceptor circuits that adapt to the background intensity [7] thus allowing the sensors to code motion over a wide range of background values.

The multiple benefits of these sensors – low-power consumption, parallel, collective computation, light weight – make them attractive for mobile, battery-powered platforms, especially for autonomous micro-flying devices. In addition, the VLSI motion outputs are more invariant to a range of spatial and temporal frequencies in the scene.

We present a motion chip with 24 pixels which is designed for a microflyer [8]. The layout of the chip is shown in figure 1. The front-end photoreceptor circuit responds to local contrast and adapts over 10 orders of magnitude of background intensity [7]. The photoreceptor output is processed by subsequent circuits that detect a pre-defined feature. Motion is then computed by measuring the time taken for the feature to travel across 2 pixels and using the time-to-travel algorithm design implemented by Kramer and colleagues [2]. Results from their design show the promise of the use of this chip on a robot in a navigation task [9].

There are three main differences in our circuits from the design in [2]. First, the pre-defined feature is detected through the use of 2 global thresholds. This allows us to

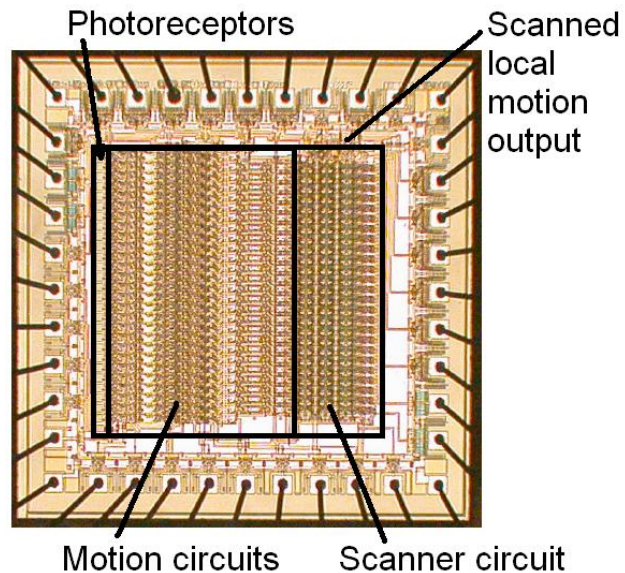


Figure 1. Layout of the motion detection chip.

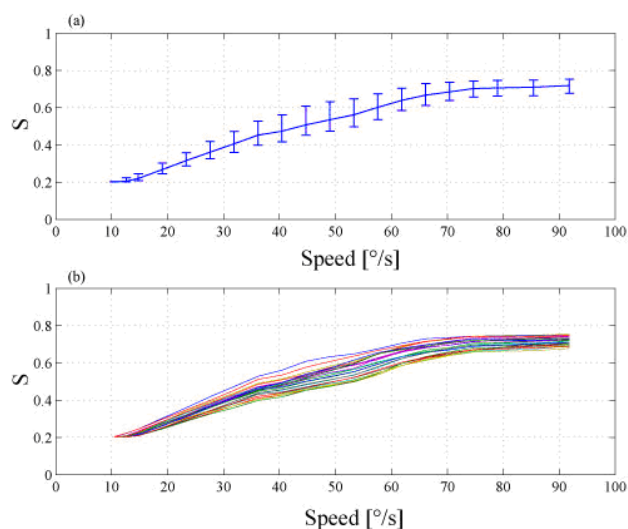


Figure 2. Measured motion output of the chip. a) Global average of average response for all pixels. Error bars showing maximum and minimum response. b) Average response of all pixels.

reliably detect a feature in the presence of noise down to a contrast of 2.5%. Second, even though the system in [2] can measure a speed range over 7 decades, the signal-to-noise (S/N) resolution of the motion output is not constant for all speeds because of the compressive encoding of the speed.

Because the micro-flyer in [8] does not need such a large range of speed detection, we have altered the circuits to give us a higher S/N ratio for 2 decades of speed. Third, we included a scanner circuit which allows readout of local pixel information and we placed the motion comparator circuits after the scanner to reduce pixel mismatch.

Figure 2 shows the measured response of the motion chips when being stimulated with noisy moving bar patterns that are displayed on a screen. The output S is calculated from the chip output V_{out} as $S=(1/(V_{dd}-V_{out}))$. Figure 2 shows that we are able to cope with the noise and that we can extract motion information over 2 decades of stimulus speeds.

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Flying Paradise: Purgatory for Simulation, Hell for Engineers

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Introduction

Flying insects benefit of million of years of *evolution*. We started only recently to mimick them [1], and we are faced with inadequate power sources and energy transformation mechanisms. Simulations get rid of this, but the complexity of the movements, the number of sensors and complex aerodynamic laws slow down the progress.

We engineers dream of doing in a few years what evolution did along millenaires—but we use inadequate technologies! In this talk, we will review current solutions and hopes for the future.

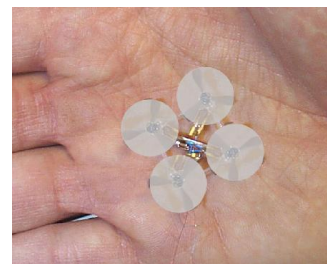
UAV (unmanned aerial vehicle) benefit from huge military money. Power from fossile fuel allows to carry the most sophisticated electronics for mostly straight line fast flights. MAV (*miniature AV*) and NAV (nano AV) have to use battery power, the hope being for a soldier to take out of his pocket a spy plane he can pilot around. University research labs work with less money on similar projects hoping to monitor environmental parameters, survey distant areas, or help for rescue. GPS, vision recognition software helps a lot in these projects. Only few try to mimick flying insects and face with the hard technological problems. Low cost flying toys makes one believe it is easy to do a flying robot. Let us try to understand where the difficulties are.



UAV



Silverlit X-ufo toy



Stanford Mesicopter

Figure 1. Three sizes, three objectives, three technologies

Similitude laws

Simple formulas show that mechanical strenght is better on small constructions. But energy storage is not good and motors loose their efficiency when dimensions decrease. Aerodynamics laws say one should fly at slow speed to save energy, but this means large dimensions and low *Reynold numbers* [2]. Models are missing to study all these aspects.

Motors

Brushless DC motor are quite powerful above 3 grams. DC “pager” motors go down to 4mm and can propel a 10 grams robot plane [3]. Smaller ones have a poor efficiency and may need a quite heavy controller. *Micro-turbines* are under research for many years. *Piezoelectricity* has limited applications. When will something like a muscle be invented?

Actuators

Actuators are required for moving control surfaces or deforming the structure. They must provide a movement or a torque proportional to a control voltage or current. Coils, geared motors (servos), *shape memory alloys* are commonly used by hobbyists. *Electroactive polymers* have quite narrow applications, and like piezo éléments, they need usually excessive voltages. *Proprioception*, essential to living creatures, must be added with adequate sensors, if possible and practical.

Construction, materials

Carbon fiber is a perfect material, light, flexible, resistant. Foams, like EPP used in toy planes, looks light, but they need volume. It is amazing how a little bit of steel or copper increases the weight. Wings and propellers are the most difficult to optimize: they get deformed in flight and models are difficult to apply, supposing they exist.

Sensors

Electronic sensors are progressing very well. Gyros, pressure, temperature, force sensors are getting smaller every year, but connectors and wiring is a major problem if the number of sensor increases above 5 (how many in an insect?).

Navigation and communications

Regarding embedded electronics, one can expect powerful functions and software in micropackages. The GPS still needs few square cm and Bluetooth much less. Their antenna need some space, but almost no weight.

Conclusion

There is still a long way from the recent first flying robots that avoid walls in a square room to artificial flying insects. Let us try to imagine the next steps taking care of the limitations of present technologies. As long as new energy sources and new 3D constructions are not found, progress will be very slow.

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Words in italic means you find good documents searching with these keywords under Wikipedia or Google.

Design of Solar Powered MAVs: Scaling Considerations and Realization

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Introduction

In recent years, the level of interest in the development of fixed-wing MAVs for various missions has risen significantly. A crucial issue concerning these aircraft is their high power consumption compared to their limited energy storage capability. This leads to an endurance that rarely exceeds 30 minutes.

One possibility to increase the up-time is through the use of solar cells. Connected via a power adapting electronic circuit, they can supply the motor and the electronics and also charge the battery. The battery would be used as a buffer when flying under clouds or in darkness. The design of the energy train, including the solar cells, MPPT, battery and the propulsion system has to be optimized to limit power consumption and increase overall efficiency. This paper presents the design of the Sun-Surfer, a 77 cm wingspan solar UAV.

Conceptual design Methodology

Within the framework of the Sky-Sailor project [1], a conceptual design methodology was developed.

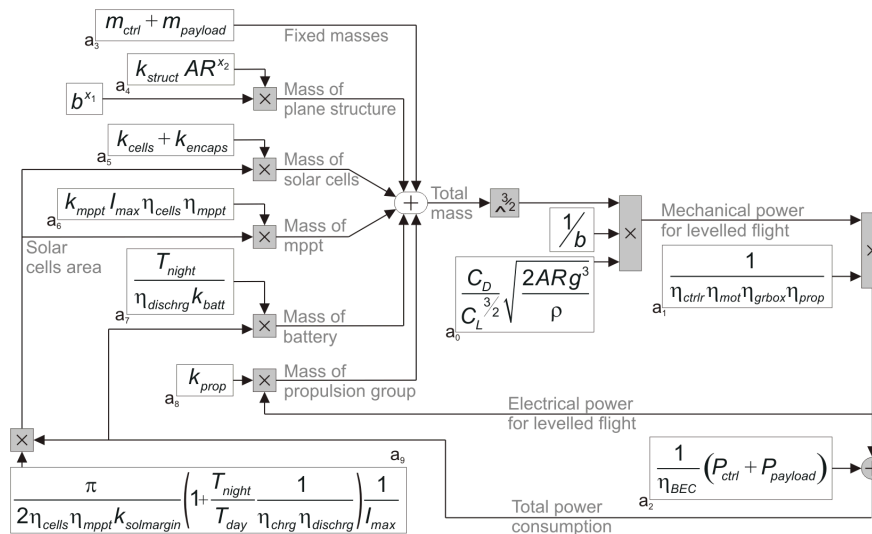


Figure 1. Schematic representation of the design methodology

The aim of this particular procedure is to be applicable for the design of solar powered MAVs, UAVs and manned airplanes. As demonstrated in figure 1, the methodology is based on a mass and energy balance that can be represented in a circular loop. Taking into consideration aerodynamics and propulsion, the combined mass of all relevant aircraft components determines the electrical power required for level flight. The resulting value in turn constitutes the input for the design of elements like the battery, solar cells, mppt, etc. Elaboration on this methodology is available in [1].

Scaling considerations

The inputs of the design methodology are parameters related to mission requirements (i.e. payload, flight time), airframe design (i.e. aerodynamics, structural mass) and available technology (i.e. battery energy density, propulsion and solar cell efficiencies, nanotechnology).

For MAVs with a wingspan under 1 m, aerodynamics properties deteriorate due to low Reynolds number induced by low speed and limited chord [4]. Difficulties also arise with efficiencies of motors and small-sized propellers. For these reasons, our work is mainly concentrated on the global design of the airplane and the study of these key elements.

Sun-Surfer

The Sun-Surfer MAV was designed with the target to carry 20 grams of payload and be able to fly continuously during favorable weather conditions [5]. Moreover, its buffer battery should be able to power the aircraft for 30 minutes on its own.

Preliminary experiments with remote controlled flights showed good stability and an efficient management of solar energy.

The next steps will focus on improving the airfoil and the general structure, looking for lightweight construction methods that allow an easy integration of the solar cells in the wing, and designing a very small autopilot system for autonomous flight control.

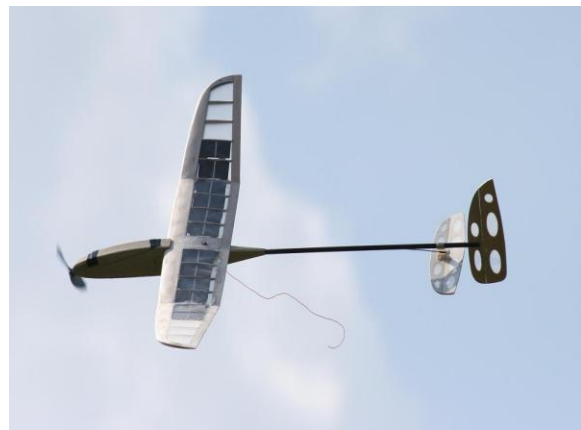


Figure 2. The Sun-Surfer prototype in flight

Potential Applications

The ability to fly autonomously for many hours makes these solar MAVs suitable for a wide range of applications. This includes surveillance mission over a crowd or exploration mission in contaminated areas where human presence is impossible.

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Bio-Inspired Structures for the Actuation System of a Flapping Wing Micro Aerial Vehicle

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Context

This paper will present structural results obtained in the frame of the REMANTA project (REsearch program on Microvehicle And New Technologies Application) [1]. This in-house funded project was carried out by Onera during the last four years in order to improve our knowledge on science fields required for realizing a Flapping Wing Micro Air Vehicle. The three addressed topics consist in unsteady aerodynamics at low Reynolds number, non-linear command laws with periodic inputs, and actuation systems for flapping movement. The latter is addressed in the present paper.

Bio-inspired structural concept

From bio-mimetic considerations, a concept for wing actuation based on a structure with induced twisting of wings was proposed. Among the insects, the dragonfly seems to be of particular interest. Indeed, the wings have a flapping movement in a plane fixed with respect to the body of the insect but no lead-lag movement contrarily to smaller insects (i.e. flies). This movement requires only one axis of rotation and so, a demonstrator using this principle of flight is easier to manufacture. It was established that during the flapping movement the shape of the wings is mainly governed by the inertial forces due to the flapping movement and only partially by the aerodynamic pressure [2]. Therefore, as a first approximation, the shape of the wings does not depend on aerodynamics, which in turn may be computed around instantaneous deformed shapes considered as rigid. In other words, aero-elastic coupling can be neglected in a first step and the structural and kinematics problems may be studied independently at first.

Resonant thorax

The flapping movement is imposed by a structure inspired from nature [3, 4]. It comprises two main parts, a stiff U shell having an elastic linear behavior and a pre-stressed plate having the shape of a cylindrical surface and a non-linear behavior. This pre-stressed plate may be assumed to be simply supported by the U shell thanks to a specific restrain design, favoring the relative motion of the two parts. This structure will be named "thorax" in the following (figure 1). When the U shell is subjected to sinusoidal forces, the upper pre-stressed plate is driven up and down by this U shell and exhibits a non-linear movement, resulting in large rotations at both supported ends of the plate. The wings attached to this plate near the junction with the U shell have also a non-linear movement characterized by an almost triangular rotation angle versus time for which the angular flap velocity is almost a square signal. This was verified experimentally on a mock-up manufactured at 10:1 scale.

