

Biological Inspiration for Agile Autonomous Air Vehicles

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ABSTRACT

The ease with which flying insects, birds and bats negotiate confined, obstacle-cluttered airspace has long inspired us with visions of human-designed aerial machines with similar performance. Flying animals exhibit capabilities for aerial acrobatics, insensitivity to wind gusts, avoiding collision with or intercepting fixed and moving objects, landing and take off from small perches, and numerous other feats of flight agility that are beyond those of human-engineered vehicles. Although we are naturally tempted to look to biological organisms for inspiration or as design templates, the performance of the resulting bio-inspired or biomimetic engineered devices rarely approaches that of the living organisms. Among several possible reasons for this, two important issues motivate and provide a focus for this paper: it is nearly impossible to correlate biological processes with engineering design principles; biological systems possess sensing-computation-actuation response architectures and processes that appear to differ from those of engineered systems in fundamental ways, those differences are poorly understood and their importance little appreciated. These issues provide rich opportunities for research to produce genuine advancements in our understanding of biological and artificial autonomy. The research will necessarily involve biologists, engineers, and mathematicians. As with any research endeavor involving multiple mature disciplines, long term research collaborations are necessary for establishing the foundation of fundamentally new science. Unfortunately, without an objective understanding of these two issues and their implications for guiding autonomous air vehicle research and development, the real promise for biology-inspired or biomimetic concepts to achieve breakthroughs in vehicle capabilities may remain an elusive dream.

1.0 INTRODUCTION

Today's tactical munitions and unmanned air vehicles (UAVs) rely on guidance systems that are based upon relatively few high-quality sensors, centralized digital data processing, model-based algorithm designs, high-speed digital microprocessors, and relatively tight tolerances on sensor, processing, and actuator subsystems. Development of future low cost munition systems, small UAVs (SUAVs) and micro air vehicles (MAVs) for more challenging engagement environments is limited by the capabilities of current guidance system technologies. To appreciate this, consider a not unreasonable extension of a wide area autonomous search (WAAS) munition operational scenario. Here small autonomous MAVs have the mission, individually and in cooperation with similar vehicles, to search for, acquire, identify, track, and intercept deceptive targets in a cluttered imperfectly known environment. The particular scenario could be a group of tactical munitions on a mission to detect and destroy missile launchers that are operating in the back alleys of an urban areas or search

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Biological Inspiration for Agile Autonomous Air Vehicles

and rescue MAVs combing a tree covered canyon for a downed aircrew. To accomplish these kinds of missions, MAVs require some combination of on-board sensors and limited communication to seek out and intercept their actual targets in information rich environments that include other MAVs, SUAVs, stationary and moving objects to be avoided, and potential targets. Given the high uncertainty associated with these kinds of scenarios, significant levels of aerodynamic agility and operational autonomy will be required. Current guidance systems technologies do not, in general, yield the kinds of performance and uncertainty robustness when applied to SUAV or MAV scales.

The notion of agile autonomy, in the sense of robust negotiation of confined airspace such as forest edges, canyons, and urban areas, provides a prime motivation for looking to biology for inspiration for MAV designs. A person who disturbs a nest of ground wasps experiences, perhaps painfully, the incredible aerial pursuit capabilities of these small animals. It is easy to imagine that swarms of MAVs could similarly prosecute fleeing terrorist vehicles in urban canyons while ignoring noncombatant vehicles and individuals. Unfortunately there are few analogues of the supervised autonomy envisioned for human war machine systems to be found in nature. Even within the most tightly social animal groups, the social ants, bees, and termites, normal large variations in individual response exist that would be unacceptable in human weapon systems. Biologists characterize these individual response variations stochastically and design behavior experiments using sample sizes as large as practical in order to detect trends and, hopefully, construct cause and effect hypotheses that explain the behavior. The behavioral variation that is inherent and essential for a robust, evolvable biological system may be a critical flaw in a human designed system. A challenge, then, is not just to identify and characterize the mechanisms underlying animal autonomous response, a difficult enough task, but to develop a framework of system autonomy from that understanding that exploits tolerable response variation while providing reasonable guarantees that critical pathological responses will not emerge.

Engineered guidance and control systems built from integrated functional components are probably poor analogues for biological sensorimotor systems. While an inertial measurement unit for an air vehicle is a device that may be calibrated and bench-tested during integration with the rest of the guidance system, the functional equivalent in dipterous flies probably involves, at a minimum, modified wing structures (halteres) and their associated strain receptors, strain receptors at the base of the wings themselves, head-neck postural receptors, and specialized neural pathways associated with the compound eye and ocellus (simple eye) vision systems. That is, the insect's "inertial sensor" consists of distributed receptor structures and organs functionally integrated with the wing control muscles through decentralized processing channels. This kind of distributed sensorimotor architecture seems to be pervasive in biology. In fact, an argument can be made that, as with body dynamics sensing in the fly, most biological sensing involves structures and processes that only function as sensors in the context of the closed-loop system responses to which they contribute. This implies that system engineering from components which have specialized and compartmented functions is a poor paradigm for understanding the design architecture of flying animals. The challenge is for engineers and biologists to collaborate on development of sensorimotor architecture concepts for context appropriate response that will provide insight into the biology and serve as guides for design of new manmade systems.

