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Preface

Bioinspired flight control

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The invention and deployment of small flying robots (drones) is beginning to influence our everyday lives. Their applications are frightening to some and exciting to others. From military surveillance, to city courier services, to near-future flying camera phones, this technology is bound to end up on everyone's doorstep. Setting privacy issues aside, the biggest challenge in successfully integrating the versatile use of drones in our society is to make them safe and reliable. Whereas we have succeeded in doing so with large passenger aircraft, it has proven remarkably difficult to adapt this technology on a smaller scale to flight in urban environments. From windy street canyons to highly cluttered alleys and parks, keeping drones in the air is actually a more difficult task than first imagined, as any hobby drone pilot can confirm. Making these flights more useful and versatile is yet another challenge. How can we adapt and innovate our technology to succeed?

Flying animals have adapted remarkably well to the new aerial environments we have created. Setting wind turbines and glass windows aside, birds, bats, and insects do well under circumstances our drones do not. And, frankly, drones that can robustly detect and avoid closed windows or turbine blades have yet to be invented. Flying animals can be found everywhere in our cities; from scavenging pigeons to alcohol-sniffing fruit flies that make precision landings on our wine glasses, these animals have quickly learned how to control their flight through urban environments to exploit our resources. To enable our drones to fly equally well in wind and clutter, we need to solve several flight control challenges during all flight phases: take-off, cruising, and landing. Ideally, we would also further expand these capabilities to include novel tasks such as pick-up and delivery, photography and streaming video, all culminating in sophisticated situational awareness by fusing images with data from advanced sensors. Remarkable utility could be achieved by figuring out which principles enable animals to outperform our drones.

In this special issue, fourteen distinguished research teams with biology and engineering backgrounds present their ideas to advance the capabilities of current drones, inspired by animal flight control. The contributions integrate biological studies—ranging from flying insects and bats to flying snakes—with engineered bioinspired solutions to improve the take-off, obstacle avoidance, in-flight grasping, swarming, and landing capabilities of drones.

Insect-inspired flight control of micro drones

Figure 1. Flying fruit fly composition illustrating a turn. *Photo credit: Floris van Bruegel.*

Of all insects, flies represent in many ways a gold standard for high-performance flight, one that engineers would like to harness in drones (figure 1). How flies achieve such remarkable control over their flight is not fully understood. Elzinga *et al* [1] used a dynamically-scaled robotic fly to study how flapping insects adjust their wing stroke to regulate and stabilize forward flight. Their results suggest that the modulations of wing motion used to stabilize flight may help simplify their sensing and computational requirements. This finding highlights the importance of co-designing sensing, actuation, and control systems in engineered platforms, to facilitate similarly effective system integration as found in flies.

To detect objects and avoid collisions in complex environments, stereo vision provides an obvious solution to estimate distance. For a tiny insect such as a fruit fly or honeybee this method falls short. Instead, they must rely on calculations of 'optic flow', the motion of image intensity over their compound eyes. Optic flow depends on the ratio of velocity to distance of an object and, therefore, provides distance cues. van Bruegel *et al* [2] developed a theory to gain insight into the control algorithms that might enable the robust landing behavior observed in flies and honeybees. To demonstrate the real-world applicability of this algorithm they demonstrate its performance using images recorded with a translating camera. The results reveal how insects can use optic flow to estimate distance effectively. This capability can improve the visual guidance of drones through GPS-denied and complex environments (see stacks.iop.org/BB/9/025002/mmedia).

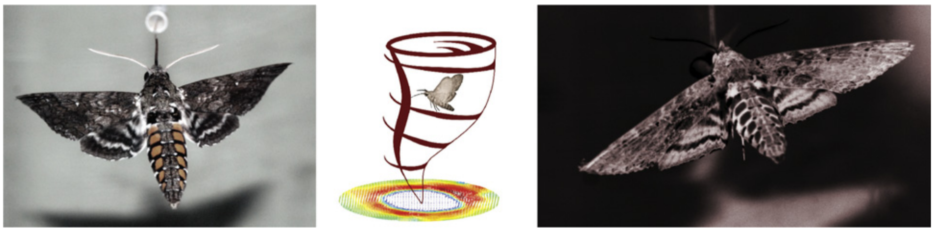

Figure 2. Hawkmoth hovering in front of a feeder without (left) and with tornado disturbance (right). *Photo credit: Victor Manuel Ortega-Jimenez.*