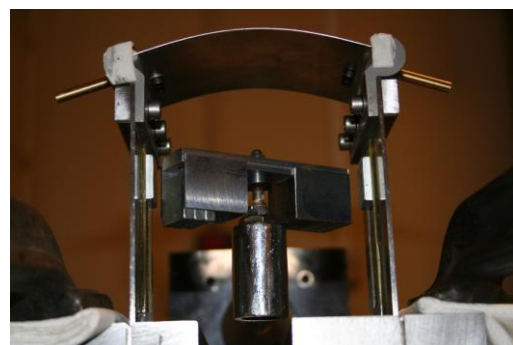


Figure 1. 10:1 scale mock up

Passive ultra-lightweight wings

The dragonfly wings may be considered as stiff at the leading edge but chord wise flexible. This flexibility may be obtained either by torsion at the leading edge, bending of the chord wise structure or both. An examination of insect wings suggested making of fiber reinforced foils. Prepreg tows consisted of carbon fibers and epoxy resin offers an attractive solution. Flexibility can be adjusted by increasing or decreasing the number of carbon tows. A thermoplastic membrane bonded to the tow network for curing of epoxy resin represents an interesting ultra-lightweight composite system (figure 2). Dynamic flexural tests show, this realization is a base quite suitable to meet the expected requirements for a MAV wing

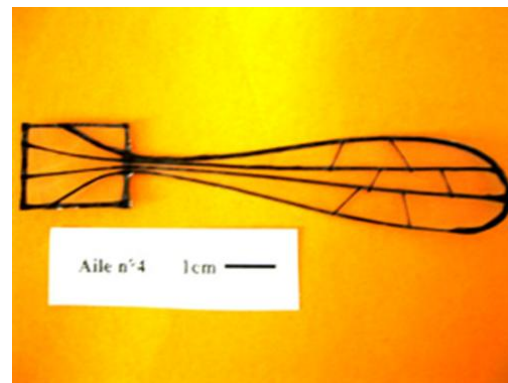


Figure 2. Ultra lightweight wing (< 100mg)

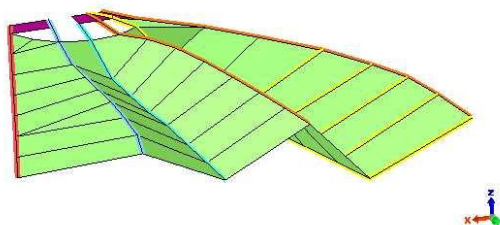


Figure 3. Structure study

Lastly, the assembling of present wings on a scale 2 mock-up was made. First tests showed that the wing is not stiff enough at the leading edge. Structural studies are in progress in order to solve this problem (figure 3).

Latest results will be presented.

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Virtual Bee in a Virtual Tunnel: Modelling Angular Speed Detection

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The first and most famous model of motion detection was proposed by B. Hassenstein and W. Reichardt [1] to account for the experimentally observed temporal frequency sensitivity of an insect visual system. However, later experiments demonstrated that the insect visual system is also sensitive to angular speed [2-5], an effect not reproduced by the Hassenstein-Reichardt model.

Here we propose a model which accounts for angular speed sensitivity in insects (Fig. 1). The left and right eyes of a virtual bee are composed of single rows of receptor units each separated by the same inter-receptor angle (three receptor units are shown in Fig.1). A receptor is activated (1) upon detecting an edge, that is, an above-threshold change in the green contrast of the observed pattern. The faster the image moves, the smaller the time difference between adjacent receptors' activations. To measure image speed, we multiply (2) receptor output by the output of the neighbouring receptor and add (3) all products for each eye. This produces a response which is pseudo-constant even for low spatial frequency patterns and increases with relative speed, as has been shown for speed detecting neurons [3, 5]. However, the summed response also increases with the apparent temporal frequency perceived by an animal, a feature not seen in behavioural experiments [6]. To remove this temporal frequency dependence, we divide (5) the sum of the products (3) by the sum of receptor outputs (4).

As there is evidence that bees adjust their speed so as to keep apparent image speed in a certain range, we modelled a bee's path in a tunnel of variable width with striped patterns on the tunnel walls (Fig. 2). The difference in the outputs from left and right eyes causes the bee to turn away from the wall generating the higher response. In this way, the model demonstrates a centring response seen in real bees [4, 6]. The simulated bee also alters its linear speed as the tunnel narrows and widens, thus maintaining the apparent angular speed of the pattern within a small range. Keeping angular speed approximately constant enables animals to use optic flow information to evaluate flown distances [2, 7]. The modelled bee was also able to navigate successfully in a tunnel horizontally moving walls with both regular and random patterns.

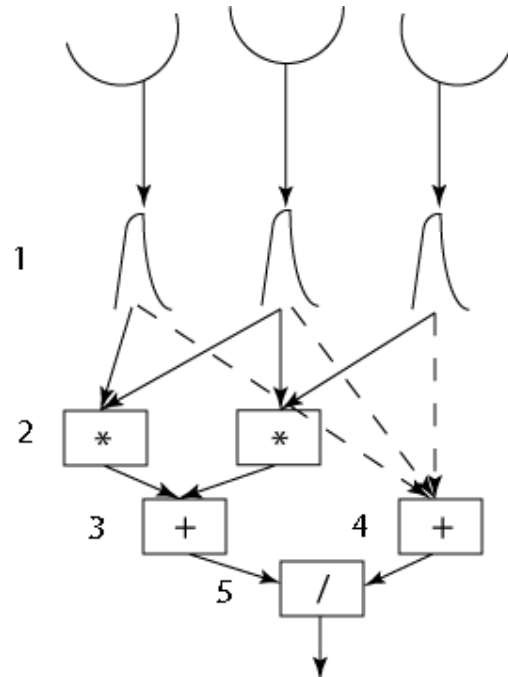


Figure 1. Scheme of the model. See text for detail.

For a more thorough assessment of the model, we have built a simple odometer from our model speed detector and assessed its performance over a range of input signals. While model performance degrades with high (linear) pattern speeds and spatial frequencies, it gives reasonable results over a range of spatial frequencies and velocities a real animal is likely to encounter.

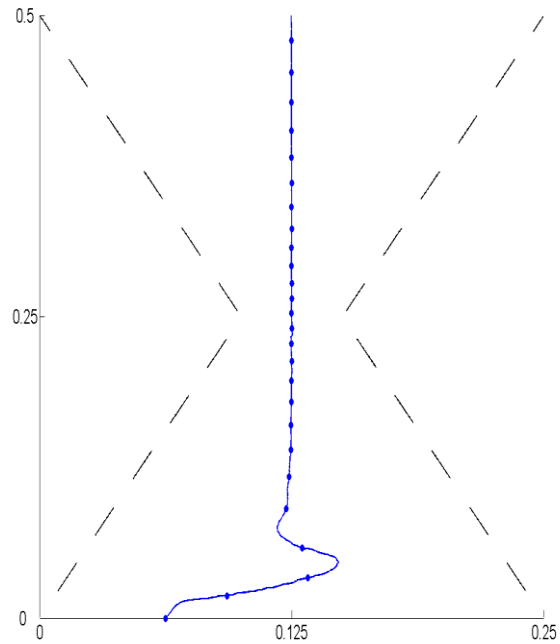


Figure 2. Example trajectory of a virtual bee viewed from above. The bee flies in a tunnel of variable width. Dots show the bee's position every 0.1s starting from the bottom of the figure.

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The Significance of Wake History on the Aerodynamics of Steering Maneuvers in *Drosophila*

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Maneuverability and stability in flying insects rely on the precise control of wing motion on a stroke-by-stroke basis. The fruit fly *Drosophila* possesses neuronal control over several kinematic parameters such as the stroke amplitude, frequency and the timing of wing rotation during ventral and dorsal flip. Since aerodynamic forces produced by an insect wing depend on several factors including the instantaneous wing motion and wake history, transient changes in wing kinematics may produce considerable alterations in the aerodynamics of subsequent stroke cycles. A transient increase in down wash velocity from a previous stroke cycle, for example, might lower the wing's effective angle of attack. Changes in vorticity shedding at the end of

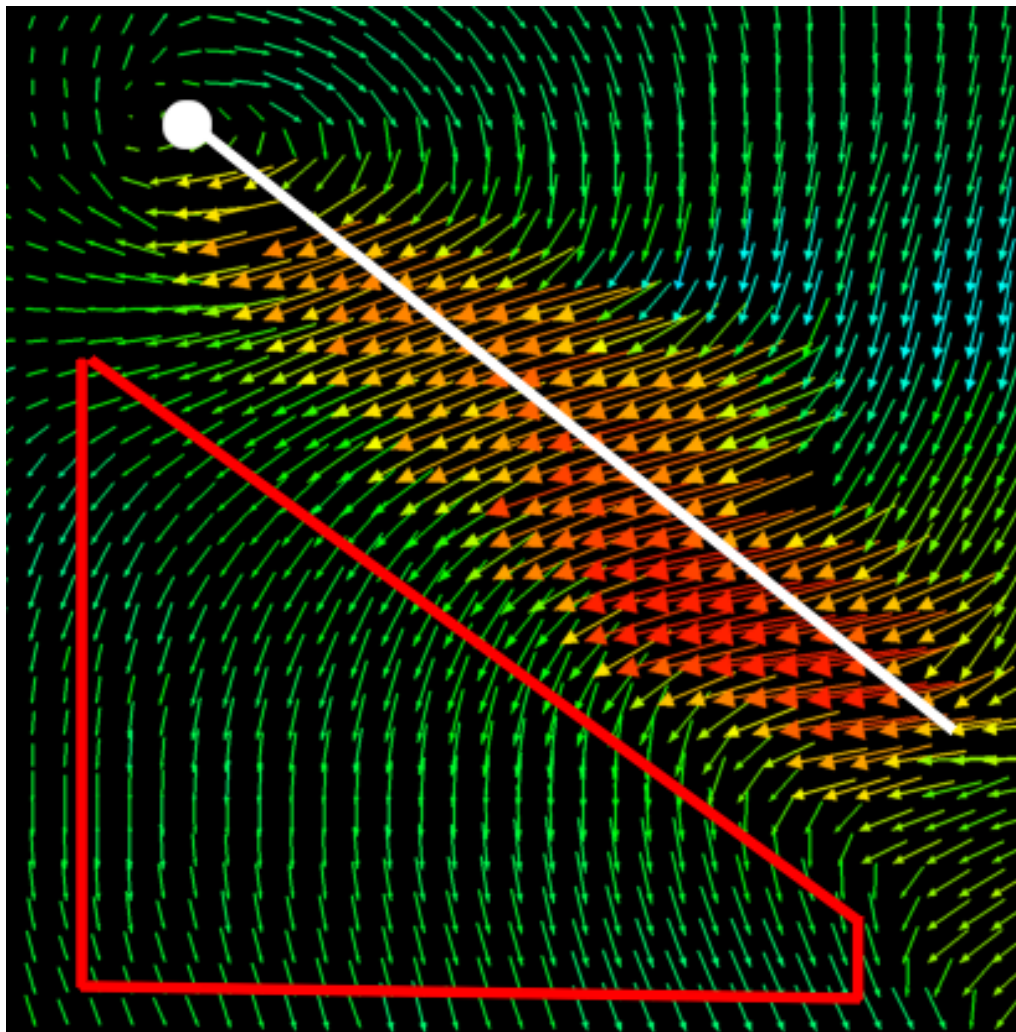


Figure 1. Flow field during mid downstroke. The white line and white circle mark the position of wing and leading edge. The light sheet intersects the wing at 2/3 wing span. The region of interest for downwash measurements is depicted as a red polygon.

each half stroke might interfere with leading edge vortex induction.

Thus, to explore the fluid dynamic consequences of wake-wing interactions during maneuvering flight, we employed a robotic *Drosophila* wing flapping with an uniform kinematic pattern. To mimic steering behavior, we systematically modified wing kinematics in a single stroke (CS, control stroke) within the sequence of 13 base stroke (BS) cycles. The induced changes in the (i) wing's effective angle of attack, (ii) circulation in the leading edge vortex and (iii) downwash velocity of subsequent stroke cycles, were determined by employing a novel type of stereo digital particle image velocimetry (3D-DPIV, Figure 1).

Modulations of the morphological angle of attack (AoA) in CS ranging from 30 to 60° suggest that the wake produced by the control stroke significantly alters downwash at least within the next two subsequent base stroke cycles. A decrease in AoA from 45 to 30°, for example, *attenuates* downwash velocity in the following cycle by approximately 10% at mid down stroke. A maximum decrease in downwash velocity of -50% we obtained at a 0° AoA control stroke. In contrast, an increase in AoA from 45 to up to 90° in CS, may *increase* down wash velocity of up to 25% in the subsequent stroke cycles, compared to downwash velocity based on BS kinematics. The above data imply that the production of forces and moments in flapping wings is shaped by the complex interaction between instantaneous flows and the wake produced in previous stroke cycles. Thus, inter-stroke wake-wing interferences should be considered as an inherent problem of any insect that attempts to achieve stable flight or perform elaborate aerial flight maneuvers.

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To scrutinize the logics behind the honeybee's lateral anti-collision system, we filmed bees (*Apis Mellifera*) flying freely through a flight tunnel and analysed the trajectory of individual bees frame-by-frame. The central part of one wall of the tunnel was moved steadily to alter the optic flow (OF) on one side (figure 1a). Kirchner and Srinivasan [1] showed that bees tend to centre in a narrow tunnel (0.12m-wide), and when one wall was moved, bees altered their lateral positioning. The authors suggested that bees would balance the left and right OFs.

a.

Video recorder

Moving wall

V_{Mp}

R_L

R_R

E_L

E_R

λ

1.5 m

1.21 m

3 m

0.25 m

0.95 m

b.

y (m)

$V_{Mp} = -0.60$ m/s

1.21

mean(V_x) = 1.67 m/s

V_x (m/s)

$V_x - V_{Mp}$ (m/s)

$R^2 = 0.99$

D_R (m)

- 91 -

When we moved one wall at a constant speed V_{Mp} , we observed that the forward speed $V_x - V_{Mp}$ of the bee relative to the moving pattern, and the distance D_L to this wall were maintained proportional to each other (figure 1b), as indicated by the strong R^2 -value of the coefficient of determination ($R^2=0.998$).

This means that the left OF (angular velocity $(V_x - V_{Mp})/D_L$) perceived from the moving pattern was held constant. Our hypothesis is that the flying bee is able to *regulate* (i.e., maintain constant and equal to a reference value) the lateral OF on one side by controlling its distance to the wall, even in a non-stationary corridor.

These results are well accounted for by an autopilot called *LORA* (*LORA* stands for Lateral Optic flow Regulation Autopilot), derived from the one we put forward [4] for insects controlling their height of flight over a contrasting terrain. *LORA* was developed to allow a miniature, fully actuated hovercraft to move autonomously in a corridor [5, 6]. This autopilot makes a computer-simulated hovercraft regulate the lateral optic flow by both side and forward controls, without any need to measure speed and distance [5, 6]. The moving wall was shown to act as a typical output perturbation that the control system was able to overcome.