2.0 WHY AGILE AUTONOMY?

A quick perusal of headlines in any major newspaper presents reminders that with the undeniable capabilities of today's military systems, conflict in mountainous, forested terrain and urban canyons remains a challenge. Threats capable of blending with non-combatant populace may be nearly impossible to detect, track, and prosecute with conventional assets in these kinds of environments. Given that military conflict of this sort may remain an avenue by which nations attempt to resolve ideological and political differences for the foreseeable future, we must explore new capabilities to meet the associated technology challenges.

Biological Inspiration for Agile Autonomous Air Vehicles

Although UAVs have established an impressive performance record during the course of the current Middle Eastern conflict, operation of large UAVs in urban canyons is not practical. Existing SUAVs and MAVs, although demonstrating considerable utility as information-surveillance-reconnaissance (ISR) assets, have only limited capabilities for operation in the confined, obstacle cluttered environs of city streets. Issues such as communication latency and drop-out; the ability to operate in close proximity to terrain, structures, and other vehicles; the ability to land and perch on stationary or moving objects; and sufficient autonomy for reasonable operator workload point to significant limitations in current technologies. Given the dynamic nature of urban combat, operation in those scenarios is dominated by uncertainties. Vehicles move, buildings are damaged or destroyed, barriers are constructed or removed, people congregate or disperse, all on time-scales that quickly render outdated the most detailed “current” information. Air vehicles capable of covert operation in urban canyons will have to contend with stationary and moving obstacles, dynamically variable winds and gusts with velocities close to those of the vehicles, severely limited line-of-sight sensor and communication paths, broadly variable illumination and spatially complex backgrounds and hostile action. These challenges drive the need for high levels of airframe agility and significant capabilities for autonomous flight using on-board sensors. (Some of these ideas receive expanded discussion in Kloeppel, 2005.)

Humans successfully mastered flight a century ago, yet the scientific understanding of low speed, small vehicle flight regimes is limited. The theory, practice and tools of aerodynamic flight mechanics, theoretical/experimental/computational fluid dynamics, aero-structural dynamics, and flight controller design currently used for large-scale vehicles seem to be of only limited use for development of small agile air vehicles operating at low speed in confined airspace. Aerodynamic flight agility remains a challenging and an elusive capability at these small scales. Even assuming that the technology hurdles will be overcome, aerodynamic flight agility is of limited use without comparable guidance agility: the ability to process sensory information and initiate maneuvers sufficiently fast to exploit the aerodynamic agility. Imagine a scenario in which the driver of an automobile negotiating an obstacle course is blindfolded, following a passenger’s verbal instructions. A tuned sports car, quick responses and honed driving skills are irrelevant if the passenger’s instructions are slow or imprecise. Moving safely at speed in a confined space requires the ability to detect an obstacle, assess relative motion and determine an appropriate response in sufficient time for the vehicle to accomplish the commanded maneuver. A sluggish vehicle has no need of fast sensory processing; an agile vehicle has an absolute requirement for fast, context appropriate sensory processing.

Since managing swarms of agile air vehicles in confined airspace will quickly exceed the abilities of a remote human operator, substantial autonomy is essential. The political, ethical, and moral issues associated with the use of autonomous systems in warfare will be debated long after the technology hurdles to their production have been overcome. Putting those issues aside for discussion in another forum, effective covert operation of unmanned systems in confined environments requires low-level autonomy for flight stabilization and successively higher levels of autonomy using on-board sensing for collision avoidance and local guidance. That is, a MAV will utilize its onboard guidance and control system for controlled agile maneuvering and for establishing feasible paths through an unknown and dynamic obstacle cluttered airspace. Given the high probability of communication dropout in urban canyons, some level of autonomous decision making capability is required. During pursuit of a group of fleeing vehicles a MAV swarm experiencing loss of communication with the operator will have to make real-time decisions on which vehicles to pursue if the fleeing group splits. (Abatti, 2005 discusses other operational issues associated with MAVs.)

Another challenge arises from the fact that humans occupy a spatiotemporal world that is dictated by our size, essentially terrestrial animal body-form, vision-dominated primate ancestry and our resulting sensory system capabilities/limitations. Extrapolation of that human-centric frame-of-reference to the design of MAVs the size of small bats, birds or insects is probably not desirable. Biology studies of the past century suggests these

Biological Inspiration for Agile Autonomous Air Vehicles

small animals not only occupy physical environments that are foreign to humans, but that they sense and perceive those environment in ways humans have difficulty comprehending and never experience directly. By analogy, dogs appear to inhabit a world of smells the complexity of which is at least as rich as that of the visual world associated with human vision. That world of odors has only been marginally sampled by human chemo-sensing devices and has never been characterized into a picture three dimensional spatial awareness experienced by the animal. MAVs are envisioned to become agents of human operators to achieve human motivated purposes, not as artificial insects, birds or bats. The degree to which the sensing and perception of flying animals should become the foundation for agile autonomous MAV design is an open question that has only begun to be addressed.

