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EDITORIAL

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EDITORIAL

Nature-inspired flight—beyond the leap

Guest Editors

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Whereas humans can outrun horses over large distances (BBC News 2004), because of their adaptation for endurance (Bramble and Lieberman 2004), their swimming performance is mediocre compared to that of tuna and sailfish, and flight is impossible. No wonder that the flight of animals and plants such as birds, bats, insects and autorotating seeds has long since inspired mankind to invent its own flying machines. Just over 100 years old, human-designed aircraft have barely taken off on an evolutionary timescale. Recently engineers have stepped up by designing small unmanned air vehicles at the scale of flying animals and plant seeds that innovate by mimicking nature's successful design principles for highly maneuverable and efficient flight. Here we feature current biomechanics flight research and bioinspired design crème. By featuring the work in nine papers of both fields side-by-side, and motivating the authors to speculate how their work could inspire the other group, we hope to stimulate future interactions between these adjacent fields of research. Here, we provide an overview of the authors' research and designs accompanied by their perspectives on the value of their work for the adjacent field.

The startling diversity of natural flight

Flight, including gliding and parachuting, evolved independently in many lineages of organisms, from insects, dinosaurs, birds, reptiles and mammals to plant seeds. Key evolutionary advantages of flight, such as energy efficient habitat exploration and dispersal, have driven the evolution of a myriad of wings that carry many members of these groups through the air. There is still intense debate on how flight initially evolved: from the ground up or from the canopy down. Regardless, flight must have started with a leap into thin air during which aerodynamic force first became a strong selective force on the evolution of organismal body plans. In keeping with this, our special issue takes off with the gecko's amazing capability to direct its fall in mid-air.

How a tail can help make the most out of a leap into thin air

By studying geckos falling under the pull of Earth's gravity, Jusufi *et al* (2010) elegantly combine observations on how geckos can right and turn their body mid-air, with insightful mathematical models, and a robot gecko that enables them to validate the principles of righting and turning, while falling to Earth. The work of Jusufi *et al* (2010) suggests that inertial appendages could simplify control of a variety of robots and unmanned aerial vehicles, because this solution allows for simple body reorientation. An airborne robot could maintain control authority at high angles of attack or zero airspeed, where lift-based control mechanisms become less effective. Next-generation, legged robots could swiftly navigate three-dimensional terrains through periods of parachuting between arboreal and terrestrial supports. Such robots could be stabilized by tails with multiple degrees of freedom to change shape and instantaneous moment of inertia more efficiently, much like the tails geckos have at their disposal (Higham and Russell 2010). This would enable these robots to take a leap into thin air and land safely on all feet.

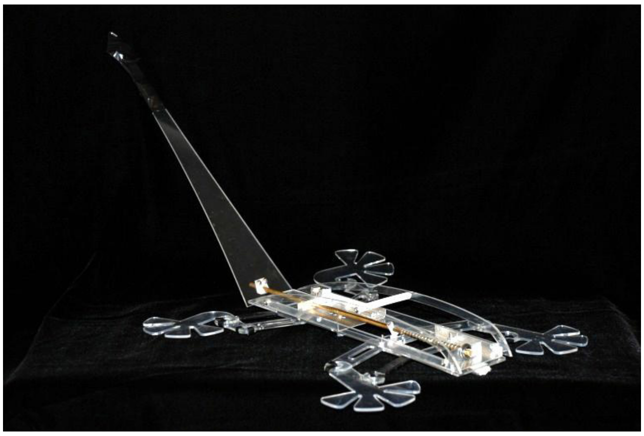

Figure 1. Robot gecko that can right itself midair during its fall to the ground. Image credit: Thomas Libby.

Slithering through the transition from parachuting to gliding

Socha *et al* (2010) investigate how aerial snakes extend their glide trajectory down to the ground while slithering their body to adjust its shape. They find that, regardless the height of fall provided to the gliding snakes in their experiments, none of the snakes reaches an equilibrium glide path. This illustrates how dynamically challenging the evolutionary transition from falling, to parachuting, and gliding flight might have been. In their outlook, Socha *et al* (2010) emphasize that a snake-inspired undulating robot that is capable of slithering through air has not yet been developed. Development of such a robot will most likely require challenging simulations and flow visualization experiments with live animals to obtain a better handle on snake-like aerial descent. Such unconventional descent approaches for climbing snake-robots might well improve their descent performance, and could expand their explorative capabilities.

Figure 2. Flying snake slithering through air. Image credit: Jake Socha.