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A Small, Biologically-Inspired Vehicle with Hybrid Air-Land Mobility

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MALV (Micro Air and Land vehicle) is a small vehicle (30.5cm wingspan and 30.5cm length) capable of both aerial and terrestrial locomotion while transmitting video from one of two on board cameras (Figure. 1) [1]. It implements biological principles for both flying and walking. The propeller driven MALV employs a chord-wise compliant bat-like wing design to achieve improved aerial stability over rigid wing MAVs of similar size. MALV walks on the ground using compliant wheel-leg running gear, inspired by animal legs, that enables Mini-Whegs™ robots to run rapidly and climb. Its two independently actuated wheel-legs are differentially activated to perform turning. The vehicle successfully performs the transition from flight to walking. Furthermore, MALV is able to transition from terrestrial to aerial locomotion by walking off a high position. Fabricated of lightweight carbon fiber its payload includes two cameras, a video transmitter, and an electronic switch to control which image is transmitted. Video from MALV is stable and clear enough to identify objects from an altitude of 33m.



Figure 1. MALV has compliant wings for greater flight stability and compliant wheel-legs to resist impacts in landing. Its wheel-legs enable it to crawl through grassy areas and climb obstacles taller than its leg length

Nature demonstrates the need for multiple modes of locomotion, especially for small animals such as insects. Pure terrestrial locomotion may be impractical at this scale simply because of the distances that must be traveled to search for food, mates, etc. However, mono-modal aerial locomotion is also undesirable because it is impossible to stay airborne indefinitely, it is difficult to land at exactly the desired location, and walking is more energy efficient than flying for short distances. Small robots have the same problems and a hybrid walking-flying vehicle has many advantages. Flight allows the vehicle to travel long distances and approach a general target area, while ground locomotion allows close inspection, surveillance, performance of tasks, etc.

Animal “neuromechanical” systems successfully reject a range of disturbances whose complexity is very challenging to address since they often induce instability or deformation of planned trajectories [2, 3]. The first response to minimize such effects, in particular for higher frequency disturbances such as maintaining posture over varying terrestrial substrates and unexpected gusts in flight, is provided by the mechanics of the organism. This biological principle is implemented in MALV in both its ground and aerial locomotion systems.

Much of the success of MALV is due to two biologically inspired mechanisms integrated into its design: a compliant wheel-leg terrestrial running gear and chord-wise compliant wings. Its wheel-legs mimic leg motions while rotating continuously

and enable it to climb over terrestrial obstacles that are taller than its legs [4]. MALV survives hard landings on concrete because its flexible wheel-legs passively comply during impact reducing the magnitude of the force transmitted to its on-board components. This mimics the same function of passive compliance found in the legs of an animal when it is suddenly perturbed [5]. Likewise, MALV's chord-wise compliant wing overcomes many of the stability difficulties associated with flight on the micro air vehicle scale through a mechanism observed in animal flight, passive adaptive washout, wherein the shape of the wing passively adapts to variations in airflow [6].

MALV is human portable, hand launched, and radio controlled or, in newer versions, semi-autonomous. It can fly several kilometers, land, and then crawl for many meters around the landing site while surmounting tall obstacles relative to its height. MALV transmits video signals from its position in the air or on the ground back to the pilot. When it lands on a building or other location that is at least two stories high, it can walk off of the structure and retake to the air.

Targeted applications include a wide range of search and rescue, safety and security mission scenario. Rescue, fire or police units would benefit from a small robotic vehicle easily transported and deployed by the unit to provide situational awareness in specific areas. Another application of a vehicle capable of flight and ground movement would be in detection of dangerous or illegal substances. While a mono-modal unmanned aerial vehicle might be capable of identifying the existence of potential threats, closer inspection is required to evaluate the validity of the threat. A small vehicle with the ability to land near and walk up to the potential hiding location would allow the operator to accurately determine the presence or absence of harmful or dangerous substances.

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An Algorithmic Basis for the Visually Mediated Control of Translatory Flight by *Drosophila*

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Flying insects exhibit stunning behavioral repertoires that are largely mediated by the visual control of flight. For this reason, presenting a controlled visual environment to tethered insects has been and continues to be a powerful tool for studying the sensory control of complex behaviors. Much is known about the responses of tethered *Drosophila* to rotational stimuli. However, the processing of the more complex patterns of motion that occur during translatory flight is largely unknown. To simulate translatory flight, flies were presented with a panoramic visual stimulus consisting of a focus of expansion and an opposite focus of contraction, with stripes moving at a constant temporal frequency between these foci. During closed-loop tethered flight, *Drosophila* robustly orient towards the focus of contraction [1]. This observation was perplexing since the forward flight profile of local velocities on the retina is a frontally-centered focus of expansion, not contraction—how then does *Drosophila* fly forward?

The paradox has been largely resolved by several significant findings. When undergoing flight directed towards a prominent object, *Drosophila* will tolerate a level of expansion that would otherwise induce avoidance. The expansion-avoidance behavior is also critically dependent on the speed of image motion; in response to reduced speeds of expansion, *Drosophila* exhibit a centering response (similar to what has been observed in freely-flying bees [2]) in which they steer towards the focus of expansion by balancing the image motion seen by both eyes. Taken together, these behaviors contribute to a model of *Drosophila*'s visual flight control as emerging from multiple behavioral modules that operate concurrently.

Simple computational models of *Drosophila*'s visual system are used to demonstrate that the experimental results arrived at by doing psychophysics on tethered animals actually yield sensible navigation strategies. A model of the *Drosophila* compound eye and motion detecting system was implemented, using recent behavioral data to fit the properties of the array of Hassenstein-Reichardt motion detectors. Simulations were conducted in both a virtual 1 meter diameter cylindrical environment (to enable comparison with previous free flight results [3]) or in a simulation of the flight arena used for the tethered flight experiments. This work has sought to bridge the gap between tethered and free flight studies by providing a model for the visual processing of translatory motion. By simulating the responses of the modeled motion detectors during translatory flight, a strong correspondence is seen between the magnitude of motion detected under observed conditions of *Drosophila* free flight and the simulated responses to the stimuli that elicit the centering response in tethered flight.

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Attitude Stabilization of a Flapping-wing Micro Drone

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Introduction

Flapping flight has shown many advantages relative to rotary and fixed airfoils due to their size, high maneuverability, energy efficiency, lift production, and noise reduction. The French project “OVMI”¹ started in 2004 aiming to design, realize and control a flying object mimicking insects in terms of flight and size, taking into consideration fluid mechanics and energy aspects.

The present paper deals with control problem, specially the attitude stabilization of a flapping body. A nonlinear state feedback control law, respecting input constraints, is proposed. Previous works have used Euler angle representation for simulating the rigid body dynamics [1]. This work has the particularity of using quaternion, which prevents numerical singularities, to represent body's rotations.

Flapping flight dynamics

Insect flight model used in this work has been developed in [3]. In this paper, only the attitude stabilization, using the quaternion tool, is studied. Quaternion is defined by a unit vector, known as Euler axis, and a rotation angle about this axis [4]. $\vec{q} = [q_1 \ q_2 \ q_3]$ and q_0 are the vector and the scalar parts of the quaternion.

The dynamics of the attitude of a rigid body are modeled as follows:

$$\begin{pmatrix} \dot{q}_0 \\ \dot{\vec{q}} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} -\vec{q}^T \\ I_3 q_0 + \hat{q} \end{pmatrix} \vec{\omega}^m = \frac{1}{2} \Lambda(q) \vec{\omega}^m \quad (1)$$

$$\dot{\vec{\omega}} = J_m^{-1} (\vec{\tau}^m - \vec{\omega}^m \wedge J_m \vec{\omega}^m)$$

\hat{q} is the skew symmetric tensor associated to \vec{q} , I_3 the identity matrix, J_m and $\vec{\omega}^m$ are the body's moment of inertia and angular vector velocity. The control torque $\vec{\tau}^m$ is generated, for roll and yaw, by the wings movements and, for pitch, by an inside moving mass.

Flapping flight attitude stabilization

The final goal being to stabilize the micro drone attitude, adequate wings' flapping and rotation amplitudes resulting from the bounded state feedback control torque (2) should be determined.

$$\tau_i^m = -\alpha_i \sigma_{M_{2,i}} (\lambda_i [\bar{\omega}_i + \sigma_{M_{1,i}} (\bar{q}_i)]) \quad (2)$$

Where $i=\{1,2,3\}$ for roll, pitch and yaw torques respectively, $\bar{\omega}_i$ and \bar{q}_i are the averaged angular velocities and quaternion over a single wing beat period, $\sigma_{M_{1,i}}$ and $\sigma_{M_{2,i}}$ are saturation functions with $M_{1,i}$ and $M_{2,i}$ the saturation bounds. $M_{1,i}$, α_i and

¹ OVMI (Objet Volant Mimant l'Insecte) is a project supported by the French National Research Agency (ANR) involving IEMN (microelectronic), ONERA (fluid mechanics), SATIE (energy) GIPSA-lab (control) and G2E-lab (actuation).

λ_i are parameters chosen as in [2]. The $M_{2,i}$'s are determined in order to respect input saturations (i.e. wings' Euler angles and body's length) relative to the Hymenoptera model adopted in this work. The maximum flapping amplitude is 50° and the rotation amplitude is taken to its maximum value 90° . Based on [3], the roll and yaw torques must remain within the set Ω (see Figure 1). Therefore, for ease of computation, the roll and yaw saturation levels $M_{2,1}$ and $M_{2,3}$ are taken so that the corresponding torques remain in the largest ellipse E held in Ω . $M_{2,2}$ should respect the saturation induced by the length of the body. As explained in [3], the roll and yaw control torques are used to calculate the amplitudes of the wings control angles applied to the micro drone at the beginning of each wing beat period.

It has been demonstrated in [5] that for high frequency systems, the averaged and time variant models are equivalent. Since the Hymenoptera has a high wing beat frequency of 100Hz, it can be shown that $\bar{\omega}_i \rightarrow \omega_i$ and $\bar{q}_i \rightarrow q_i$. The stability of the control law can be proved based on [2].

The control laws (2) stabilize the rigid body to the origin ($q_0 = 1, \bar{q} = \bar{0}, \bar{\omega} = \bar{0}$). The roll, pitch and yaw initial values are respectively ($50^\circ, 30^\circ, -60^\circ$). The evolution of the system is plotted on Figure 2. Tracking control can also be derived that way.

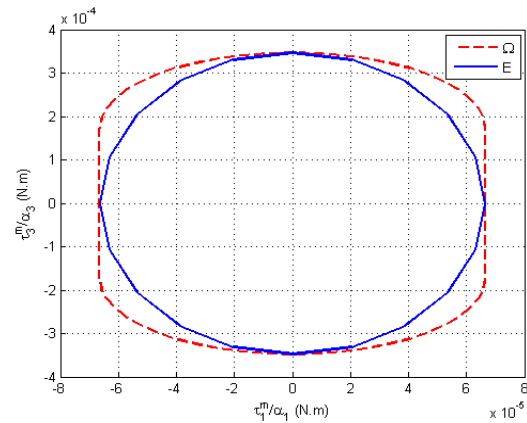


Figure 1. Yaw versus roll torques saturation set Ω approximated to an ellipse E .

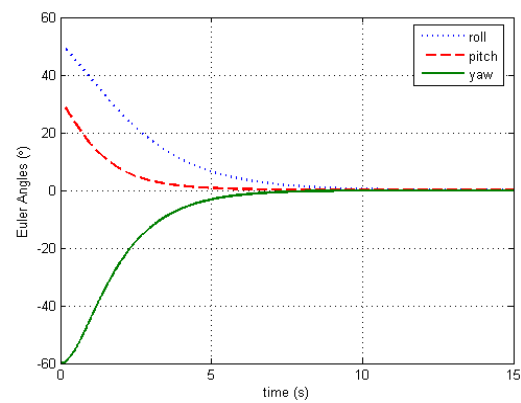


Figure 2. Convergence of roll, pitch and yaw angles of the flapping micro drone.

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Visual Groundspeed Control in Free Flying Fruit Flies

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Synopsis

Insects rely strongly on optic flow for flight stabilization and maneuvering [1,2]. However, whereas visual processing of optic flow was extensively studied in the context of course control in tethered flies, less is known about its functional role in free flight. To this end, we performed a rigorous system analysis in *Drosophila melanogaster*, following 4 steps:

1. We developed '**FlyTrack**', a virtual-reality equipped wind tunnel.
2. We measured instantaneous flight responses in visual **open loop**.
3. We established a **control model** using the identified parameters.
4. We verified the model's predictions for natural **closed loop** conditions.

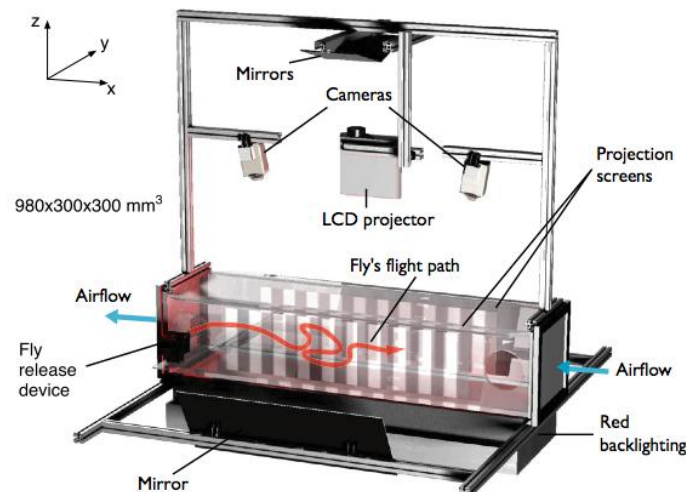


Figure 1. 'FlyTrack'. The red line shows a possible flight path, the blue arrows indicate airflow direction. The LCD projector (60 Hz refresh rate, flicker-free) displays the stimulus via a mirror system onto the lateral walls. The 3D position of the fly is tracked by two cameras (50 Hz sampling rate) and used to compute the live image. Total system delay is less than 25 ms.

Methods

1. To achieve precise visual stimulation in free flying fruit flies, we developed 'FlyTrack', a wind tunnel equipped with a 3D tracking system and a virtual-reality projection system. 'FlyTrack' allows us to couple the visual stimuli to the movement of the fly in real time (see legend of fig.1 for details).
2. We stimulated single flies with sine gratings of defined retinal temporal (TF) and spatial frequencies (SF) and with natural images with defined retinal slip speed. This 'virtual open loop' [3] paradigm requires adjusting the pattern phase according to the fly's position in real time.

3. We determined the control scheme using system identification on the parameters identified in the experiments.
4. Applying a closed-loop paradigm, we measured the responses of single flies stimulated with patterns moving at constant speeds with respect to the wind tunnel's frame of reference.