Two broad areas of exploration of biological sensing can be defined: one area involves sensing for operational considerations such as biological or chemical agent detection, vehicle tracking, even for detection and identification of humans; another area, and the principle focus for this paper, involves sensing required to operate within confined airspace. These areas are by no means mutually exclusive for animals, as evidenced by echolocating bats that utilize their sonar for detecting and intercepting prey as well as for navigation and collision avoidance in dark caves. Given the limited payload capacities of MAVs, multifunctional sensors are certainly desirable and probably required. Unfortunately, using the same sensor for flight control and for providing operational data presents significant challenges to the system designer. Consider a camera providing some measure of body motion based on optic flow to augment an onboard inertial navigation system. In the absence of a global frame of reference (e.g., loss of GPS), the optic flow enhanced inertial navigation solution will provide the vehicle with a local frame of reference for stabilizing body perturbations from wind gusts, for achieving steering commands to divert around an obstacle and for locating a potential target on the operator's tactical map. The first requires relatively high bandwidth but relatively low resolution sensing, sufficient to stabilize the body dynamics. The second may also require relatively high bandwidth, moderate resolution sensing to enable detection and avoidance of obstacles in a dynamic scenario. The last can tolerate somewhat lower bandwidth, but will require high resolution sensing, sufficient to be compatible with the operator's map resolution requirement. In a closed loop configuration in which an output from a camera is used to steer and stabilize the vehicle, the sensed kinematics nonlinearly couple with the dynamics that drive the vehicle and hence the camera's motion. This coupling can destabilize the vehicle response and introduce errors into the estimate of a target's position. While addressing this kind of dynamic coupling associated with guidance systems with only a few sensors is still an open research area in the controls community, insects seem to do quite well in integrating many sensors with relatively small nervous systems. Dragonflies engage in highly dynamic aerial pursuits (e.g., pursuer whole body responses to an fleeing animal's maneuver have been measured from video at less than 40msecs) using a guidance system that seems to be dominated by compound eyes which have low resolution but high motion sensitivity. Gaining insight into the principles by which this is accomplished in biological systems may open entirely new avenues for engineered guidance and flight control system design.

3.0 WHY LOOK TO BIOLOGY?

Arguably, tactical air intercept missiles are the most agile autonomous air vehicles yet developed. A reasonable baseline agile MAV guidance system design might therefore begin with application of current state-of-the-art missile guidance and control system methodologies. The design process is typically based upon the vehicle six degree-of-freedom rigid-body dynamics and intercept kinematics; a quasi-static aerodynamics model derived from simulation or wind-tunnel tests; computed or experimentally derived flexible body dynamics, sensor and actuator dynamics models; and often accounts for computational latencies and sensor noise. Since the resulting mathematical model is complex and, in any case, is known only

imperfectly, it is usually simplified by making various assumptions that allow the relatively fast body dynamics to be decoupled from the slower intercept kinematics. An inner-loop controller for the rigid-body dynamics uses sensed inertial body rotation rates and accelerations to compute commands to the fin actuators; it is typically bandwidth-limited to avoid exciting the body flexible dynamics and actuator dynamics. The outer-loop controller, a guidance law, computes commands to the inner-loop controller from estimated relative kinematics between the missile and its target. This estimate is typically provided by a dynamic filter that correlates seeker measurements of the relative motion with predicted motion based on an internal model of the target dynamics. In spite of extensive work on modeling of target dynamics, missile guidance estimators introduce potentially destabilizing latencies into the guidance system response when used in scenarios differing significantly from those assumed during the design process.

A MAV guidance system based on this approach exhibits a kind of compartmented functionality. Time or frequency-based separation into a relatively high-bandwidth inner-loop and a lower-bandwidth outer-loop requires that the physical response of the vehicle in its interactions with its surroundings be separable into slow and fast dynamics. While this natural separation is usual and physically justifiable in manned aircraft and large UAVs, it may not be applicable to SUAVs and MAVs which are expected to operate in close proximity to terrain, obstacles and other vehicles. In aggressive maneuvers in confined airspace, the relative kinematics between a MAV and other nearby objects may be as fast as its body dynamics; this to a degree only approached in the last few seconds of a missile intercept scenario. Imposing the usual separation of slow and fast dynamics on a MAV guidance system design (that is, reducing its guidance response bandwidth to mitigate coupling with its body dynamics) will result in stable but sluggish vehicles that have only limited capability to operate in confined airspace. (See Lin, 1991 or Zarchan, 2002 for more on missile guidance.)

Biological sensory response systems, while having some functional similarities with engineered systems, seem to have very different architectures. For example, insects appear to have relatively fast inner response loops dominated by mechanosensors, with slower outer response loops dominated by vision. However, it does not appear that biological sensory response systems are characterized by the relatively rigid separation of slow and fast dynamics typical of engineered flight control systems. The aforementioned body sensing system of dipterous insects is a case in point. Vision and mechanosensing are apparently used at all levels of a sensory response flight control system that is characterized by massive sensory interconnection and feedback. Certainly biologists have not yet resolved the detailed architecture and dynamics of any insect nervous system, but the behavioral and neurobiological work to date suggests much more coupling of sensorimotor system dynamics than is found in engineered systems.

