A REVIEW OF BIRD-INSPIRED FLAPPING WING MINIATURE AIR VEHICLE DESIGNS

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ABSTRACT

Physical and aerodynamic characteristics of the bird in flight offer benefits over typical propeller or rotor driven miniature air vehicle (MAV) locomotion designs in certain applications. A number of research groups and companies have developed flapping wing vehicles that attempt to harness these benefits. The purpose of this paper is to report different types of flapping wing miniature air vehicle designs and compare their salient characteristics. This paper is focused on mechanical design aspects of mechanisms and wings. The discussion presented will be limited to miniature-sized flapping wing air vehicles, defined as 10 to 100 grams total weight. The discussion will be focused primarily on designs which have performed at least one successful test flight. This paper provides representative designs in each category, rather than providing a comprehensive listing of all existing designs. This paper will familiarize a newcomer to the field with existing designs and their distinguishing features. By studying existing designs, future designers will be able to adopt features from other successful designs. This paper also summarizes the design challenges associated with the further advancement of the field and deploying flapping wing vehicles in practice.

1 INTRODUCTION

Birds and other flapping fliers possess a varied flight envelope, with capabilities ranging from hovering, high-speed forward flight, backward flight, perching, quick take-off, and long distance soaring requiring almost no flapping. There are over 10,000 species of birds in the world, ranging in size from less than an ounce to over forty pounds [1]. There is great inspiration for researchers that can be drawn from flying animals. In our opinion, flapping-wing flight represents an important future segment of man-made fliers, and if mastered, a totally new set of abilities will be available for various useful applications. There is still much work to be done to fully understand the aeromechanics of flapping wing flight [2] [3].

One of the primary reasons for the superiority of flying animals is the ability to have control over many degrees of freedom, including the ability to actively change the shape and size of the wing. Flying animals have been refined through millions of years of evolution, and exhibit a variety of complex flapping motions comprising multiple degrees of freedom, speed-varying flapping motions, and wing shape morphing. The combination of these features allows for a level of maneuverability that is so far impossible to recreate with man-made unmanned aerial vehicles (UAVs). However, as missions have developed to require more agile, efficient, and maneuverable UAVs, flapping flight has become an increasingly attractive alternative to the traditional forms of flight, including rotary-wing and fixed-wing air vehicles. As motor, battery, and control technology have improved in recent years, the ability to realize bird style of flight is becoming a step closer to the reality.

Animal-inspired flight provides the following advantages over traditional forms of UAV propulsion. Animals are capable of extremely agile flight maneuvers that would translate to useful behaviors such as perching, hovering, navigating tight spaces, and maintaining stability in the presence of strong variable disturbances. Animals are capable of tailoring their flight characteristics to changing aerodynamic demands. Depending on the particular size, some animals can sustain flight with very low energy consumption, allowing for extended flight duration and excellent glide properties. Variation in angle of attack, wingtip trace pattern, wing area, and complex adjustments to feather orientation are combined to enable advanced flight capabilities. Additionally, animals employ a complex neural control system and distributed actuation of many degrees of freedom. Many current gas and electric prop-driven UAVs produce a highly detectable noise profile, and have an obviously man-made appearance in flight. Ornithopters, or aircraft that fly by flapping their wings, have an extremely realistic appearance and are quieter at low flap rates, making them well suited for reconnaissance operations.

The first known ornithopter, figure 1, was created in 1870 in France by Gustave Trouve, powered by a bourdon tube filled with gunpowder [4]. Trouve's ornithopter covered a distance of 70 meters in a demonstration for the French Academy of the Sciences. Since that initial demonstration, the field of ornithopter research has blossomed into many categories comprising all of the different types of avian-like flight, as well as insect-like flight. Today the applications for flapping wing fliers are highly varied, as a variety of potential users have come to appreciate the benefits of bird-inspired fliers. As smaller ornithopters gain an increasing level of sophistication, they will be useful in search and rescue, military operations, border patrol, security, biology experiments, farm inspection, and entertainment applications.

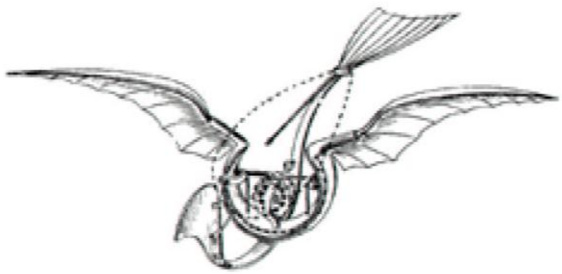

Figure 1: Gustave Trouve's ornithopter [4]

The goal of this paper is to develop a general classification of flapping-wing vehicles based on a survey of published designs to aid a designer in determining which aspects of proven designs may be useful in a given application. This paper focuses on mechanical design aspects of mechanisms and wings. Aerodynamic analysis and optimization of wings is a very important aspect of flapping wing design. However, because of space constraints, we will not discuss aerodynamics issues.

We have tried to include representative designs in this survey. We restricted our scope to only those designs that are published in the literature or are commercially available. This review will help the designer to understand the strengths and weaknesses for various designs. By studying existing vehicles, future designers will be able to create new designs by adopting features from successful solutions. The review also summarizes the design challenges associated with the further advancement of the field and deploying these vehicles in practical applications.