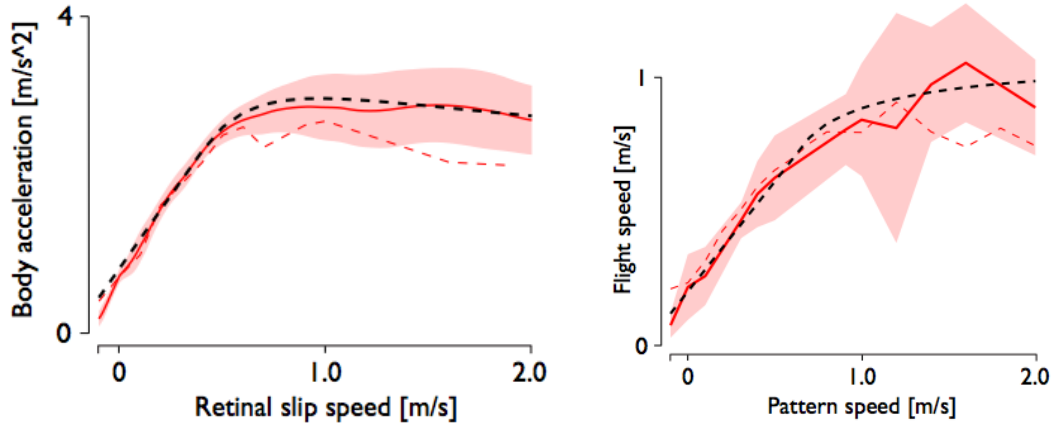


Figure 2, left. Open-loop response characteristics for pattern speeds between -0.1 m/s and 2 m/s. Response strength, measured from the fly's mean acceleration, is shown in solid (median) and shaded (25-75 percentiles) red for sine gratings, and dashed red for natural images. The response of the model is depicted with a dashed black line. **Right.** Closed-loop response characteristics. Response strength was measured from the fly's terminal speed during the last 80 ms of testing.

Results

Our experiments show that the visual system encodes true pattern velocity, which serves as input to a 2nd order controller. Response strength (red traces in fig. 2) is proportional to pattern velocity ($v = TF/SF$), up to a saturation limit that depends on the fly's *airspeed*. A straightforward speed controller with 6 free parameters captures the overall open and closed loop behavior (black dashed lines in fig. 2), as well as the transient response characteristics.

Discussion

Our model captures the transient and steady-state characteristics of translational flight speed control. The relevant input to the controller is true pattern velocity for all chosen stimuli. This identified control system is straightforward and lends itself to a direct robotic implementation.

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Bio-inspired Long-jumping and Gliding Robot for Locomotion in Unstructured Terrains

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Introduction

This paper describes the design of a fast long-jumping and gliding robot conceived to move in unstructured environments through simple feed-forward control laws. This locomotion strategy can let the robot perform relatively long airborne phases without a propeller, and is intended at combining walking and gliding in a future prototype. This robot wants also to model the influence of scale effects on legged locomotion. Comparing different gait strategies adopted in nature by different sized animals [1], it can be inferred that in small dimensions interested by high Froude numbers ($F_r = v^2/gl$), jumping is more effective than walking or hopping [3]

Design

The grillo prototype is a long-jumping and gliding mini robot. The aim is to develop a platform able to locomote with high efficiency in unstructured terrains. Studies done on frogs and jumping insects showed that the elastic properties of muscle-skeletal system are exploited to store and deliver the required energy with a peak power output several times higher the maximum muscle power [2].

Using an elastic energy storage and a release mechanism, a light robot can jump over several body lengths, and using adaptable wings, cover long distances while gliding airborne.

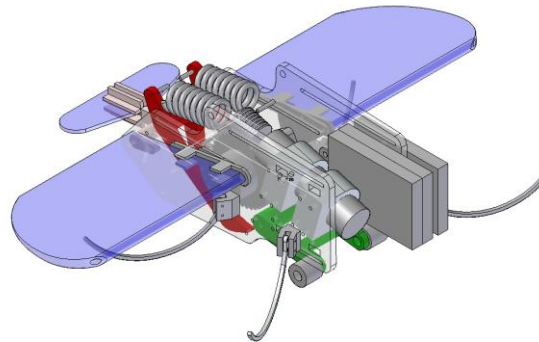


Figure 1. The CAD assembly for the long-jumping prototype.

The robot we propose has a very simple structure: two degrees of freedom for jump powering and steering, passive forelegs and a feed-forward control. The robot's rear legs are actuated by a spring loaded during the whole jump by a small motor. At take-off, an escapement mechanism let the spring release the stored energy, generating a peak of power several times higher the motor one. On the other hand, passive compliant forelegs cushion the ground contact and partially store the impact energy to empower the subsequent jump.

Previous work done on jumping robots showed that a stable jumping gait can be achieved thanks to a stabilizing tail wing. This 80-g prototype was about 10 cm long, and able to run at about 4 body length/s. Despite its relatively heavy weight, it could jump over 30 cm (10 leg lengths) (fig.2) [3].

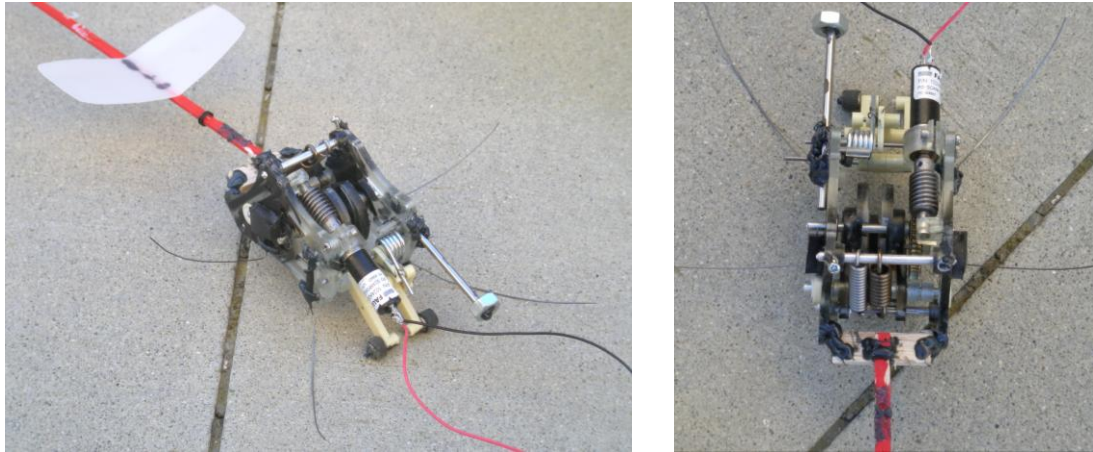


Figure 2. The jumping robot. Here small aerial appendages are present, with a short flight phase

Our goal is here to re-design the prototype, in order to obtain a lightweight robot able to perform jumps with a long airborne phase. Wings will be added to support the gliding phase through lift forces and to stabilize the body rotations via drag forces. Passively adjustable attach angle would be used in order to comply with the different requirements of take-off and gliding phases, while a four-bar mechanism could be used for steering during the flight phase (fig.3).

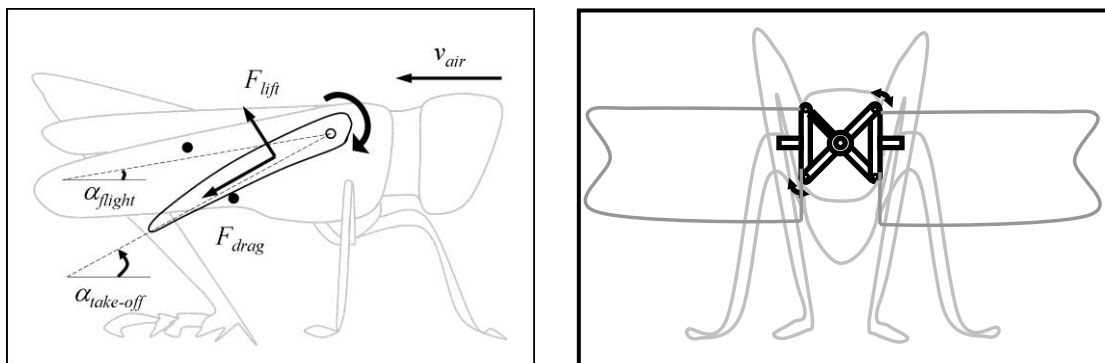


Figure 3. The proposed design for the movable wings

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High-speed Analysis of Wing and Body Motions in Flying *Drosophila* Using Fluorescent Markers

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Understanding the aerodynamics of maneuvering flight in insects requires both (i) a theoretical framework that describes the mechanics and aerodynamics of wing and body motions, and (ii) experimental data on wing kinematics at different classes of flight maneuvers. In the past, the majority of kinematic reconstructions were performed on tethered animals and only few studies addressed wing and body motion in a freely maneuvering insect [1]. In general, those studies are time-consuming because motion analysis mostly requires to manually digitize the wing's position on single high-speed video frames with high accuracy. To build up a data base for wing and body motion in flies performing various classes of flight maneuvers, we here present a method based on fluorescence markers that potentially permits automatic tracking of wing and body positions on high-speed video using conventional motion analysis software.

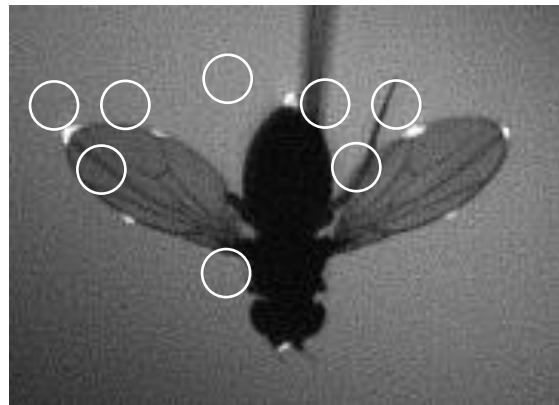


Figure 1. Video image showing wing motion at mid down stroke of a tethered flying fruit fly *Drosophila*. White circles surround fluorescent markers on wings and body.

To achieve this goal, we marked female fruit flies *Drosophila* with small dots of fluorescent dye at leading and trailing edges including the tips of the wings, the head and the tip of the abdomen. The mass of a medium sized dot was near $0.1\ \mu\text{g}$ that is approximately 3% of the wing mass [2]. The dye is non-toxic and may not be removed from the cuticle during cleaning behavior. To evaluate the potential effects of the wing markers on wing kinematics, we have flown tethered flies in a closed-loop virtual-reality flight arena and scored their wing beat frequency within the initial 30 s of flight. The data suggest that the extra load of 6 fluorescence markers (3 on each wing side) slightly but not significantly attenuated wing beat frequency by approximately 3.8% compared to unmarked flies (unmarked: $207 \pm 15.0\ \text{Hz}$, marked: $199 \pm 17.6\ \text{Hz}$, t -test, $P > 0.05$, means \pm S.D., $N = 10$ flies).

We stimulated the fluorescence markers with short, high current pulses of ultraviolet light (UV) produced by 12 light emitting diodes (LED, $\lambda_{\text{Peak}} = 401\ \text{nm}$, 15 nm width of the peak at half height). The UV-LEDs were mounted on a ring-shaped holder around the camera lens. We used several optical filters to limit the range of wave lengths passing through the lens: (i) an infrared-cut filter, (ii) a filter that blocks UV light, and (iii) an orange filter that closely matches the emitted light coming from the fluorescence markers ($\lambda_{\text{Peak}} = 601\ \text{nm}$, 45 nm width of the peak at half height). The combined filters have a light transmission of almost 90% at wavelengths ranging from approximately 547 to 748 nm. We tracked the position of fly's wings and body within a stroke cycle employing conventional black and white high-speed video cameras. To avoid motion artifacts (blurring) on the images, flash duration of the UV-diodes amounted to only approximately 60 μs duration at 5 KHz repetition rate. Figure 1 shows the fluorescence markers on a tethered flying fruit fly during mid down stroke.

To enhance image contrast and thus to extract the markers from the image, we used several numerical filters before performing motion analyses.

In sum, our video technique represents a simplified method to automatically record and analyse wing and body motion in tethered and freely flying insects. However, since UV light may be detected by both the ocelli and the compound eye, we explored the UV-induced behavioral response of tethered flies flying inside a closed-loop flight arena. In these experiments, the animals actively tried to fly towards a black visual object displayed in the frontal part of their visual field while we illuminated the fly from dorsal using a single UV diode (60 μ s pulse duration at 5 KHz). The data show that fixation behavior, defined as the ratio between the time during which the animal keeps the visual object in a 90° frontal region of the eyes and total flight time, decreases from 0.75 ± 0.31 to 0.45 ± 0.20 when UV light is present (means \pm S.D., N=5 flies). Nevertheless, despite of these changes our marker-based video analyses offers several advantages compared to infrared-video techniques in which shape and orientation of wings and body is identified manually from the recorded images.

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A Planetary Landing Device Inspired by Gliding Cockroaches

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Demands for planetary landing

Unmanned exploratory missions to e.g. Mars involve a landing phase, where the spacecraft descends vertically to the planetary surface. In order to minimize the impact during landing a breaking system of parachutes and airbags is employed. This system is uncontrolled and hence not able to adapt to unforeseeable situations. Indeed, landing spacecraft may easily hit a stone, slide down crater rims or be dragged along by strong winds on the planetary surface. In all these events, the costly mission is highly endangered as failures in landing systems in the near past have proven. Due to the communication round-trip delay time between the spacecraft and ground control, external supervision of the descent is impossible. As a consequence, a landing device is desired that can autonomously stabilize the descent and visually guide the spacecraft to a safe landing place.

Auto-piloting systems as known from modern aircrafts are capable of landing safely. However, such systems cannot be employed for planetary landing for several obvious reasons such as the lack of predefined and properly equipped runways. Besides, a system with rigid wings and complex control architecture would require a too large fraction of the highly restricted and costly payload during launch.

Gliding cockroaches

In sight of the constraints of conventional technological solutions, ESA's Advanced Concepts Team explores biological 'landers' as a source of inspiration for the conceptual design of a lightweight and simple yet autonomous and reliable system that qualifies for future unmanned missions to planetary surfaces. The male of some cockroach species (e.g. *Blatta orientalis*, figure 1) have only very rudimentary flying abilities. If such a male cockroach falls off from an elevated point, it can be watched using its rigid and small wings to obtain control over their descent and hence minimize the impact on the ground [Seidl, personal observations].



Figure 1. *Blatta orientalis*. While the female (right) are wingless, the male (left) obtain of rather short and rigid wings that allow for gliding descents. (Photo taken from www.wikipedia.de)

Concept of a 'cockroach lander'

Assuming that gliding descents are generally far less complex in its control architecture, more robust in its technical design [1] and volume-mass efficient than other flying systems (be it technical ones with rigid wings or biological ones with flapping wings) would be, we aim at mimicking the cockroach's descent behavior. Three fields are in the focus of our interest: (i) wing design, including robustness, aerodynamics and kinematics during descent (ii) the control architecture of the auto-

piloting system, focusing on the exploitation of both visual and air-flow stimuli and (iii) the way of choosing an appropriate landing site, especially real time surface characterization and object avoidance [2].

Perspective

The concept of a 'cockroach lander' integrates three biomimetic approaches at the same time. The sensorial mechanisms of navigation and piloting flying and running insects are well understood and in some cases already on the way to technical implementation by various research groups (e.g. [3-8]) and hence would soon be available for integration. The field of Artificial Intelligence has a strong emphasis on feature extraction of visual data and hence would play an important role in this project. The gliding behavior of cockroaches so far is not examined and only some neurobiological data on flying cockroaches are available [9]. Additionally to that its performance in the Martian environment needs to be estimated. The challenge of this project is a deepening of the required biological knowledge and the successful integration of the three systems in order to mimic the deserved biological behavior.