Flying insects display a wide diversity of body morphologies, many of which are capable of impressive feats of aerobatic flight. Dragonflies, like many insects, have two pairs of membranous wings independently driven directly by flight muscles. Hoverflies, a kind of dipterous fly, have only a single pair of wings driven indirectly by muscles that rhythmically contract the thorax; the hind wings have become specialized as small body rotation sensors (halteres). Butterflies and moths have two pairs of wings that flap in synchrony, functioning effectively as a single pair of low aspect-ratio wings. Each group contains insects capable of hovering and highly maneuverable flight, apparently achieved by exploiting unsteady aerodynamics produced from precisely controlled wing kinematics. Compound eyes provide wide field-of-view motion sensitivity that, integrated with a variety of body mechanosensors (e.g., halteres in dipterous flies, antennae in moths, and perhaps sensors at the base of the wings themselves in those and other insects) and various proprioceptors and strain sensors distributed throughout the body, provide the necessary feedback for stable controlled flight. The compound eyes, often augmented by small simple eyes (ocelli), provide attitude reference information essential for level flight. The compound eyes also track small targets, often in specialized regions of higher acuity facets, providing the sensory feedback necessary for prey or mate pursuit, for predator evasion or with

Biological Inspiration for Agile Autonomous Air Vehicles

other sensory modalities for food localization. In addition to the vision system, chemoreceptors, especially in the antennae but also localized in other body regions, and tactile sensory hairs distributed over the body provide insects with a nearly spherical field-of-regard sensing capability. (A large and growing literature on insect sensing exists: good places to start are McIver, 1985 for mechanosensing, and Warrant and Nilsson, 2006 for insect vision.)

Flying birds, ranging in size from tiny hummingbirds to eagles, likewise have impressive flight capabilities. Bird wings are feather covered, highly modified vertebrate forelimbs in which the wrist and finger bones are fused and reduced in size. The wings, which are deformable due to the elbow and wrist joints and elastic due to flexibility of the feathers, are powered by specialized pectoral and coracoid muscles attached to a deeply keeled sternum. Terns have high aspect-ratio wings and fly much like manmade aircraft while soaring but are capable of agile precise flight when picking small fish from the water surface. Eagles, with broad powerful wings, exploit thermals in extended soaring but are capable of aggressive controlled maneuvers in which the wings appear to become completely stalled during takeoff, landing, or prey capture. Falcons can plummet at high speed to snatch a small passerine bird from within a flock, while accurately maneuvering to avoid potentially crippling collisions with other birds in the flock. Hummingbirds, unlike other birds, exhibit insect-like wing kinematics during hover, completely reversing the upper and lower surfaces during a full wing stroke. Somewhat surprisingly, given the similarity in wing kinematics, unlike insects hummingbirds do not appear to generate lift on the recovery upstroke. All birds have vestibular organs providing body motion information that, perhaps with wing muscle load sensing and probably with input from vision motion sensing, allow for stable controlled flight. High vision acuity in the fovea of the vertebrate eye, cued from peripheral vision motion sensing and other senses, provides vision-dominated sensory systems that allow hummingbirds to feed on flower nectar while hovering and swifts to feed on insects in flight. The well known auditory capabilities of owls represent an elaboration of a sensory modality that is important in all birds.

Bats, the third and evolutionarily most recent example of extant flying organisms, demonstrate flight maneuver capabilities that are at least the equal of those of insects and birds. The wings are skin membrane covered, highly modified vertebrate forelimbs in which the fingers are greatly elongated and flexible, comprising up to half the wing span in some bats. Bat wings are actively deformable from the elbow, wrist, and finger joints and from the aerodynamic loading of an extraordinarily flexible anisotropic membrane covering limb bones and flexible fingers. Flying foxes, with wingspans approaching a meter, locate and feed on fruit in tropical tree canopies. Nectar-feeding bats exhibit hovering behaviors and capabilities comparable to hummingbirds or hoverflies but with dramatic deformations of the wing shape during each stroke. Insectivorous bats likewise exhibit in-flight feeding behaviors comparable to dragonflies, swifts and kestrels but with very different wing motions. Like birds, bats have vestibular organs providing body motion information that, with wing muscle load sensing and probably with input from vision motion sensing, allows for stable controlled flight. High vision acuity in the fovea of the bat's typical vertebrate eye, cued from peripheral vision motion sensing, provides vision-dominated sensory systems in old world bats and augments the extraordinary echolocation system of new world bats. Like most other mammals, hearing and olfaction are important sensory modalities for all bats.