Boosting glide performance through efficient exploitation of thermals

Ákos *et al* (2010) compare strategies of birds and unmanned air vehicles to exploit thermals, hot columns of air rising in the atmosphere, to boost their glide performance. Such soaring harvests potential energy from warmed rising air that lifts both birds and aircraft. The challenge is finding the thermals in time and staying in them long enough to maximize flight performance. These workers show that bird and human pilot soaring strategies correspond and can be successfully implemented in unmanned air vehicles. Ákos *et al* speculate that even though bird feathers have no inherent sensory capabilities, they are able to sense the airflow across the wing through the different mechanoreceptors around the follicles of the feathers (Brown and Fedde 1993, Shim and Husbands 2007). It is possible that soaring birds that depend on the exploitation of the atmospheric energy (thermal updrafts, wind gusts) can also detect local updraft information along the entire surface of their wings from changes in the distribution of pressure (Usherwood *et al* 2005) sensed by the mechanoreceptors. Ákos *et al* argue that the design of an unmanned air vehicle that could measure detailed airflow information similar to birds could help these vehicles to fly along local updrafts and hence minimize energy loss. Airflow sensing would also enable the unmanned air vehicles to find more easily the center and the border of the thermal updraft.

Figure 3. Storks outfitted with GPS trackers that helped decipher their soaring strategies. Image credit: Zsuzsa Ákos.

From gliding to powered flapping flight

Tobalske (2010) shows how many of the smallest birds have specialized in being either highly accomplished cruisers through bounding flight, such as budgerigars, or effective hoverers, such as hummingbirds. He illustrates how these different flight modalities have far-reaching implications for the body plan, neural flight control, and aerodynamic mechanisms that these birds employ to stay aloft. Based on an extensive overview of how small birds fly, Tobalske (2010) suggests that micro-air vehicles should hover like a hummingbird and cruise like a budgerigar. Hummingbirds are uniquely adept at hovering and flying slowly, whereas intermittent flight appears to be an energy-saving strategy for flying over a wide range of speeds. Mechanical and energetic power requirements vary according to a U-shaped curve with flight speed, but the shape of this curve, and efficiency of converting chemical energy into mechanical work, can vary with wing design and kinematics (Ellington 1991, Thomas and Hedenström 1998, Tobalske *et al* 2003). To maximize efficiency over a broad range of flight speeds, a useful solution would be to design a robot with the capacity to alter wing posture and pause flapping intermittently as a function of flight speed. The robot should hover like a hummingbird, using continuous flapping with extended wings and long-axis rotation at the end of each half stroke. Then, like a budgerigar, it should shift to flap-gliding at slow and moderate speeds and to flap-bounding at fast speeds. A flexible wing design would enable it to progressively flex its wings during upstroke to reduce drag as speed increases.

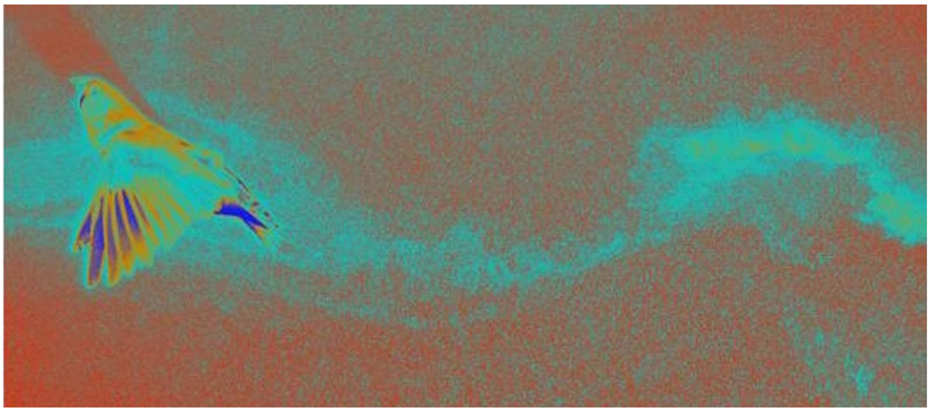

Figure 4. Airflow around a flying zebra finch seeded with a mist of micro olive-oil droplets. Image credit: Bret Tobalske.

Getting a grip on the physics of flight

Whereas biomechanics experiments are crucial for quantifying how organisms fly, deeper insight into the underlying mechanisms can arise from studying the physics of flight. In the past hundred years or so, our understanding of the physics of airplanes has vastly increased our understanding of flight. One remaining challenge, however, is that the aerodynamics of flight is highly sensitive to the scale of organisms compared to that of aircraft, due to so-called low Reynolds number effects. An even more challenging difference between planes and organisms is the flexible morphology exhibited by flying animals. Whereas the wings of maple seeds are similarly rigid as airplane wings, insect wings are inherently flexible, bat wings have muscle fibers in their wing membrane that can actively stretch the wing's surface, and birds can dramatically change the shape of their wings through movement of joints and overlapping feathers, while retaining an efficient aerodynamic shape. The fluidity and flexibility of wing shape in these organisms are just starting to be fully appreciated through physical analysis. We hope that this emerging field will be further explored within a biologically relevant context. A promising approach is the use of modeling techniques that can explore the parametric design space of flexible wings, as presented below.