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Stability of Flapping-of-Wings Flight of Butterfly

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Objective

The objective of this study is to clarify principles to stabilize flapping-of-wings flight of a butterfly, which is rhythmical periodic motion. To clarify the unknowns, this research proceeds by the following plan [1,2]: (1) construction of dynamics model and simulator, (2) experimental measurement of butterfly motions and aerodynamic forces, and (3) discussions for the stable flapping-of-wings flight through the simulator.

Experimental Measurement

In this paper, the present authors report on experimental measurement of aerodynamic forces and motions of flapping butterflies. They have constructed an experimental system (Figure 1) with a low-speed wind tunnel, a measure, and an optical measurement system. The system measures the aerodynamic force and the motion simultaneously using a measure and an optical measurement system.

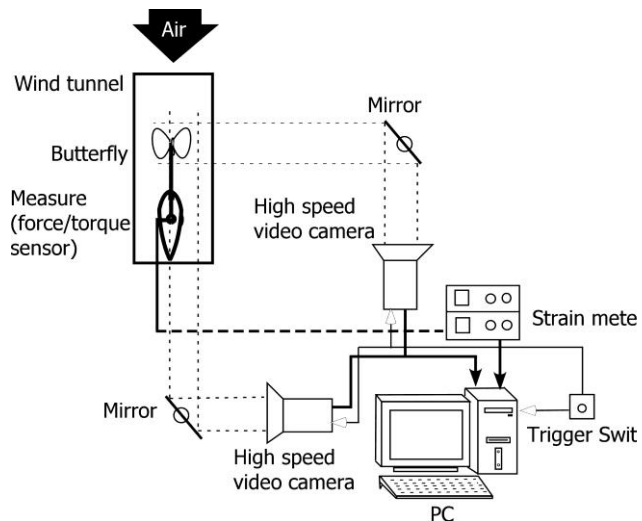


Figure 1. Experimental setup.

Mathematical Models

A dynamics model of a butterfly is derived by Lagrange's method, where the butterfly is considered as a rigid body system. For the aerodynamic forces, a panel method (Figure 2) is applied. Validity of the mathematical model is examined by the good agreement of the numerical results with the measured data. Figure 2 illustrates a wake from the right wing for two flapping cycles computed by the panel method. The panel method model calculates time-varying flow field induced by free-vortices in wakes from both wings and obtains aerodynamic force applied to the butterfly.

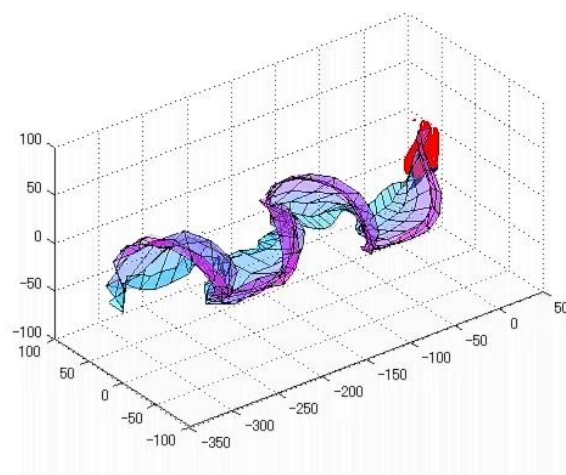


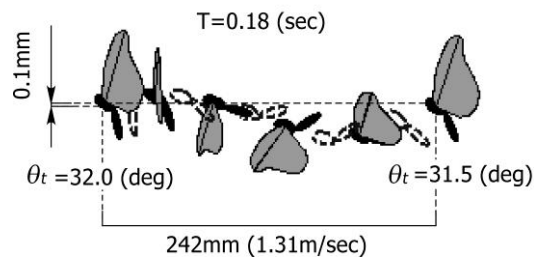
Figure 2. Wake from right wing by panel method model.

Stability of Models

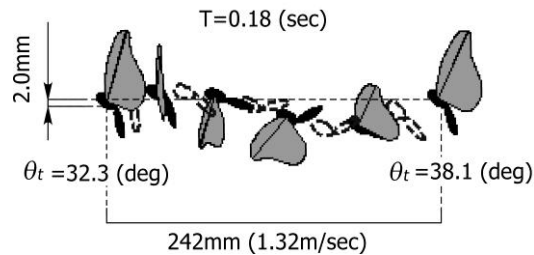
A periodic orbit of a flapping-of-wings flight is searched in order to fly the butterfly model. An almost periodic orbit is obtained as Figure 3 (a), where the flapping-of-wings flight is slightly unstable. To consider the effect of the wakes induced flow, the same procedure is applied to a mathematical model as Figure 4 (a), where the wakes are removed from the model. Figures 3 (b) and 4 (b) are the flights started from the initial states of Figures 3 (a) and 4 (a) with same small perturbations. The unstable level of Figure 4 (b) is larger than Figure 3 (b). This result shows that the free-vortices in the wakes are essential for the stabilization of butterfly flights.

In addition, the sampled-data systems are derived from the original continuous periodic systems by observing their states every flapping cycle. The highest unstable poles of the sampled-data systems are 8.6 and 17.0 for the panel method and the panel method without free-vortices, respectively. This result gives support to the simulations above.

The unstable level of the panel method model is smaller by considering free-vortices in wakes. Meaning that the wake-induced flow has a type of feedback stabilization effect.

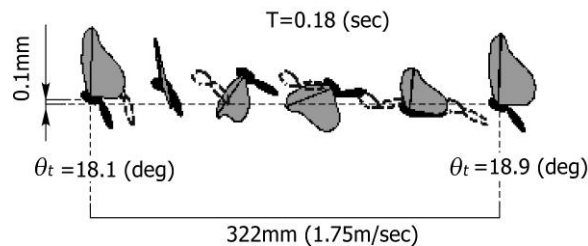


(a) Almost periodic flight

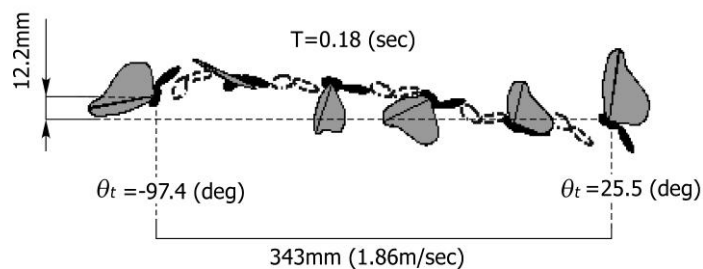


(b) Flight with initial perturbation

Figure 3. Wake from right wing by panel method model.



(a) Almost periodic flight



(b) Flight with initial perturbation

Figure 4. Flapping flights of panel method model without wakes.

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A Simple Evolutionary Framework for Generating Robust Flight Manoeuvre in a Physically Simulated Flapping Wing Robot

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This work demonstrates a successful evolutionary framework to generate the neural network controller of a physically simulated simple 3D flapping wing flying robot which shows robust flight manoeuvre and tolerance to external perturbations. In contrast to recent studies which dealt with the artificial evolution of neural network for steering flight [1,2], this work generates a robot which uses both asymmetric wingbeats and its tail for steering behaviours and retains its flight trajectory even in the presence of external perturbations.

The simulated robot has two flat wings with 3 degrees of freedom (dihedral, sweep, and twist) and a tail with 2 degrees of freedom (bend and twist) (figure 1). Two bilaterally symmetric 8 node fully connected continuous-time recurrent neural networks (CTRNN) [3] were used for the controller. The controller has five sensors which are pitch, yaw, roll, altitude, and forward speed, which are connected to every neuron in the circuit. Roll and yaw sensors are connected separately at each side of the circuit to give inputs with opposite signs. In order to avoid unnecessary antiphase movement of the wings, the subnetworks are not connected. Setting the number of neurons to 8 ensures sufficient possibilities for searching two briefly distinct motor circuits which act as the pattern generating motoneurons and the cascaded neural circuits [4]. The time constants, biases, and connection weights of the neural network are optimised using a geographically distributed genetic algorithm typically with a population of 100 (10×10 grids) for 50000-70000 evaluations. For each simulation, take-off by a single push was used as the starting strategy to prevent initial gliding or somersaulting of the robot. In order to gain maximum fitness, the robot should maintain its flight path which is a straight line of a certain altitude, over the entire simulation time.

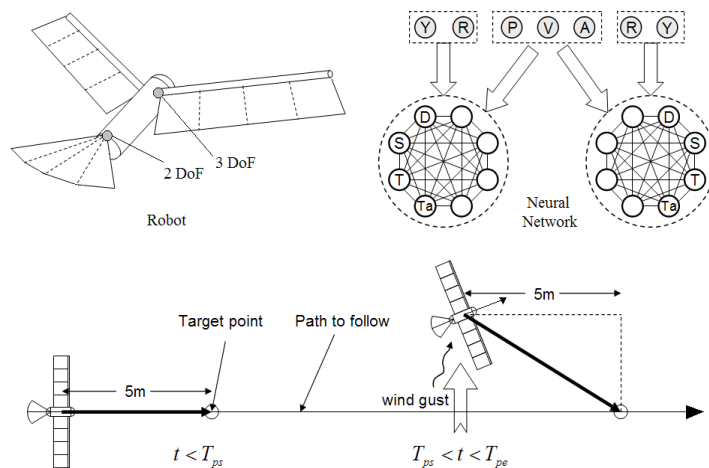


Figure 1. Overview of the system. During a certain period ($T_{ps} < t < T_{pe}$), the robot receives wind gust. After perturbation, the robot should stabilise its attitude while keeping its position as close as possible to the target path. Shaded circles are sensors denoted by Y: yaw, R: roll, P: pitch, V: flight speed, and A: altitude. Lettered unshaded circles represent motoneurons (D: dihedral, S: sweep, T: twist, Ta: tail). Tail bend receives the average output of left and right neurons ($((\text{left} + \text{right})/2)$), and tail twist receives the difference ($((\text{left} - \text{right})/2)$) of them.

The evaluation strategy proceeded in two stages – take-off and perturbation. In the early time of the simulation, the robot only has to reach the desired altitude without receiving any perturbation. After successful take-off, a couple of wind gusts of a few seconds duration are presented in order to push the robot off the target path. The perturbed robot should return to the path line as soon as possible and should maintain its flight path continuously. The velocity of the wind and the time of its presentation varied over a small range of random values. In order to boost the evolutionary search, those individuals whose flight altitude was lower than 50cm after 5 seconds from the start of the simulation were regarded as failed robots which have non-repetitive flapping controllers, and those individuals were deleted from the population.

This simple evaluation strategy effectively ensures a selection pressure encapsulating many aspects of sophisticated flight control. Because of the highly nonlinear nature of the robot-environment interaction and the tight couplings between the spatial axes for aerodynamic force generation, the robot is forced to capture a variety of capabilities through this simple perturbation method.

The evolved robot showed successful compromises between stability and manoeuvrability which are two conflicting characteristics of flapping flight, despite the simple and intuitive evolutionary system. Some movie clips are available at <http://kucg.korea.ac.kr/~ysshim/flyer.html>

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Silicon-based Biomimetic Flying Insect

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With the increasing development of new technologies, micro-robots researches are in great progress since few years. Some teams are currently involved in the fabrication of centimetric prototypes. The advancement of MEMS technologies allow to envision the realization of a flapping wings object with the same dimensions as a real insect.

This paper presents an overview of the French National Research Agency supported project OVMI (kick-off in 2006). The project attempts to provide Silicon-based Biomimetic Flying Insect (SBFI). The achievement of this goal requires combining backgrounds in silicon-micromachining, microfluidic, microactuators, micro-sensors, energy micro-sources and IC chips. The main goal is to privilege a design inspired from the nature. In a first part, the global morphology of the SBFI (i.e. geometry, mass distribution on wings, pterothorax, abdomen) is developed by reproducing the insect's ones. Moreover, a great attention is paid on the membrane cuticle and the veins distribution and dimensions as shown in figure 1.



Figure 1. Silicon-based Biomimetic Flying Insect

In a second part, we propose to include different micro-actuators (piezoelectric, EAP) according to the flying motion, i.e. flapping, wing torsion etc. The way of actuation will be similar to the insect's ones. Some finite element simulations are already under investigation to visualize the behaviour of the static and dynamic structure induced by a suitable distribution of micro-actuators.

All these works are supported by a wide range of literature [1, 2] devoted to the principle and the mechanism on how insects fly.

About energy source, scientists from various institutes are working on technologies that will make it possible to achieve greater power densities and, when combined with batteries in hybrid energy systems, extend operating times. In our case, we focus the research on the opportunities offered by "energy harvesting," or drawing power from multiple energy sources available in the environment of the device. The concept of energy harvesting refers to using light, heat or motion to generate energy. For example, we can employ piezoelectric materials: energy is generated by a motion source such as the wing's vibration during the fly. Micro-integrated photovoltaic cell can also be used to generate electric energy.

The complete aerodynamics unstationary effects which occur around a flapping insect wing are heavily complex, and remain today not precisely known as it is the case for the fixed- or rotary-wing flight. This is due in particular to the low Reynolds number, a quantity characterizing the importance of fluid inertial forces over viscous ones. As a consequence, it appears important to ensure that the control law used for the stabilization and closed-loop control will be robust enough to compensate for the model uncertainties, or even for some further modelization refinements.

ONERA previously developed a complete, flight-mechanics oriented simulation model for a flapping-wing Micro Air Vehicle named OSCAB (which stands for *Outil de Simulation de Concept à Ailes Battantes* or Flapping-wing concept simulation tool) [3]. This model features a 2D aerodynamic approach: the wing is decomposed into smaller elements (slices) and the aerodynamic forces and moments are calculated for each slice as a function of the relative velocity of the considered element with respect to surrounding air. Those forces and moments are then integrated in order to provide the relative velocities and positions of the Micro Air Vehicle along the 6 degrees of freedom. The simulation model takes into account various unstationary, insect-flight specific aerodynamic effects such as rotational circulation and added fluid mass. This model will be used as a first validation of the control laws developed by GISPA-lab. The approach consists in parametrizing the wings movements with few parameters (flapping amplitude, frequency, etc.). A relation between these characteristics and their mean effect on the body of the insect is then obtained (in simulation or by experimental measures). Using averaging theories, one can prove that very simple control laws developed for rigid bodies [4] can be used to stabilize the attitude. The simplicity is here a necessity because of the limitation of the embedded micro-controller. The saturations and dynamics of the actuator are taken into account.

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Visual Guidance of Flight in Flying Insects: An Introductory Review and Summary of Recent Progress

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Flying insects, with their relatively simple nervous systems and brains weighing less than a milligram, offer an excellent opportunity to investigate mechanisms of flight control and visual guidance that are fast, effective and computationally cheap.

Much of what we know about this subject comes from the classical studies of the so-called 'optomotor response', which helps an insect maintain a straight and level course [1]. Involuntary deviations in yaw, roll or pitch are sensed visually by large-field motion-sensitive neurons, which deliver appropriate commands to the flight motor to correct these deviations [2,3]. Yaw, roll and pitch are also stabilized by signals from the halteres, which act as miniature gyroscopes to sense angular rotations of the body and send appropriate corrective commands to the flight musculature [4,5]. In addition, three light-sensitive organs known as the ocelli view the horizon (two laterally, and one frontally) and act to sense and stabilize roll and pitch [6-8]. In long-range navigation to a known goal, the correct heading is set and maintained with the aid of a 'celestial compass' which uses the sun and the pattern of polarized light that it creates in the sky [9-11].