4.0 EXPLORING BIOLOGICAL FLIGHT

In the quest for principles upon which to base the design of vehicles with agile autonomy comparable to insects, birds, and bats, several areas of potential biology contributions emerge. The most obvious of these is to understand aeroelastic, flapping wing flight at low Reynolds numbers. Significant open questions remain in the fluid dynamics associated with flapping wing motions at high angles of attack. Studies of the detailed

Biological Inspiration for Agile Autonomous Air Vehicles

three-dimensional wing kinematics, flow visualization and/or limited force measurements have been made for several insects, several birds, and a few bats. Experiments with rotating or flapping scale model insect or hummingbird wings indicate that quasi-steady forces produced during a high angle-of-attack wing stroke are augmented by a stable leading edge vortex that increases circulation around the wing. Rapid spanwise rotation at the end of each stroke in small insects produces force spikes that appear to be used for maneuvering. Unlike insect wings, bird wings can be actively morphed to give the same bird soaring capabilities when extended and high speed dives when tucked. The degree to which birds exploit this wing morphing for flight stabilization and control has not been determined, though casual observation and some video studies suggest it is a common behavior. As with insects and bats, aeroelasticity allows for passive gust rejection, although again studies quantifying the relative contribution of other aerodynamic force producing mechanisms have yet to be made. There is some evidence that surface topology and texture of hummingbird wings makes significant contributions to net force production during the wing stroke. Bats, with their highly morphable wings, have received far less study than insects and birds but recent elegant wind tunnel experiments have produced qualitative flow visualization that shows the incredible complexity of flows associated with bat flight. Videos of bats during tight turns show extensive wing morphing, probably actively controlled by the animal as well as passively produced by aerodynamic and inertial forces. The importance of this morphing to the flight stability and control of the bat is the subject of current study. (Azuma, 2006 provides an interesting overview of animal flight.)

Another area of potential contribution is to explore the sensory-rich, multi-scale feedback associated with animal flight. Insects are literally covered with sensors that, with the limited processing available from the few hundred thousand neurons in an insect brain, allow these animals to fly with damaged wings, order of body mass payloads (e.g., foraging bees with a load of pollen, blood satiated female mosquitoes) and in gusty wind conditions. Flies have modified hind wings, the halteres, that flap in antiphase with the aerodynamic wings and respond to Coriolis forces generated by body rotations. Patches of strain sensors at the base of the halteres provide signals that directly modulate the flight muscles controlling wing kinematics; this may be somewhat analogous to the rate feedback from gyros used for providing rate stability in aircraft autopilots. Augmenting this, the compound eyes sense optic flow, the apparent image motion produced from body rotation and translation, and provide signals that modulate the haltere feedback to the flight control muscles. Coordination of the two wings and input from other body sensory modalities occurs at the thoracic ganglia and with sensory input from the head sensors in the subpharyngeal ganglion. Other insects similarly integrate mechanosensory signals (e.g., antenna as body rotation sensors in moths and butterflies) with vision and other sensory modalities to produce stable yet agile flight capabilities. (See for example Dudley, 2000 and Burrows, 1996.)

Birds and bats have flight control sensory systems elaborated from the basic vertebrate sensor suite. Both have vestibular organs providing attitude and body rotational feedback that apparently is complemented by input from the vision system, particularly peripheral motion sensing, in the brain cerebellum. Muscle strain sensors potentially provide both groups of animals with the ability to sense dynamic wing loading, which could be useful for both local active damping of wing motion to complement the passive aerodynamic damping from wing flexibility and as another sensory feedback for controlling the wing kinematics. Bird feathers contain sensory neurons at their bases providing tactile sensing that may potentially be exploited as additional flight control feedback. Videos captured from on board cameras of soaring and landing eagles show deployment of a row of leading edge covert feathers, presumably concurrent with the shift in stagnation point associated with an incipient wing stall. Whether this is a passive or active aerodynamic mechanism roughly analogous to leading edge flaps on aircraft or a sensory mechanism employed by the bird is unknown and the subject of current study. Bats have small sensory hairs, a few millimeters in length, distributed in patches over the wing surface. Studies are underway to investigate the roles of this sensory modality, if any, in flight stabilization.

Biological Inspiration for Agile Autonomous Air Vehicles

At the other end of the sensory-response chain, biological flight control involves multiple complementary actuators, the flight power and control muscles. In all organisms, limb movement is produced by muscles that work in pairs since muscles can only produce force during contraction. Dragonflies, locusts, and many other insects utilize muscles that directly drive the wings. The wing kinematics, including in-plane and out-of-plane motion with spanwise rotation during and at the end of the wing strokes, are controlled by precise timing and modulation of several muscles. Like most body muscles, these contractions are controlled by direct innervation from motor neurons. Dipterous flies and many other small bodied insects use orthogonal pairs of power muscles that produce alternating dorso-ventral and longitudinal flexure of the thorax from rhythmic contractions similar to heart muscle activity. The wings, attached to the thorax with a complex segmented hinge structure, beat passively with the thoracic contractions. Very small neuronally innervated muscles attach to the hinge segments and, in concert, change the mechanical properties of the hinge to produce the three-dimensional wing rotational kinematics. Insects also use body musculature to control abdomen, head, and leg postures during flight, presumably contributing inertial as well as additional aerodynamic forces to produce maneuvers. (See Dudley, 2000 for an in-depth description of insect flight.)