Flapping wing flexibility can be tuned for force control

Mountcastle and Daniel (2010) explore the aerodynamic performance of a compliant flapping wing cross-section, the airfoil, with variable flapping kinematics and variable chord-wise flexural stiffness. In their two-dimensional model they combine an efficient vortexlet method with a basic finite element method for flexible beams. The computational efficiency of this approach allows for the quick exploration of the parametric design space of compliant wings. In doing so, they find that lift and thrust of flexible wings are highly sensitive to variations in chord-wise flexural stiffness, for which the performance optima lie in different flapping-phase regions. This sensitivity could be employed by animals, such as hawkmoths, to tune and control force production of their flexible wings. Mountcastle and Daniel suggest that important flight performance parameters such as lift and thrust of insect-scale wings can be tuned through simple phase modulation. Whereas insects regularly actuate their wings along three axes of rotation: sweep, elevation and pitch, their work suggests how modulation between just two axes of actuation is sufficient and could simplify control. A wide range of translational and rotational flight forces on the body could be generated, simply via the control of sweep/pitch phase, employed differentially between the left/right wing pair. Indeed, flies have been shown to use a similar control strategy, generating yaw turning forces through asymmetric timing of wing pitch rotation (Dickinson *et al* 1993).

Figure 5. Simulated vortex wake generated by a flexible airfoil (arrows indicate aerodynamic force). Image credit Andrew Mountcastle.

From complex to simple bioinspired airplanes

The burning question of how a growing understanding of the biomechanics of flight can direct unmanned air vehicle design and inspire new conceptual solutions to becoming and staying airborne remains largely unresolved. In our opinion the main challenge is combining a deep insight of flight biomechanics within its ecological, developmental and evolutionary context, with sound engineering design principles based on a balanced mix of proven and novel technology. Because biologists and engineers are typically trained quite differently, which equips them with different scientific insights and capabilities, this contributes to the gap between the biologist's understanding of natural flight and the engineer's expertise in designing vehicles that function well. In the middle are a few pioneering engineers who are able to bridge both fields by mastering enough biological insight to design novel biologically inspired air vehicles that work. Here we feature key designs that not only work, but nicely illustrate how these designs can range from complex to simple. These biologically inspired engineering solutions illustrate the potential for bridging these two fields, but also demonstrate the current gap between biology and current engineering designs. Whereas current engineering designs benefit from simplicity, future ones might be more sophisticated with a much wider performance envelope and broader range of applications inspired by biology's vastly different scales of architectural organization and robust multi-functionality. Below, we begin by considering complex biologically inspired designs that fly and finish with successful simple designs that could have a direct societal application now.

Gaining control of micro-flapping wings

Finio and Wood (2010) present several innovative insect-scale robotic thorax designs capable of producing asymmetric wing kinematics similar to those observed in nature and utilized by flies and other two-winged insects to maneuver. Inspired by the thoracic mechanics of such insects, which entail a morphological separation of power and control muscles, these designs show that such distributed actuation can also modulate wing motion in a robotic design. Although, Finio and Wood focus here on active control of wing kinematics for body torque generation, which has been studied in insects, they also have a parallel research area that focuses on passive body torque regulation using purely mechanical feedback systems (Sreetharan and Wood 2010a, 2010b). For their design work, it would be instrumental to know to what extent such passive mechanical feedback is present in insect flight—for example, do insects actively compensate for asymmetric wing loading due to perturbations, aging or damage, or does some passive balancing mechanism allow the insect to continue flight?