More recent work, over the past twenty years or so, is revealing that insects use cues derived from the pattern of image motion that is experienced by the eyes in many additional ways to guide flight.

Although most insects lack stereo vision, they use a number of ingenious strategies for perceiving their world in three dimensions and navigating successfully in it. For example, distances to objects are gauged in terms of the apparent speeds of motion of the objects' images, rather than by using complex stereo mechanisms [12, 13]. Objects are distinguished from backgrounds by sensing the apparent relative motion at the boundary [14]. Narrow gaps are negotiated by balancing the apparent speeds of the images in the two eyes [15, 16]. Flight speed is regulated by holding constant the average image velocity as seen by both eyes [17-19]. Bees landing on a horizontal surface hold constant the image velocity of the surface as they approach it, thus automatically ensuring that flight speed is close to zero at touchdown [20]. Foraging bees gauge distance flown by integrating optic flow: they possess a visually-driven "odometer" that is robust to variations in wind, body weight, and energy expenditure [21-24]. As in humans and higher vertebrates, the perception of motion in bees appears to be 'colour blind', even though the animal as a whole possesses excellent trichromatic colour vision [25, 26]. Hoverflies [27] and dragonflies [28] appear to shadow conspecifics by moving along a trajectory that causes their own motion to be visually camouflaged. Whether this is a 'consciously' stealthy maneuver, a genetically evolved reflexive response to a target of interest, or an interesting by-product of a tracking strategy, remains to be investigated.

Many of the strategies for visual guidance described above have been translated into biologically-inspired algorithms for controlling flight of autonomous terrestrial robots and unmanned aerial vehicles [29]. Some examples are terrestrial and aerial robots that avoid obstacles (e.g. [30-32]), navigate through corridors (e.g. [33-35]) and use a polarized-light compass to maintain heading [36], aircraft with vision systems to

stabilize altitude and attitude [37-42], and vision systems for panoramic imaging and ranging [43,44].

Depending on available time, recent work in our laboratory in the areas of odometry, landing, target tracking and aerial robotics will be outlined.

Among the challenges for aerial vehicles of the future are autonomous, visually guided landing, tracking and interception of moving targets, control of flight modes in which optic-flow cues are weak or absent, and fully autonomous, long-range missions that do not rely on radio control, telemetry or GPS, but, rather, on the entirely self-contained resources of an animal such as an insect.

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The references listed here are by no means exhaustive. They are intended merely as a guide and a starting point into this literature. My apologies for any important omissions.

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Modelling Visuomotor Control in Flying *Drosophila*

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Introduction

Flying fruit flies are thought to detect visual expansion in order to avoid looming obstacles [1,2]. This study seeks to uncover the nature of these expansion detectors, in terms of their spatiotemporal characteristics and the ways in which they modulate flight parameters.

Behavioural experiments

Flies are tracked in 3D at 50Hz flying in an arena similar to that described by [1] (figure 1). Our work thus far has focused on the effects of the visual environment on flight. It has been found that saccade amplitude varies according to the pattern on the arena walls, and also according to the angle at which the wall is approached. This challenges the view that saccades represent a fully stereotyped motor sequence [1]. We also find evidence for obstacle avoidance by gradual, non-saccadic turning. This behaviour is promoted by environments with high horizontal contrast, but is inhibited by the presence of vertical contrasts. We hypothesise that this turning is due to the fly's optomotor response being triggered by an illusion of rotation caused by the geometry of the arena. Finally, the disruptive effect of horizontal stripes indicates that the spatial summation of local motion signals is non-linear, mirroring the electrophysiological findings of [3].

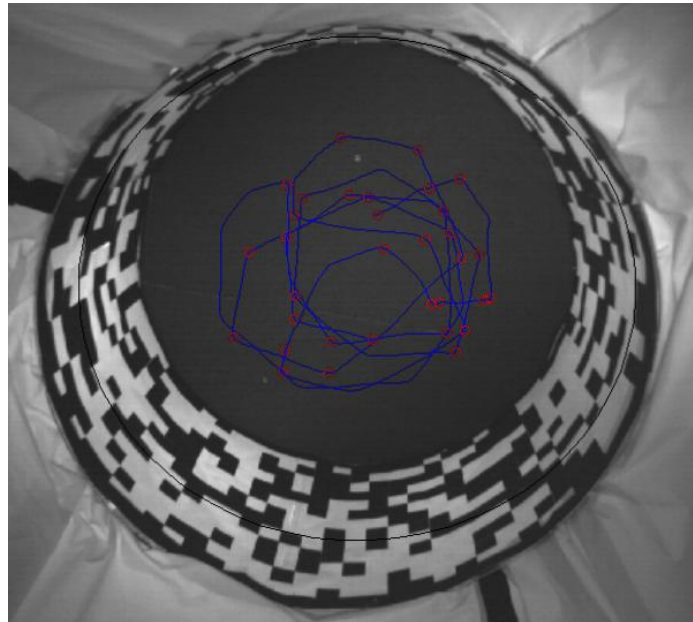


Figure 1. The arena (as seen by one of the IR-sensitive tracking cameras) with a fly trajectory overlaid. Red circles denote saccades.

Modelling

By replaying recorded trajectories in simulation we can reconstruct the fly's visual experience and thus identify the spatiotemporal patterns which tend to precede saccades, in an attempt to uncover a saccade-inducing signal that is invariant across visual environments. This process provides detailed data to implement and validate closed-loop models of the fly's visuomotor control system. These models use Reichardt elementary motion detectors and analogues of the lobula plate tangential cells to detect optic flow patterns. This work is carried out both in simulation and using a gantry-suspended robot, the purpose of the latter being ultimately to investigate the integration of olfaction and vision.

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Control of Flight in a Simulated *Drosophila* Model: Successful Centering Depends on Actively Structuring Sensory Input

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Background

We are developing a simulation environment to investigate control of insect flight through physically and biologically plausible models of the environment, visual physiology, actuation, rigid-body dynamics, and aerodynamics (Fig. 1) [1]. A fundamental motivation of this work is to integrate bottom-up modeling with biological experimentation and high-level models. Although the initial implementation is based on experimental studies of fruit flies, the model is more easily applicable to other insects.

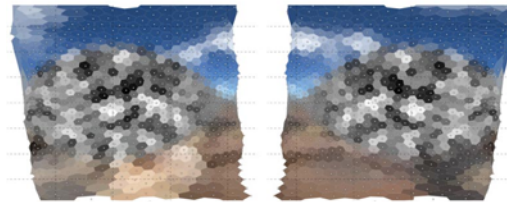
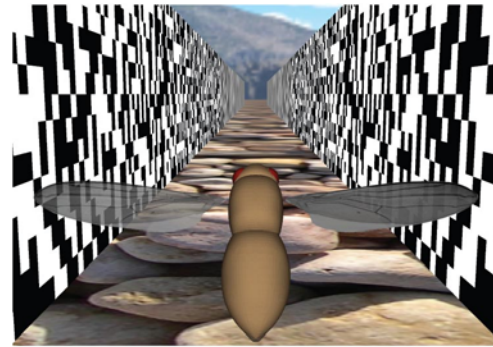


Figure 1. Simulation contains models of environment appearance (upper panel), photoreceptors (lower panel), higher-level neural processing, kinematic control laws and aerodynamic force generation.

Centering response

In particular, we are investigating the centering response, in which an insect tends to fly along the midline of a corridor. This behavior has been studied extensively in bees [2], where it is thought to result from the balancing of visual motion experienced on the left and right sides of the animal's visual field. The centering response has also been the subject of a control theory analysis of the wide-field integrators used in steering [3]. It was shown that summation of local velocity detectors with equal direction and velocity sensitivities arranged around the equator results in a wide-field integrator with response R :

$$R_{ideal} = A\dot{\psi} + By,$$

where A and B are constants (when flying in a corridor of fixed width at constant velocity) and $\dot{\psi}$ is yaw rotation rate and y is the lateral position with respect to midline. Although this result is based on idealized motion detectors with zero-lag, perfect estimates of velocity, and is derived from a linearization around the reference trajectory, it is a useful starting point for considering centering behavior.

Flight simulations

We sought to create a control law for a simulated fly to center within a corridor using as sensors a biologically plausible wide-field visual motion integrator and a simulated haltere system to provide angular velocity estimates $\dot{\psi}$. An estimation of lateral position y was made using:

$$y = \frac{R_{simulation} - A\dot{\psi}}{B}.$$

This visual estimate of y was temporally low-pass filtered to minimize variance (first order lowpass, time constant 200 ms) and used to create an azimuth set point for lower-level kinematic controllers ψ_{ref} . The most successful control law we implemented, as judged by success in centering without colliding into corridor walls, was:

$$\psi_{ref} = -2/\pi k_1 \tan^{-1}(y/k_2)$$

where k_1 and k_2 are constants. Within the simulated corridor, this control law produces trajectories that consist of relatively long periods of straight flight punctuated by brief periods of rapid turning. By using such a control law, sensory input was structured into periods where angular velocity was near zero and thus reliable estimates of lateral position could be made. Other control laws that we tried would generate continuous turns of varying magnitude, resulting in unreliable estimates of lateral position.

We intend to further investigate visual-motor behavior using this bottom-up simulation in combination with biological experiments on flies to suggest and evaluate potential control strategies that endow insects with their remarkably robust flight performance. Furthermore, such quantitative modeling will inform physiological investigations into the neural implementation of the fly's control architecture.

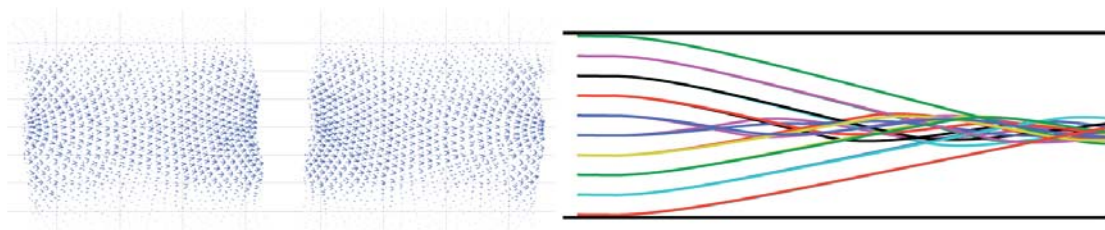


Figure 2. A simulated wide field integrator weights the output of each correlator-based motion detector by a value proportional to the length of the vectors as shown (left panel). A top view of the trajectories generated when using the control law described in the text at several starting positions repeated with two, differently scaled visual textures on the sides of the corridor (right panel).

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View-Reconstruction and Visual Homing in Ground-Nesting Wasps

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Introduction

When leaving the nest for the first time in the morning, or when they had difficulties finding the nest during the previous return, ground-nesting wasps (*Cerceris australis*) perform highly structured flight manoeuvres, called learning flights, around the nest entrance, see [1] and figure 1b. Although there is evidence that these movements are necessary to ensure a successful return to the nest, it is still unclear what visual information is extracted and what spatial representation is memorised during learning flights.

Methods

To understand the functional significance of learning flights, we recorded learning and return flights with a high-speed and high-resolution stereo camera system that allowed us to determine the three-dimensional flight paths including the wasp's head orientation (figure 1a-c). The image sequences perceived by the wasps were then reconstructed by moving a panoramic imaging device attached to a computer controlled robotic arm along these trajectories.

We started our analysis by testing an image-matching hypothesis motivated by the "snapshot model" of Cartwright & Collett [2], and calculated image differences of reconstructed learning and return flight sequences. An example of the resulting image difference matrix is shown in figure 1d. Unlike several robotics approaches, e.g. [3], we do not assume that wasps are able to rotate images "mentally" in order to find the best matching orientation.

Results and Conclusions

We found that the values of the image difference matrix are mainly affected by orientation differences – particularly for image parts above the horizon that are more likely to show distant objects. For lower elevations there is an additional strong dependence on position differences. Due to the complex flight patterns with their frequent changes in orientation, the image difference matrix has several minima (figure 1d), which may indicate that wasps rely on several "snapshots" from different locations.

Furthermore, wasps move their head in a saccadic fashion during learning and return flights (figure 1c). Between saccades, gaze is held constant, and wasps experience mainly translational optic flow. This finding suggests that the main purpose of the flight maneuvers is not to generate a pivoting parallax field centered on the goal [1], but to estimate distances in the surrounding area and to separate objects from background. Thus, in future work we will take into account a possible spatial representation that is based on the depth structure of the scene [4]. Also, the complex flight patterns may actually serve more than a single purpose: wasps could match images with multiple snapshots while detecting distances to objects through motion parallax [5, 6].

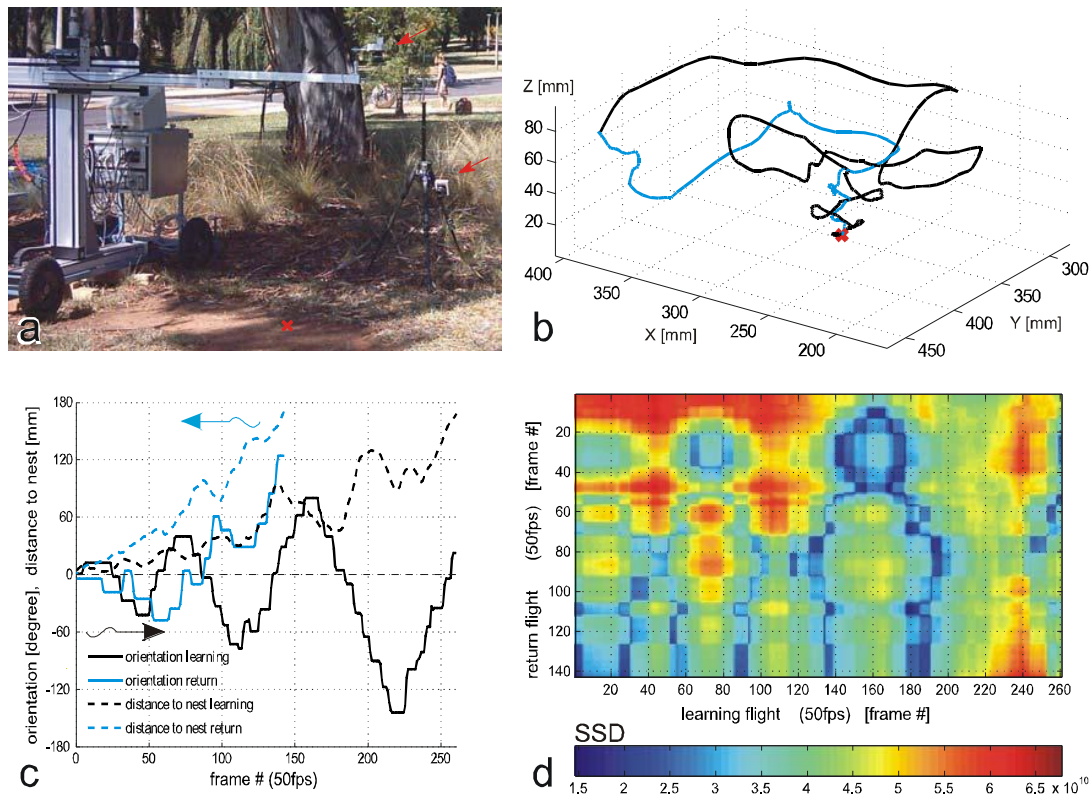


Figure 1. Reconstruction and analysis of a wasp's visual input during learning and return flights. (a) Robotic gantry and two high speed cameras (marked by red arrows). The red cross shows the position of the nest entrance. (b) Reconstructed 3D-trajectories of a learning (black) and a return flight (blue). (c) Corresponding head orientation and distance to the nest (arrows indicate the progress of time for learning and return flights). (d) Matrix of image differences (Sum of Squared Differences, SSD) between the return and learning flights depicted in (b).