Birds and bats have neuronally innervated skeletal musculature modified from the typical vertebrate plan. Powerful pectoral muscles provide the downstroke and other thoracic and upper forelimb muscles produce the balance of wing rotational kinematics used for flight. Both birds and bats, unlike insects, can also utilize the forearm musculature to actively extend and retract the wing and to change both the chordwise and spanwise shape. Bats, in particular, have astounding control over the three-dimensional wing shape at all phases of the wing stroke. Birds produce yaw forces through active control of the shape and position of the tail. At least some bats have membranes attached to the legs that may similarly produce lateral stability and control. Like insects, bats and birds can actively use body posture to augment aerodynamic flight control from the wings. Given the large number of muscles controlling large degree-of-freedom force effectors, substantial control redundancy is available to both animal groups.

In addition to precise agile flight, these musculoskeletal wing systems exhibit impressive amounts of robustness. Bats with large tears in their wing membranes or with young attached to their abdomens appear to fly quite normally. Some small birds nearly double their mass just prior to laying eggs; others lose significant wing feathers to molt or near escapes from predators and still are capable of seemingly normal flight. Dragonflies experiencing the loss of half of one wing, bees with legs packed with pollen, butterflies or moths with torn and frayed wings likewise are capable of apparently normal flight. These largely unstudied, mostly anecdotal observations suggest that biological flight control systems, which consist of structural, passive dynamic, and active sensorimotor control mechanisms, have robustness and performance characteristics that would be very desirable and probably essential for agile autonomous MAVs.

As human pilots attest, agile flight and flight in confined airspace require wide field-of-view situational awareness. Insects possess paired compound eyes that, in several insect groups, together yield a nearly completely spherical field-of-view. In addition to wide field optic flow sensing for flight stability, specialized vision circuits detect and track small objects moving relative to the background. Since compound eye resolution is poor, limited for the most part by the facet instantaneous fields-of-view and inter-facet spacing, insects exploit vision motion processing as a dominant sensory modality for aerial prey or mate pursuit, predator and obstacle avoidance, local navigation, visual odometry and food source detection. Some insects have regions of higher visual acuity which allow more precise object tracking. Since the eyes are fixed to the head, gaze stabilization and control is effected by control of head to body posture with neck muscles. Complementing vision, insects employ olfaction and taste chemoreceptors as well as tactile hair cells to obtain a three-dimensional information source for interacting with their surroundings.

Similarly, birds and bats employ relatively wide field-of-view eyes for the same sorts of behaviors, though exploiting very high resolution fovea, multiple in birds of prey, to obtain detailed shape and texture imaging of their surroundings. Bats, like other mammals, use small muscles to move the eyes in their sockets, complemented with head movement controlled by neck musculature, to track small rapidly moving objects. Given the limited mobility of their eyes, birds utilize head motion for gaze stabilization and object tracking similar to insects. Birds have acute auditory sensing; barn owls, especially, are well known for being able to use their hearing to locate and precisely track small mammals. New world bats, of course, use high frequency echolocation both for navigation in caves or attics and for detecting and tracking insect prey on the wing.

All animals exploit movement to enhance sensing. Flying insects, birds and bats require depth perception to negotiate confined airspace. Although binocular vision may contribute to varying degrees, translation induced parallax, suitably filtered to remove the apparent motion induced by body rotations, is probably the primary source of relative distances and closing velocities to surrounding objects that are required for pursuit or avoidance behavior. Recent elegant studies on honeybees suggest that passive ranging from small amplitude lateral casting during forward flight may be part of the animals' height regulation mechanisms (Baird, et al., 2006). Similarly, stereotyped lateral motion just prior to landing on a vertical surface may give bees range information for precise landings.

5.0 UNDERSTANDING BIOLOGICAL FLIGHT

The first, and perhaps the greatest challenge to engineers and other nonbiologists who attempt to look for biological solutions to their problems of interest stems from differences in training, methodologies, tools, and viewpoints. Engineering and most of the other physical sciences lend themselves to somewhat reductionist approaches for both analysis and synthesis. Complex engineered systems are built from components integrated into functional subsystems that are, in turn, built into operational systems. Considerable effort and expense is required to verify that performance meets specifications and to validate the acceptable operational regime for the system. Efforts to develop system design methodologies that yield performance and stability guarantees are very active areas of control theory and software systems research. Powerful techniques exist for analysis at the component or subsystem level; unfortunately, these do not often scale to the system level.