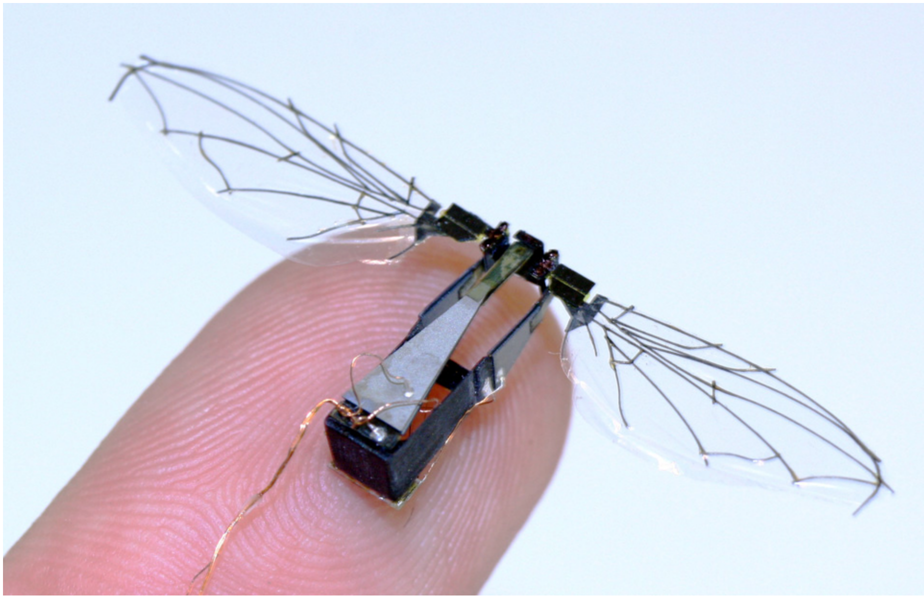

Figure 6. Thorax design of the Harvard robot fly. Image credit: Robert J Wood.

Mobile joints facilitate extreme wing morphing

Grant *et al* (2010) provide an overview of their micro-air vehicle designs which are equipped with a series of mobile joints inspired by seagulls to alter either the dihedral or sweep of the wings. This direct control over extreme wing morphing enables these vehicles to trim with significantly increased angles of attack and sideslip compared to traditional fixed-wing aerial vehicles, particularly during a descent or in the presence of crosswinds. Grant *et al* speculate that future designers will rely more and more on experimental biology for a myriad of applications. These include the devices and types of feedback used by nature to sense the flight environment, the distribution of structural elements and actuation to maintain a desired shape despite changes in loading, as well as the complex aerodynamics that result from non-steady biological flight performance. These workers believe that our basic understanding of the the brain could play a major role in design, as biologists study information management and decision making in nature, which could provide inspiration for novel autopilot design. Hence, a deeper understanding of how a bird's brain controls flight would be much welcomed.

Figure 7. The mobile joints of seagull wings inspired Grant *et al* to design innovative morphing wings. Image credit: Mujahid Abdulrahim.

Losing your tail could be the next best thing

Hoey (2010) has constructed a series of radio-controlled glider models which duplicate the aerodynamic shape of soaring ravens, turkey vultures, seagulls and pelicans. Hence, his models have no vertical tail, although such a tail is critical for the lateral stability of full-scale airplanes. Through flight testing, Hoey determined the level of longitudinal and lateral-directional static stability. Through a combination of basic theoretical flight dynamics and clever experimentation, Hoey identified two factors that enable birds to be passively stable while gliding without a vertical tail. First, the use of tail-tilt to control small bank-angle changes, as observed in soaring birds, was verified. Subsequent tests, using wing-tip ailerons, inferred that birds use a three-dimensional flow pattern around the wing tip (wing tip vortices) which not only generates a small amount of forward thrust in gliding flight, but also controls adverse yaw to mediate lateral stability. Eliminating a vertical tail has the potential of reducing both weight and drag of unmanned vehicles, and could therefore find application in current designs. Hoey explains that there is a significant unknown element as to what shape to model in his artificial birds, since birds are highly flexible and are continually adapting the wing shape to local conditions. Understanding how birds adjust their wing shape during gliding and the extent to which this is under active versus passive control could be extremely useful in furthering an understanding of how birds use their outer wing panels for lateral stability and control.

Figure 8. These elegant models of a pelican, sea gull, and a turkey vulture can soar stable without a vertical tail. Image credit: Robert Hoey.

All you need is a single wing to take off

Ulrich *et al* (2010) present the first at-scale robotic maple seed. Their design is directly inspired by their own observation of maple seed geometries and descent dynamics when released from height. They found that body roll and pitch angular rates for the various descent trajectories are coupled to variations in wing pitch, which therefore provide a simple and direct means of flight control. The novelty in the control strategy lies in its surprising simplicity. Flight control through wing pitch not only allows for controlled hovering and climb, but also lateral translation. This makes their vehicle not only highly useful; it also shows how future micro-helicopters could be much simplified compared to current designs. Ulrich *et al* find the flight dynamics of their robot and maple seed to be substantially similar. They speculate this could be of interest to those studying population dynamics of samara-bearing trees as it provides a low-cost platform with a derived flight dynamics model which can facilitate future testing of samara reaction to horizontal winds. It also provides a platform for the testing of various wing efficiencies, as the wing is interchangeable and can be used to measure the power required to hover for a given geometry and flight modality, which may give novel insight into the seeds' population dynamics.

Figure 9. At scale robotic maple seed. Image credit: Evan Ulrich.

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