When it comes to negating the effect of unexpected gusts, drones need dramatically better-tuned methods to respond to aerodynamic perturbations. A casual observer will attest that tiny insects seem to fly unfazed through gusts with velocities that are of similar magnitude to their flight speed. Not only is gust magnitude large, turbulent eddies spin and induce roll moments and other orientational perturbations, which require an adequate response. Ortega-Jimenez *et al* [3] used a novel vortex chamber to study hawkmoth flight stability and control under varied whirlwind conditions. They found that hawkmoths flying in a whirlwind exhibit a suite of asymmetric and symmetric changes to wingbeat amplitude, stroke plane inclination, and wing angle of attack in order to remain aloft (figure 2). However, moths in the most intense whirlwinds were only able to sustain flight control briefly. Since these moths fly mostly during the evening and night (when the wind settles and turbulence levels are moderate) the results were perhaps to be expected, but they do show that yaw turning is probably the most critical response mode to flight in vertically oriented, tornado-like vortices. This insight can guide the design of appropriate test facilities to assess the robustness of drones to environmental turbulence (see stacks.iop.org/BB/9/025003/mmedia).

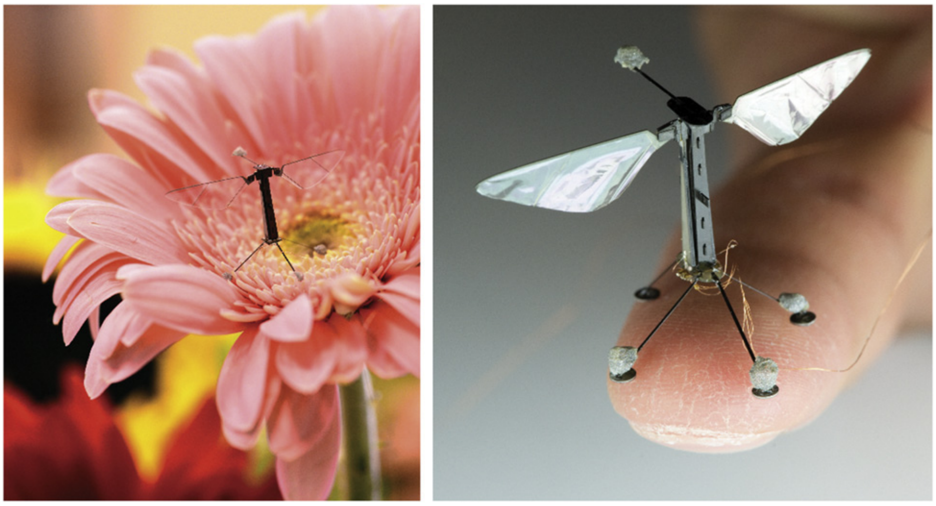

Figure 3. The tiny drone from Harvard comfortably positioned on a flower. *Photo credit: Harvard Microrobotics Laboratory*.

The remarkable flight capability of small insects is something engineers dearly want to harness in micro drones at the scale of a fly. Tiny drones that fly like insects are now becoming feasible due to design evolution and new millimeter-scale manufacturing approaches (figure 3). However, flight control for these vehicles poses new challenges, in particular because it is difficult to manufacture identical drones that can be controlled with the same controller parameters. Chirarattananon *et al* [4] present a robust control algorithm that can deal with these uncertainties in the drone-manufacturing process. This capability is essential to enable mass production and deployment of these micro drones regardless differences in their flight capabilities due to manufacturing limitations. Finally, the algorithm affords the tiny robots to make more precise and useful flight manoeuvers as demonstrated in their online video (stacks.iop.org/BB/9/025004/mmedia) that demonstrates hovering, lateral maneuvers and landing while beating the wings at 120 Hz like a fly.

Figure 4. Vortex wake generated by a flapping flexible foil. *Image credit: Annika Eberle*.

To better understand how insects achieve their remarkably effective maneuvers, we can take a first-principles approach by expressing and solving Newton's laws of motion for both the fluid and flexible wing. Eberle *et al* [5] present a computationally efficient model that allows many more parameter permutations than are feasible in an animal experiment (figure 4). They show that the deformation of insect wings during flapping is dominated by the inertia induced by the actuation of the wing base, rather than by the fluid loads imposed upon it. Their simulations of insect wings suggest that the fluid and solid mechanics may be modeled separately, which makes these simulations dramatically more efficient. This finding can help micro drone designers to quickly evaluate different flexible wing designs on a laptop.