Biology as a science consists of a suite of interrelated disciplines each with specific terminology and a particular foundation of theory and practice. Just as modern aeronautical engineering is built on a base of dynamics, mathematics, fluid dynamics, structural dynamics, and computer science; so systems biology is built on fundamental concepts from evolution, ecology, behavior, anatomy, physiology, developmental biology, genetics and statistical analysis. Unlike many engineering fields, no unified suite of mathematically based physical laws has yet been developed for any biology discipline, much less for the entire science area. This makes biology seem to be observational, heuristic, and a bit of a soft science to many practicing physicists, chemists, and engineers. Of course, mathematical analysis, particularly statistics, has become an essential tool for biologists who must digest large amounts of observational data into coherent concepts from which biological principles may be deduced. Dynamical models in ecology, population dynamics, genetics, biomechanics, biochemistry and many other areas has become more important in the past half century but most still lag in predictive capabilities when compared with those of the physical sciences.

It is important to not overly emphasize this lack of mathematical unity as a limitation of biology as a science. For one thing, while the mathematical foundations for many engineering disciplines are well established, the area of engineered complex systems lacks mathematical unity and many of the applicable mathematical tools are *ad hoc*. Since all biological response, even locally, involves complex sensory/processing/actuation responses the mathematical tools simply do not exist to reliably characterize them. More importantly, theories

Biological Inspiration for Agile Autonomous Air Vehicles

associated with genetics, biochemistry, developmental biology, ecology, and evolution provide a unifying foundation for the seemingly disparate disciplines of biology. Thus biologists can study moth, hummingbird, and small bat flight with an appreciation of the developmental, ecological, and evolutionary pressures influencing and constraining the apparently different solutions to flapping flight at similar conditions. These biological studies are essential complements for the fluid dynamics, flight mechanics, control systems and other studies performed by engineers and physicists to ultimately yield a complete picture of biological flight.

Issues of scale dominate any serious study of biological sensorimotor systems. An amazing diversity of organism types inhabits our world, from bacteria and other single celled organisms through the many types of multicellular animals. In looking for biological prototypes for engineered systems, this diversity offers a sometimes staggering array of potential sources of inspiration. The mechanisms of natural selection, working upon the variation produced by processes of reproduction and inheritance, yield organisms that, to varying degrees, are both adapted to their particular modes of life and robust to variations in their respective environments. Any species exhibits significant variation among individuals, very loosely analogous to an automaker's entire range of passenger vehicles rather than to the small differences among cars of a particular model. A species' ability to persist over time in the face of changes in habitat, fauna, flora, or climate largely results from this variation. Hence, adaptability, when used in reference to a species, implies that sufficient stable variation exists for the species to tolerate substantial selection pressures produced from these or other ecological forces. Thus, biology offers a large range of viable solutions, not necessarily highly optimized ones. In fact, even in species exhibiting high degrees of ecological or behavioral specialization significant individual variations exist; these variations are typically much greater than would be tolerated in engineered systems. The extent to which these variations are a casual byproducts of imprecise developmental mechanisms versus the products of evolutionary mechanisms essential for species robustness has not been systematically investigated in any organism. This provides a cautionary note for those pursuing biomimicry, direct replication of biological features: essential aspects of those biological features may be driven by secondary characteristics or functions unrelated to the features' primary functions. The bat wing, with all of its elegant modifications for flight, is an obvious example. It is derived from a typical vertebrate forelimb with all of the associated musculature, skeletal, and neuronal architectural characteristics that were originally developed for terrestrial or aboreal locomotion. That is, it was not designed for propulsive flight *a priori* as an engineered device might be, but was modified from other structures that originated for other functions. (Gerhart and Kirschner, 1997 provide an in-depth but accessible discussion on the interplay of biochemistry, genetics and embryology in animal evolution; Wagner, 2005 describes biological concepts of evolvability and robustness.)

Paradoxically, along with these variations, underlying similarities unite organisms in ways that may seem mysterious to nonbiologists. Living organisms, unicellular and multicellular, share common structural, biochemical, genetic and organizational processes. These processes function to various degrees throughout an organism's life during all interactions with the local environment. All parts of any multicellular organism (organelles, cells, tissues, organs, and organ systems) exhibit these processes individually as components and collectively as subsystems comprising the entire organism. These processes also function continuously during each stage of a multicellular organism's development, from cell through embryo through adult. So flying insects and birds with similar flight capabilities have eyes of very different structures and different functional capabilities; that were evolved through different phylogenetic histories; and that have been fixed into their respective adult forms by different developmental processes. Because organisms exhibit such integration, reductionist methods of component analysis are not, in general, adequate for understanding biological sensorimotor functionality. For example, the morphology, phototransduction, and neuronal characteristics of the eye comprise only a limited part of an animal's vision system, which requires the associated brain neuronal circuitry, proprioceptive mechanisms and musculoskeletal system to function as a sensor! (See Gerhart and Kirschner, 1997 for additional discussion and examples.)

Another aspect of scale arises from the fact that flying animals occupy a large range of body sizes. The smallest insects, such as midges and fruitflies, exhibit flight capabilities similar to bats and birds that are seven orders of magnitude larger in body mass. The sciences of flight mechanics and aerodynamics, developed for steady flight at size scales appropriate to manned vehicles with Reynolds numbers in the millions, are limited in their abilities to describe animal flapping flight at Reynolds numbers of a few thousand to hundreds. Unsteady aerodynamic mechanisms that seem to be exploited in the maneuvering flight of small animals are typically minimized, often at great expense, in the design of aircraft. While the utility of such mechanisms for small air vehicles is yet to be quantified, it is clear that animal sensorimotor flight control systems actively utilize them even during what we might think of as steady flight. The questions of whether and how much these mechanisms should be designed into small air vehicles have not yet been answered. Results to date from biology suggest that their use will require rethinking the sensory and flight control suites currently employed on engineered small air vehicles.