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Hemispherical Depth Perception for Slow-Flyers using Coaxially Aligned Fisheye Cameras

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Small flying robots, like their biological counterpart, require a number of sensory modalities for flight stabilisation and guidance. Due to stringent constraints imposed by their physical size and weight on the payload capabilities, motion and range sensing technologies commonly employed in robotics (i.e. structured light system or millimetre wave radar) cannot be used. Image sensors provide a viable sensing solution for slow-flyers as new mega-pixel imagers are lightweight, low power and capable of instantaneously capturing a snapshot of the environment. Vision-based techniques for stabilisation, egomotion estimation and depth perception are being developed in our laboratory. The research presented here focuses on the design, implementation and evaluation of a novel compact hemispherical stereo sensor for robotic slow-flyers. Our aerial vehicle demonstrator *Dragonfly.v1* is depicted in Fig. 1(a) and Fig. 1(b). The proposed vision system is composed of two miniature fisheye cameras. As illustrated in Fig. 1(c), the coaxial alignment of the two cameras in our design leads to a straightforward computation of 3D depth over a near 2π steradian solid angle.

In the computer vision literature, several methods have been proposed for depth perception over a large field-of-view (FOV). Omnidirectional *Structure From Motion* (SFM) [1] has been successfully used to concurrently recovering 3D structure and motion from a single moving catadioptric camera. However, SFM from monocular video sequences requires high computational power and is thus not practical for *real time* embedded applications. Previously, Gluckman *et al.* [2] suggested an omnidirectional stereo system consisting of two catadioptric cameras. Fast panoramic stereo imaging [3] can be achieved by the orthographic projection of parabolic mirrors vertically aligned. The main practical problem with such catadioptric sensors is that bulky and heavy telecentric lenses are used to approximate orthographic projection while keeping the cameras close to the mirrors. In addition, these designs do not allow simultaneous

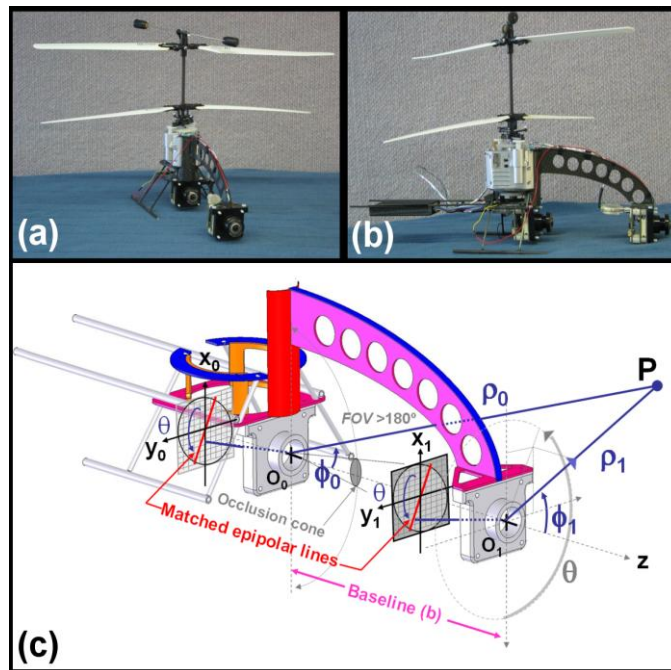


Figure 1. (a) and (b) *Dragonfly.v1*, our robotic slow-flyer; rotor $\varnothing = 300\text{mm}$, weight = 250g, flight time $\approx 6\text{min}$. (c) Schematic overview of our hemispherical stereo sensor; In theory, for a pair of coaxial fisheye images, corresponding points must lie on radial lines - matched epipolar lines - with the same polar angle θ .

panoramic and forward-looking viewing - hence our interest in miniature optical fisheye lens.

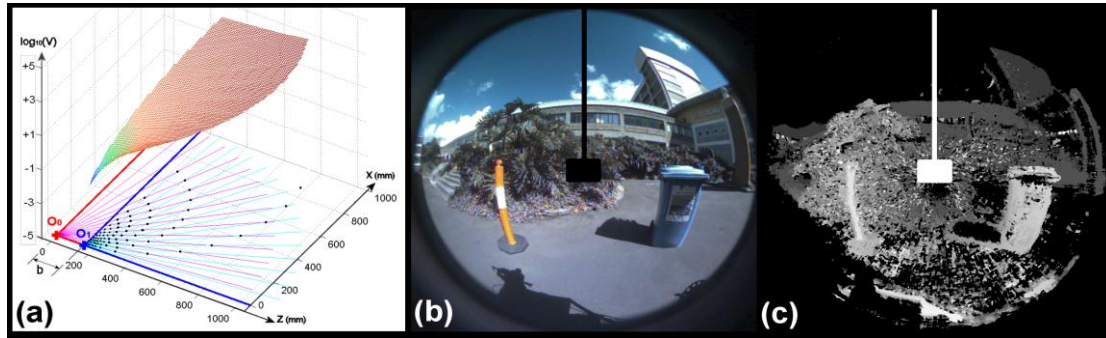


Figure 2. (a) Depth resolution: each point on the epipolar plane XZ corresponds to the depth of a pair of matched points; the reconstruction accuracy is approximated by the uncertainty volume V of intersection of the two solid angles subtended by the corresponding image points. (b) *Aft* view of a hemispherical stereo pair of fisheye images. (c) Estimated disparity (the white rectangle represents the occlusion cone).

We first review our previous work on the projection model of fisheye lens and the epipolar constraint between a pair of coaxially aligned fisheye cameras [4]. We introduce a new geometric characterization and calibration method. The proposed geometric model for the camera takes into account the radially symmetric distortions introduced by the fisheye lens as well as the misalignment between the image detector and the optical system assembly. We have shown that this complete camera model is essential in accurately describing the epipolar geometry of our compact hemispherical stereovision sensor [5]. We then derive the non-uniform depth resolution across the hemispherical view in order to give an estimation of the reconstruction uncertainty in 3D as shown in Fig.2 (a). We conclude by describing a dense stereo correspondence algorithm for use in the proposed system and by presenting some experiments to validate the concepts. An example of disparity map is shown in Fig.2 (b) and Fig.2 (c).

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A System for Controlled Visualisation of Flapping Wings

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Introduction

The basic mechanisms of flapping wing flight have been determined from analysis of insects in flight [1] and by recreating insect wing motion in dynamically scaled models [2], but this understanding does not immediately allow the construction of efficient wings for MAVs. Efficiency and performance of current flapping wing MAVs are poor, so improvements are required before the construction of MAVs capable of performing useful tasks is possible.

Computational analysis and dynamically scaled experiments can both model MAV-scaled wings [3], but in these experiments it is difficult to accurately include effects such as aeroelasticity, which has been shown to have a significant effect on wing efficiency [4]. For this reason, experiments on 1:1 scale prototype wings offer the most accurate method for wing analysis. One important technique is flow visualisation, but it is difficult to analyse the desired wing position and the unsteady airflow rarely gives clear images. A high speed camera allows observation of flow at all wing positions, however due to the unsteady flow, these images may not be representative of the typical flow paths.

This abstract presents a new visualisation system that enables improved visualisation of flapping wings. By controlling the triggering of strobes and other devices, it allows visualisation of the desired wing position at both constant and varying flapping frequencies. The accuracy of the system also allows the use of long exposure photographs to record the average of several flapping cycles.

Developed system

Figure 1 shows the system developed for controlled visualisation. This system

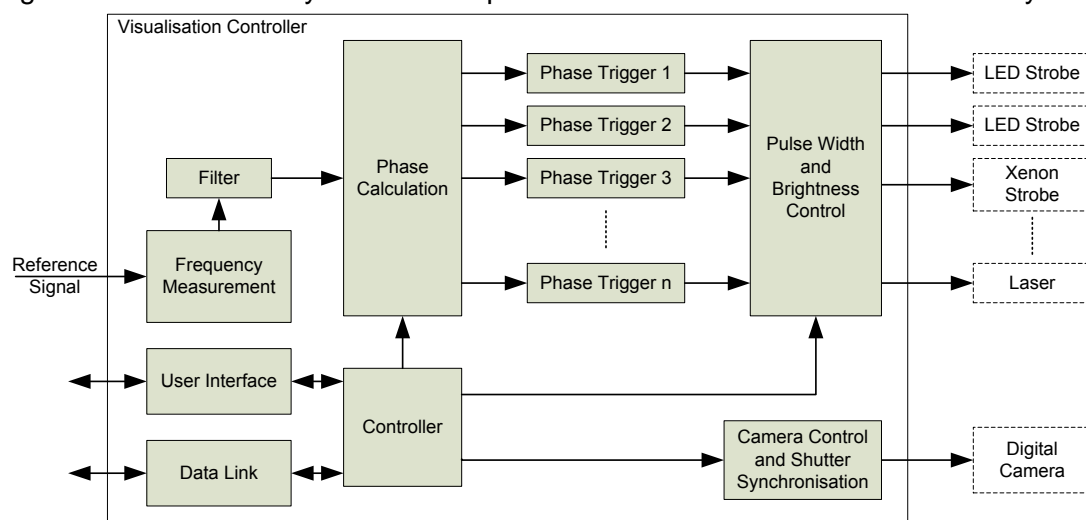


Figure 1. Diagram of visualisation system

enables devices such as strobes, lasers and cameras to be triggered at precise phases in the flapping cycle, regardless of the flapping frequency. The system

continuously synchronises to the flapping frequency, then calculates the trigger timing for events such as strobe flashes, based on user settings. This allows accurate analysis even if the frequency rises or falls during testing. If the frequency is unstable, a digital filter can be enabled to reduce the effect of random errors. The system can also be used for precise analysis of aeroelastic deformation of wings throughout the flapping cycle.

Results

The system performance was tested with a signal generator operating at 20 ± 0.0001 Hz and a flapping mechanism with encoder operating at 20 ± 0.1 Hz. Using the signal generator, the trigger position error was less than 0.01 degrees phase error at all positions. Using the flapping wing, maximum phase error was 1.8 degrees with no filtering and 0.12 degrees with filtering enabled.

As the system can reliably trigger a strobe or laser at the same point over many flapping cycles, it is possible to take long exposure photographs, effectively recording the average air flow. This results in high quality images which much more accurately represent the flows around the wing under test (Fig. 2). The system has also been used to analyse aeroelastic deformation of the wing over the complete flapping cycle using image processing.

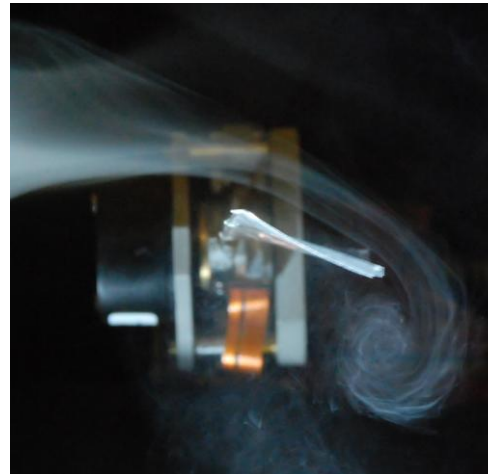


Figure 2. Flow visualisation of 5 flapping cycles using the developed system

Conclusion

This abstract has presented a system that enables controllable visualisation of flapping wings, regardless of frequency variation. Experimental evaluation of the system showed highly accurate results, with low error at all trigger positions. The system allowed flow visualisation images to be taken which accurately represent the average flows around the wing. This system will now be used for analysis and comparison of different flapping motions for MAV scaled flapping wings.

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An Insect Brain Architecture for Robotics

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Insect-inspired approaches to robotics have, to date, focussed on algorithms that exploit direct sensorimotor loops with the environment to obtain robust behaviour without complex symbolic processing. For example, a number of 'matched filters' have been employed for extracting flight control information from visual signals. The robotic implementations have also led to better understanding of these mechanisms in insects. However, insects are also capable of much more complex behaviours – including learning, integration of multimodal cues, real world navigation and flexible behavioural choice – which outstrip the abilities of any existing autonomous robots. As they achieve this competence with relatively small brains, there is much we can still learn from them for building more intelligent robots.

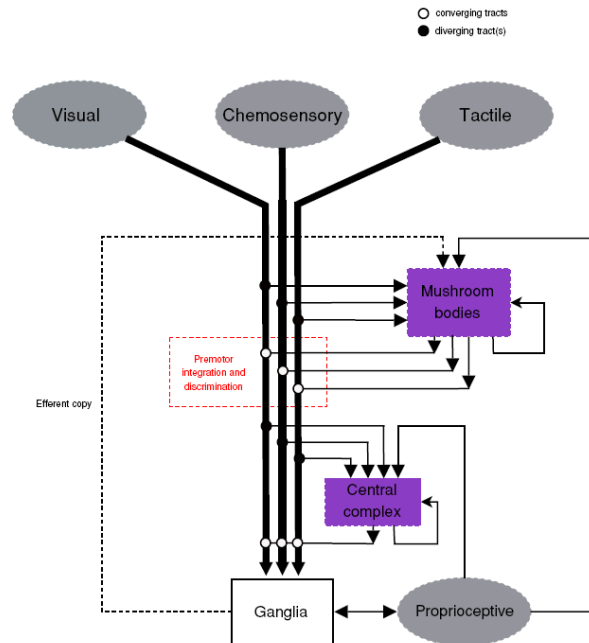


Figure 1. Schematic of the proposed insect brain architecture for a robot.

Based on a review of insect brain research [1] we have proposed an architecture that reflects some of the important features (figure 1). The basis of this architecture is parallel, domain-specific sensorimotor loops such as those described above, and these may interact in additive or inhibitory ways at a variety of levels (at the sensory or motor periphery, in ganglia, or in the brain). However, complex behaviour is not obtained by adding ever more such modules, but rather by the introduction of secondary, indirect pathways, that serve to associate several modalities and to modulate the underlying sensorimotor loops. In the insect brain, two such regions, with interesting neuroarchitectures, are the mushroom bodies and the central complex. The mushroom bodies are known to play a role in learning, and in particular may be essential for more complex aspects of learning such as context dependence, generalisation and non-elemental association [2]. The central complex could be involved in integrating multimodal information, for example, for path integration [3] and in co-ordinating locomotor output.