Bat-inspired flow and membrane tension control

Figure 5. Lesser long-nosed bat flying in the Lund animal flight wind tunnel. *Photo credit: Anders Hedenström*.

Bats are the only mammals that evolved powered flight. Their unique wing anatomy includes a large number of muscles that can tension and camber the membrane to provide tight control over the airflow over their wings. This capability affords bats modulation of the shape of their wings within a beat, adapting membrane tension to optimize aerodynamic shape over a large range of speeds. During slow hovering flight, bats boost the lift of their wings using so-called leading edge vortices, which are tornado-like vortices that are stretched parallel along the leading edge of the wing. The low-pressure core of these vortices helps to increase the lift significantly, but probably at the cost of additional drag. Muijres *et al* [6] discovered that bats do not generate these lift-enhancing vortices during fast forward flight (figure 5). During cruising flight bats benefit from the high flow speed over their wings induced by forward body motion. This high-speed flow enables them to generate lift by simply overcoming body drag, which makes the leading edge vortex obsolete, and in turn reduces drag in the process (see stacks.iop.org/BB/9/025006/mmedia).

Figure 6. Bat *Artibeus jamaicensi* flying in the Brown bat flight wind tunnel (left) and bat-inspired flapping robot tested in the same wind tunnel (right). *Photo credit: Sharon Swartz and Kenny Lab at Brown University*.

The highly compliant membranous wings of bats uniquely position them to match membrane stiffness to the aerodynamic conditions (see stacks.iop.org/BB/9/025007/mmedia). Cheney *et al* [7] found that during flight, bats activate a muscle array embedded within their wings. Muscle activation is known to change muscle stiffness; it is also know that a slack membrane wing does not facilitate aerodynamic efficiency. The most plausible interpretation of the function of muscle activation in the membrane is therefore that it helps bats modulate wing membrane stiffness in order to extend the range of conditions under which they can achieve high aerodynamic performance. These findings provide new ideas for actively modulating wing tension of the membranous wings of bat-inspired drones (figure 6).

To better understand the aerodynamic performance of membranous bat-like flapping wings, Bahlman *et al* [8] used a robotic flapper to simulate key aspects of bat flight. With this novel robot they made experimental permutations in flapping wing parameters that are unethical in living vertebrates. The robot not only emulates the multiple wing elements unique to bat morphology, it also allows for isolating the effects of kinematic parameters such as flapping frequency, amplitude, stroke plane angle, downstroke ratio, and wing retraction. The team uses a custom-designed load cell rig that records the effect of these parameters on the energetic consequences of the lift and thrust force. This comparison of relative efficiency of different wing motions can help bat-inspired drones to take off into the night.

Bioinspired improvement of drones

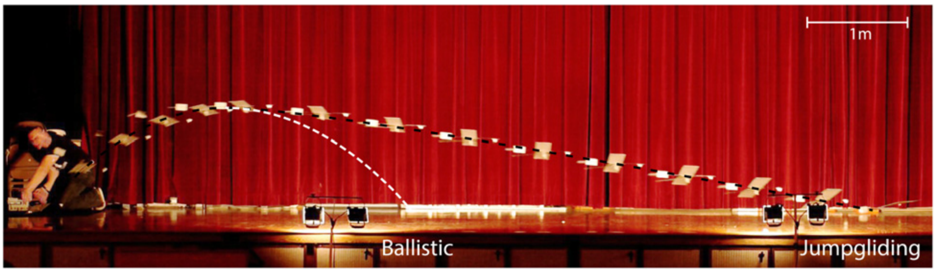

Figure 7. Stage performance of the Stanford jump glider versus a theoretical ballistic jump. *Photo credit: Alexis Lussier Desbiens.*

For many drone missions it would be convenient to simply hop from one place to the other like a bird does foraging on the ground. Birds and several gliding arboreal animals use a gliding phase to extend their range and limit the energy needed to make distance. Here Lussier Desbiens *et al* [9] designed a bioinspired jumping glider (figure 7). Through their design iterations they found that small adjustments in airfoil surfaces can be used to alter the trajectory of a jumping and gliding robot with minimal drag penalties. Another helpful insight is that it turns out that jumping from a slippery surface can be enhanced by creating negative lift to allow for a steeper angle of ascent during the jump to achieve similar ranges. This finding suggests that it would be interesting to see how jump gliding animals might use positive versus negative lift to vary their trajectories during ascent and descent (see stacks.iop.org/BB/9/025009/mmedia).