These lessons suggest that comparison of closely related animals of different sizes will be useful for developing a science of biological flight. Likewise, comparison and contrasts of much more distantly related but ecologically and behaviorally similar animals, for example hummingbirds, hawkmoths, and small nectar feeding bats, will yield insight into the principles exploited by animals for maneuvering flight. Some of these principles are likely to be of use in the design of agile autonomous small air vehicles. Some may turn out to be useful only in the context of understanding the various constraints and influences imposed by biological pressures. Distinguishing these principles may turn out to be the most difficult task associated with biologically inspired flight and will require close collaborations of biologists and engineers. It is important to note that most biologists, even when conducting controlled experiments on particular features of their study animals, appreciate the complexity of factors associated with biological system responses and are usually careful to qualify their conclusions based on the artificial conditions imposed by the methods of the studies. Productive engineer and biologist collaborations usually require a fair dose of patience on both sides and rarely emerge over night!

6.0 BIOMIMICRY OR BIOLOGICAL-INSPIRATION

Mimicry of biological systems, in the form of precise mathematical or physical dynamical modeling, is yielding impressive insight into the underlying functionality and mechanisms of the biological systems themselves. Robot devices that capture insect leg kinematics provide the foundation for studies of the sensorimotor mechanisms of walking with six legs (Ritzmann, et al., 2004). Computational analyses of insect flapping wing flight complement experiments with model wings flapping or rotating at appropriate Reynolds numbers. Such studies are allowing characterization and quantification of the underlying aerodynamic mechanisms associated with flapping flight (Azuma, 2006). Analog and digital models of insect vision motion processing provide useful tools for studying the role of optic flow processing in biological flight stabilization and local guidance. While these and other mimicked biological features are being explored for direct application to engineered systems, the payoffs have thus far been much more limited than for gaining insight into the biology.

Biological inspiration has an impressive and long history, extending perhaps to the roots of human technology. The physical and biological world provided our ancestors with inspiration for techniques and tools that allowed them to extend their physical capabilities. Methods of earliest human agriculture, exploitation of fire for clearing land and cooking meat and cooperative hunting methods all emerged at a time when humans were bound into the same kinds of ecological cycles as other similar-sized savannah dwelling animals and were, therefore, intimately familiar with their natural surroundings. Although mankind is

Biological Inspiration for Agile Autonomous Air Vehicles

generally removed from that world by today's technologies, all of the human pharmaceutical industry, current medical practice and modern agriculture are founded on our understanding of biology. Thus, the study of biological locomotion seems to be a natural route to expansion of the capabilities of flying robots. Ironically then, the most universal technologies associated with human locomotion, the wheel, the rigid wing and the rotating propeller, are not found in nature. This irony provides a cautionary note that human engineered systems may have attributes and constraints that, ultimately, preclude biological solutions.

To date, legged robots or flapping wing air vehicles exist primarily as laboratory experimental devices. Roboticists working with biologists have designed wheel-legged robots that, with a single driving motor, clever transmissions, and a jointed body, are capable of climbing stairs and negotiating uneven terrain using rotational leg kinematics that are inspired from studies of the insect three-legged walking gait (Ritzmann, et al., 2004). Another engineering team designed a flying micro-air vehicle that, using a rigid forward wing with two clapping tail wings, was originally inspired from an unsteady aerodynamic mechanism first identified in certain flying insects, but that operates as a system much more like swimming fish than an insect (Jones, et al., 2005). Other engineers in collaboration with insect vision neurophysiologists have explored the use of paired UV and green light sensitive photodiodes driving a simple analog comparator circuit to produce pitch and roll attitude stability in a model aircraft. The prototype device concept, functionally analogous to dragonfly ocelli, offers the potential for a scalable, low cost attitude stability system for MAVs. Another group of engineers, also working with insect vision neurophysiologists, is developing a concept for a local guidance and collision avoidance system that is inspired by studies of insect optic flow processing (Humbert, et al., 2005 and Shoemaker, et al., 2005).

It is intriguing to imagine some of these or other similar efforts in the not to distant future yielding the first demonstration of a biologically inspired agile autonomous MAV. Whether such a system will utilize the wing kinematics of insects, birds, bats, or more conventional aerodynamic mechanisms remains to be seen. The degree to which such a system will require the complex sensorimotor integration that seems to characterize biological systems is also yet to be determined. What can be stated with some confidence is that, given the limitations of current state-of-the-art MAV flight technologies, studies of biological flight will yield insight into propulsive flight at these small scales that will almost certainly accelerate the development of agile autonomous MAVs.

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Biological Inspiration for Agile Autonomous Air Vehicles