We are currently exploring models of associative learning in the mushroom bodies in several closed-loop tasks. The first [4] is based on *Drosophila* learning in the flight simulator using visual stimuli for non-elemental association tasks (e.g. learning to associate patterns A and B with a positive response but the combination AB with a negative response). The second [5] involves the association of a visual cue with an auditory cue, such that the insect can maintain the appropriate heading, relative to the visual cue, when the attractive auditory cue is turned off. The third is a spatial memory task in which the insect has to relocate the cool spot on a hot plate using the

visual surroundings to home. The control architecture has been tested in simulation and is now being transferred to robot hardware for testing in real environments.

Acknowledgements: This work has been supported by EU grant IST-004690 SPARK.

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Springy Shells, Pliant Plates and Minimal Motors: Abstracting the Insect Thorax to Drive an MAV

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Designers aiming to develop small flapping MAVs capable of hovering and low-speed manoeuvring face significant difficulties in maximising the induced airflow to a level where the weight is fully supported. Power is at a premium; and minimising both weight and the inertial cost of flapping are major design considerations. Appropriate wing kinematics are also essential: it is relatively easy to build a simple fast-flying flapper, whose wings undergo minimal change in shape and attitude, but slow flight requires the wings to twist or to change shape between the half-strokes; and the timing of twisting may be essential in generating significant unsteady forces around stroke-reversal, and in fine control [1].

How do insects achieve these? Their engineering is highly unorthodox. They minimise weight and inertia by using versatile, light-weight composites for the thoracic skeleton, which is also the transmission, and for the wings. The pterothoracic skeleton of 'advanced' insects is a thin, flexible shell – a kind of deformable monocoque - which is cyclically deformed by the power-producing muscles to flap the wings as first order levers over a lateral fulcrum, and to twist the wing base to some extent at each stroke reversal. The form of these basic movements is automatically determined by the structure of the thorax provided that the correct sequence of muscle contractions is followed; but they can be modified by the action of other, controlling, muscles, often contracting tonically, that stress parts of the shell and alter its response to the cyclically contracting power muscles [2]. Inertial power is minimised by cyclical elastic energy storage and release in the skeleton and the muscles; this is a resonant system.

The wings themselves are unique structures [3,4]. They are essentially smart aerofoils: selectively flexible, membrane-filled frameworks with no internal actuators, constructed to deform automatically and appropriately in response to the aerodynamic and inertial forces they receive in flight, and apparently tuned to do so at their working flapping frequencies. As with the thorax, these automatic responses can in many groups be modified remotely by controlling muscles. Mass and inertial cost and stress are minimised by the use of relief, rather than bulk, to give stiffness.

These solutions seem to have much to offer to MAV designers. Many of the actions of the thoracic skeleton can be reproduced in a five-bar linkage, though an optimised springy shell is probably a better long-term aim. The smart properties of the wings can be mimicked surprisingly easily in thin plates and space frames.

However, major simplifications and compromises are necessary. The extraordinary local versatility of the insect skeletal material is beyond our reach, and so, probably, are ultra-thin wing membranes with the necessary strength. On the other hand, insects have limitations which engineers do not. Their actuators are all linear in action, and they can only pull, not push, so that each needs to be opposed by another, or by a spring. They have no access to rotary bearings, and hence to cams, cogs, worms and wheels. Their other functions: walking, feeding, reproduction, irrelevant to MAVs, place constraints on their structure. Finally, evolving insect lineages need always to build on the characteristics of their immediate ancestors; they are not free, as are engineers, to select best solutions from widely different groups and designs. Engineers have many resources that insects do not.

This consideration provides some comfort when one faces the most daunting aspect of insect flight systems: the number of actuators they use. Dragonflies, superlative fliers with an essentially archaic design, have around 50 flight muscles. Muscle reduction has been a repeated theme in all insect lineages, but even higher flies, with only one pair of aerofoils, use about 20 muscles, plus eight more for the sensory halteres – the modified hindwings. 28 actuators in a small MAV would pose considerable problems of weight and control.

The best approach may be to follow the insects in the use of a pliant, springy shell to combine the functions of body and transmission, and of thin, smart plates as wings; but to resort to more orthodox technology, using the lightest possible materials and a good deal of ingenuity and lateral thinking, to drive and control the system with the minimum number of actuators. Both wings and body should be resonant systems, tuned to the flapping frequency: elastic energy storage is essential for greatest economy and minimal actuator size and weight. The necessary kinematic variables are few: frequency; stroke plane angle; amplitude; twist, and the timing of twist; and scope for lateral stroke asymmetry; but controlling these is a major challenge. As in insects, as much kinematic information as possible should be incorporated in the structure of the skeleton, so that instantaneous control is restricted to modulating the basic movements of flight.

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Stealthy Target Tracking in Satellite Flies

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The satellite fly tracking system

Female satellite flies (Sarcophagidae: Miltogramminae) track ground-nesting wasps (Sphecidae: *Cerceris* sp; back to their nests with the aim of depositing one of their larvae on the prey of the wasp, just before the wasp enters her nest. Parasitic pressure can be so high in wasp colonies that up to four satellite flies simultaneously track one wasp, sharing the airspace behind the wasp. In contrast to other examples of target tracking in insects, the aim of the flies in this task is not target capture, but the stealthy pursuit of the wasp back to her nest and a fast final approach to deposit the larva. We used normal and high-speed digital video cameras to reconstruct three-dimensional flight-paths, head and body orientation of tracking flies and their targets to identify the control variables used by the flies [1,2].

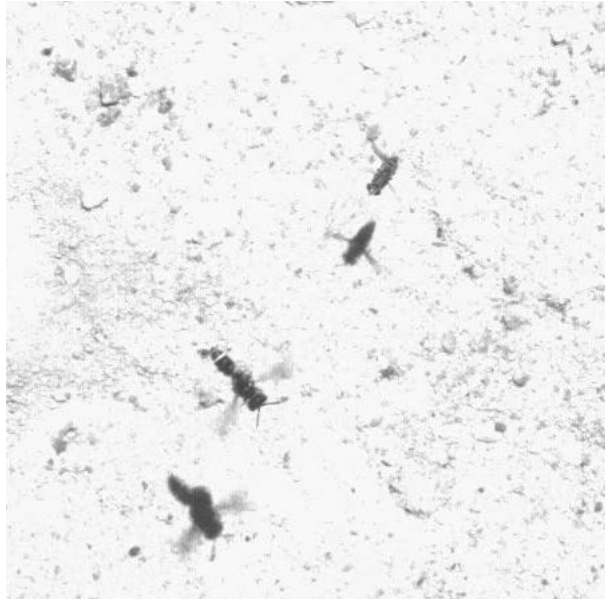


Figure 1. A female satellite fly shadowing a prey-laden wasp approaching her nest

The structure and control of satellite fly tracking

Flies perch in the vicinity of wasp nests and orient to flying insects with rapid body saccades, that can be followed by the initiation of a shadowing episode (Figure 1). During the resulting tracking sequence, the flies control their distance to the target wasp to within 6 to 8 cm, independent of their bearing relative to the wasp (Figure 2). Much like hoverflies, satellite flies have exquisite control over change flight direction independently of body axis orientation and employ both yaw rotations and translational movements to control distance and line-of-sight to target. Cross-correlation analysis shows that the delay between error angle and fly angular velocity is extremely short (<10ms). Forward velocity is positively correlated with target distance at delays of 90 to 100ms. The control of distance to target is not achieved by controlling angular size or derivatives thereof, but must involve absolute range information. The flies possess an extreme frontal acute zone, with greatly enlarged facet diameters, long focal length and long rhabdoms, all suggesting that both signal-to-noise ratio and resolving power is enhanced. Anatomical and *in-vivo* optical analysis of the flies' compound eyes suggests that the flies may be able to use binocular cues to determine their distance to the target. The final approach is triggered by the disappearance of the wasp.

Elements of stealth in satellite fly tracking

Satellite flies achieve stealth in at least four distinct ways: (1) they always point at the target wasp through adjustments to their body axis orientation around both yaw and pitch axes. The flies thus present their smallest cross-section to the wasp and maintain an angular size of between 0.5-1.5 degrees; (2) the flies keep a constant distance to the target wasp and thus minimize the amount of looming cues they present to the wasp; (3) the flies preferably position themselves behind the wasp where the wasp's visual field may be limited and where visual resolution is likely to be worst; and lastly, (4) we identified brief periods of motion camouflage, in which the fly moves in such a way as to appear at a different spatial location as seen from the view-point of the wasp [3]. These instances of motion camouflage can be explained as emergent properties of the flies' tracking control strategy.

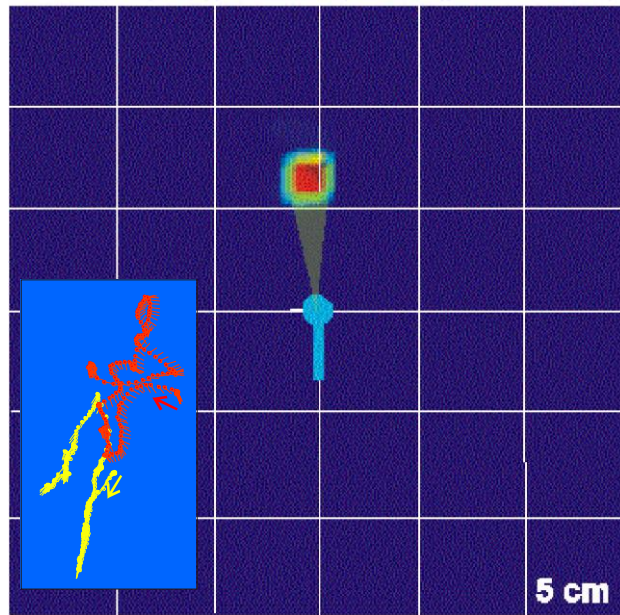


Figure 2. Frequency distribution of wasp target in fly coordinate system during 4 seconds of tracking (see inset, wasp red, fly yellow)

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Insect-inspired Autonomous Microflyer

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Autonomous flight in cluttered environments such as houses or offices requires high maneuverability, fast mapping from sensors to actuators and extremely light overall weight. Although flying insects are well capable to solve this problem, roboticists have been at pain to reproduce such capabilities. At the Laboratory of Intelligent Systems, we are taking inspiration from flying insects to progress toward this goal. The latest version of our microflyers, the MC2, takes advantage of principles found in flying insects in order to autonomously fly in a textured experiment room.

The MC2 airframe is a 5-gram fixed-wing airplane (figure 1) made out of carbon fibers and thin Mylar covering foils [1]. Choosing a non-flapping platform is motivated by its simple mechanical design, its robustness, and its capability to fly in tight spaces, e.g., 1m-wide corridors or 9m² rooms. Indeed, the research efforts in this project are focused on control rather than aerodynamics or complex flapping mechanisms.

With this kind of microflyers, it is impossible to use classical sensors such as full-featured inertial measurement units, GPS, ultrasonic or laser range finders because they would not fit the available payload (approximately 5g). Inspiration has thus been taken from flies, which possess fast, but low-resolution eyes [2], tiny vibrating organs acting as gyroscopes [3], hairs and antennas allowing for airflow

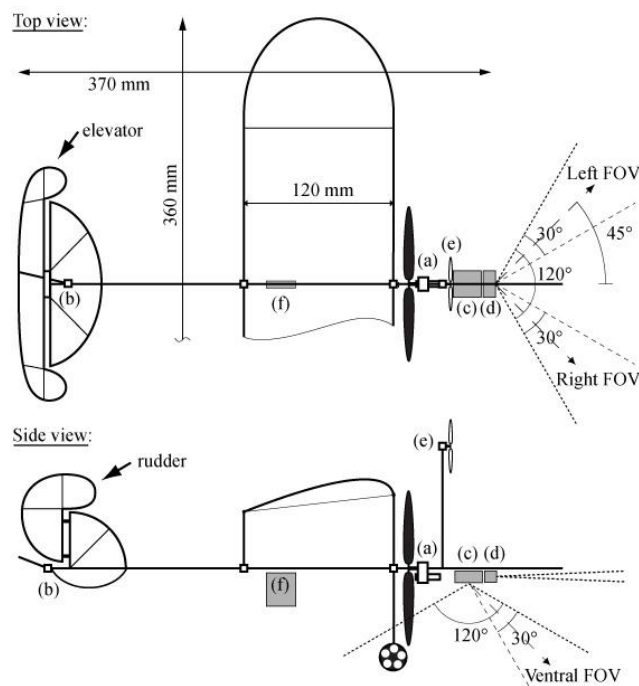
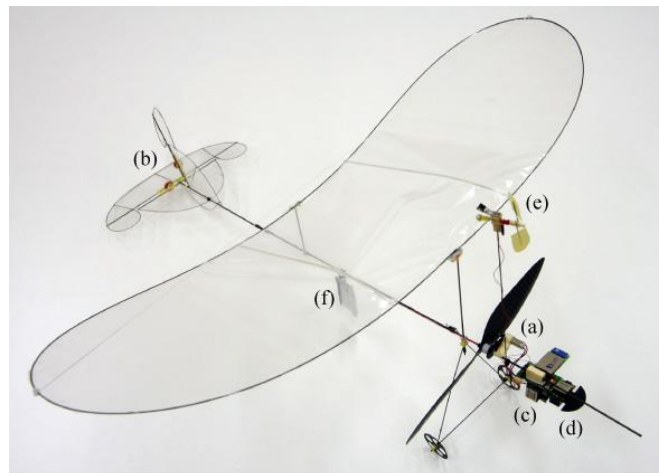


Figure 1. MC2 microflyer. The on-board electronics consists of (a) a 4mm geared motor with a lightweight carbon fiber propeller, (b) two magnet-in-a-coil actuators controlling the rudder and the elevator, (c) a microcontroller board with a Bluetooth module and a ventral camera with its pitch rate gyro, (d) a frontal camera with its yaw rate gyro, (e) an anemometer, and (f) a Lithium-polymer battery.

sensing [4]. Accordingly, the MC2 is equipped with tiny visual sensors – out of which less than 100 pixels are used – small MEMS rate gyros measuring pitch and yaw rotational velocities, and an anemometer to sense airflow.

These sensors are complemented by a small 8-bit microcontroller, in which image sequences are processed to estimate radial optic flow in three different locations at 45° off the forward direction of the airplane: on the right, on the left, and on the bottom (figure 1). These optic flow estimates are then corrected for body rotations using the onboard gyros in order to simulate gaze stabilization present in insects [5]. Autonomous control is achieved by means of simple connections between these optic flow inputs and the control surfaces (rudder and elevator). It essentially relies on the fact that translational optic flow is inversely proportional to distance [6]. In addition, the anemometer input allows for controlling the main motor in order to keep the airspeed within a reasonable range.

Once released in its environment, the microflyer would fly for a few minutes while avoiding collisions with surrounding surfaces (walls and floor) until it is caught by hand (see video at <http://lis.epfl.ch/microflyers>). This result showing full autonomy of a 10-gram indoor microflyer is based on preliminary studies in lateral and vertical vision-based collision avoidance, both in simulation [7] and reality [5].

Next steps include autonomous take-off and landing as well as the replacement of the onboard cameras with custom-developed neuromorphic vision chips [8] in order to adapt to a wider range of visual contrasts and background light intensities. These efforts will pave the way toward fully autonomous flight in unmodified indoor environments.

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