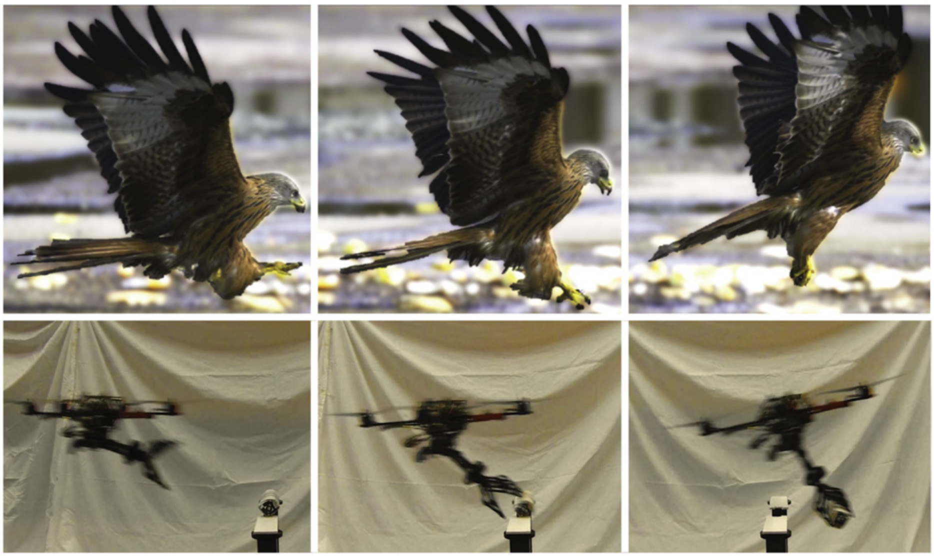

Figure 8. Grasping eagle with real claws versus drone with eagle-inspired grasper. *Photo credit: (top images) 'The Slow Mo Guys'; (bottom images) Justin Thomas.*

While gliding or flying above the ground it would be useful to be able to pick up samples or parcels to be delivered elsewhere during at touch and go manoeuver. Trying to solve this problem Thomas *et al* [10] noted that eagles grasp objects with great precision while moving at high speeds. They decided to engineer this capability into a new quadcopter to achieve high-speed object grasping and manipulation to pick-up and deliver sensitive payloads (figure 8). They demonstrate that high-speed grasping can be accomplished using an underactuated gripper, with the help of an external motion capture system that provides accurate information of the position of both the quadcopter and the object to be grasped. They much expanded the impact of this technology by also demonstrating this capability based primarily on the visual feedback from an onboard camera, one that hobby drones can easily be equipped with (see stacks.iop.org/BB/9/025010/mmedia).

Figure 9. Quadcopter equipped with insect vision algorithms to avoid obstacles (left) and a swarm of quadcopters controlled by an algorithm-inspired by pigeon flocking (right). *Photo credit: J Keshavan* (*left*) *and Csaba Virágh* (*right*).

To extend the visual capabilities of quadcopters Keshavan *et al* [11] process the images of an onboard camera to enable a quadcopter to avoid obstacles. Similar to insects they decided to use the optic flow cue to avoid collisions by estimating the velocity compared to the proximity of objects. They implemented this capability using freely available cameras and processing architectures that are simple to implement on current drones.

Whereas single flying drones can already accomplish many novel tasks, the future in drone operation is probably relying on redundancy and combining the data of many individual drones that are directed as a swarm (figure 9). Inspired by their earlier research on flocking pigeons, Virágh *et al* [12] present a new control framework for flying robot swarms. They demonstrate the capability of this framework for a flock of quadcopters that collectively can track a moving car (see stacks.iop.org/BB/9/025012/mmedia). A flock of quadcopters might help future search and rescue workers to perform an efficient distributed search. A second application is continuous distributed field monitoring, and finally, these quadcopter flocks could be used to quickly deploy ad hoc communication networks in remote areas.

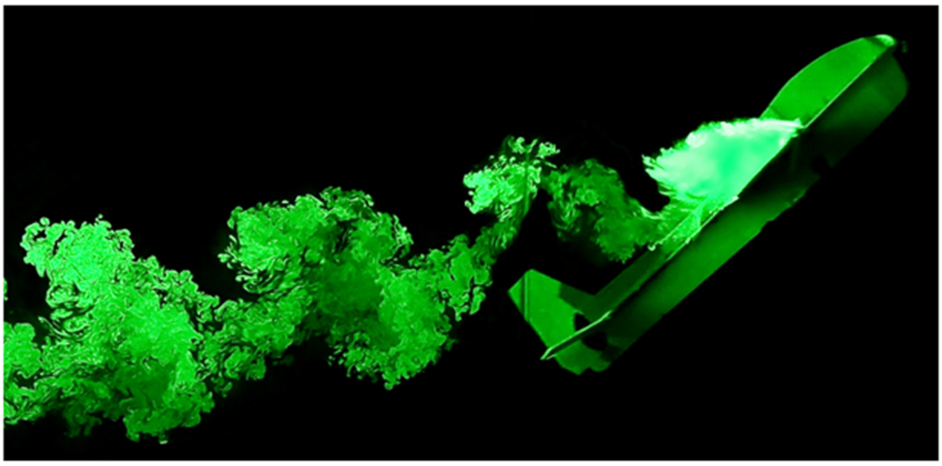

Figure 10. Dynamic-stall vortex-wake generated by a small drone performing a bird-inspired perching manoeuver. *Photo credit: Rick Cory.*

Current drones must land to refuel or recharge at some point and ideally, they would not rely on smooth roads or lawns with perfectly cut grass. To recharge away from the mission base engineers figured the large amount of energy transferred by power lines can be tapped into. Whereas birds land on powerlines on a day by day basis, drones cannot. Moore *et al* [13] demonstrated bird-like perching maneuveres on a wire that exploit the massive pressure drag of bird-like high-angle attack maneuveres that cut 'runway length' (figure 10). This affords these drones to land on a perch with a precision that comes close to birds. To achieve such remarkable precision they used a special algorithm, so-called LQR-Trees, which provide robustness to a wide range of perturbations. This capability is essential to compensate for the wind gusts that typically disturb perching on powerlines and tap into the grid (see stacks.iop.org/BB/9/025013/mmedia).

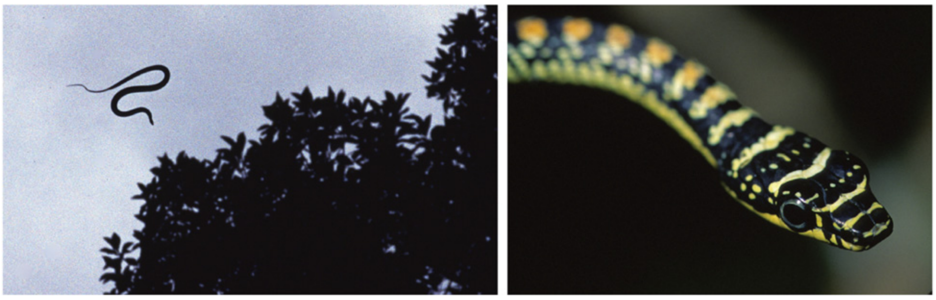

Figure 11. Flying snake about to land in a tree and close-up after landing showing-off its charming appearance. *Photo credit: Jake Socha.*

Finally, I would like to share that this special issue primarily celebrates the astonishing diversity of animal flight, ranging from insects, bats, and birds to the diverse lineages of arboreal jump gliders around the world. Of all flying animals that can inspire flying drones, the flying snake is perhaps the most horrifying. Not surprisingly, it has captured the media's attention time and time again. In contrast to earlier captivating headlines, the image on the right suggests, however, that these snakes are possibly… cute (figure 11). Yet, witnessing the quick aerial undulating motion at a distance will probably first provoke deep angst. Jafari *et al* [14] overcame this angst and remained inspired by the remarkable flight display of aerial snakes. To understand the basic principles that underlie how the undulation and posture of the airborne snake's body enables it to glide, they developed new aeromechanical models of gliding snakes. They find that the effective tandem wing configuration of the snakes tail improves self-stabilization in the pitch direction during flight. This suggests that the neural control of this remarkably complex gliding behavior is simpler than expected. Obviously, these principles could likely be harnessed in super scary snake-inspired flying drones that terrorize our backyards. Instead, I propose to use the new insight in the flight mechanics of these charming jump gliding snakes to increase public awareness for their endangered natural habitats, which represent a celebration of the Earth's breath-taking biodiversity.

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