Based on the survey conducted, the general categories of comparison for the flapping wing vehicles were determined to be: (1) directional control scheme, (2) wing design, and (3) mechanism design. Generally, these are the three systems that are most important in determination of a given MAVs flight envelope. The criteria for selection of the design examples include availability of detailed mechanical design information, knowledge of intended application, and validation of design functionality through a controlled, flying prototype. Finally, representative designs will be compared in this work and the results of the comparison discussed in detail to explain why certain design aspects may be more or less effective.

2 DIRECTIONAL CONTROL SCHEME

Successful flight of most MAVs requires the use of a tail for stabilization and/or control purposes. Since wing flapping generally produces large oscillatory forces that can disturb the balance of a MAV, the tail helps to keep the vehicle flying in a relatively straight path. Depending on the sophistication of the tail design, certain improvements to the flight envelope of the MAV are possible. The tail can provide multiple degrees of freedom for control of the vehicle, through the use of a variety of control surface schemes. The control styles that will be discussed include static or non-controlled tail, rudder style, and some non-traditional layouts. Most examples draw inspiration from traditional aircraft configurations, with the use of various styles of rudders and elevators. One example discussed accomplishes its control with independent wing control, something that insects typically exhibit in flight.

2.1 Static Tail

Static tail ornithopters are generally the least controllable version of MAVs, and are exhibited in a variety of research examples, as well as in the toy market. Researchers at the University of Delaware have created an ornithopter, figure 2, with the purpose of improving energy efficiency of the flapping mechanism [5]. The ornithopter was able to successfully complete a flight under its own power.

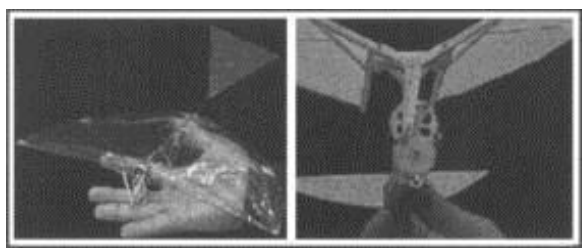

Figure 2: University of Delaware ornithopter [5]

Another example is the Microbat, figure 3, developed as a joint venture by California Institute of Technology, University of California, Los Angeles, and AeroVironment, Inc.

Microbat was meant to be a study on producing wings using MEMS technology that would be very repeatable and sturdy while leveraging unsteady aerodynamics for better flight properties. The Microbat was the world's first electrically powered flying ornithopter, with the first prototype flying in October 1998 [6]. The earliest version of this ornithopter used a V-shaped tail for stabilization, but had no control actuators. In early testing, the Microbat only had enough power to complete flights of nine seconds, so control actuators were too heavy to include. Later models eventually had larger power capacity and included control systems mounted in the tail.

Figure 3: Microbat prototypes [6]

In addition to the research models discussed, the toy market has created a MAV that falls into the static tail category. The I-fly Vamp and Wasp are cosmetically different but function in the same manner. These MAVs are advertised to be the world's smallest flying bats, with a weight of 13 grams for each [7]. The Vamp and Wasp operate using two flapping wings as the source of lift, thrust, and control. By varying the angle of the entire flapping mechanism relative to the body of the ornithopter, the wing geometry is altered during the flap cycle. The angle of the net lift and thrust vector is skewed, resulting in turning with minor loss of altitude. This is a departure from the typical control scheme at this size scale, where the tail is angled to induce yaw in the ornithopter, while maintaining constant wing geometry. The flapping rate is proportionally controlled by radio, as well as the angle of the flapping wings, thus providing two degrees of freedom from the wings and none from the tail. The tail is not involved in the control of the ornithopter, but provides stability in flight. These toys are not very complex, however they provide a good example of an alternative form of steering.

2.2 Rudder Tail

Rudder tail ornithopters can be thought of as the traditional form of steering control for a flying vehicle, since they use the same principle of operation as most airplanes. A single fin rotates to the left or right, creating a yaw force on the MAV and causing a turn. In all the cases discussed, the tail also provides the stabilizing force of a static tail, with the added element of control surface actuation. The first example to be discussed is the Microbat, in its later versions. As development continued, the power source changed from supercapacitors to a three gram nickel cadmium rechargeable battery. Currently the best flight endurance recorded for the Microbat is forty-two seconds. With the extra power capacity came reductions in mechanism weight, thus allowing for some weight to be devoted to a radio control and actuation system. The newest version of the Microbat is equipped with 0.1 gram shape memory alloy wires embedded inside the tail to provide separate elevator and rudder control, in a layout similar to most aircraft.

The University of Maryland Small Bird, figure 4, was designed and constructed in the Advanced Manufacturing Laboratory at University of Maryland [8].

Figure 4: University of Maryland Small Bird [8]

The tail is actuated in a rudder-style motion using a lightweight magnetic actuator. In continuation of this project, the same group also created a Big Bird, figure 5, a larger and improved version of the Small Bird.

This version uses a servo as the basis of actuation. By mounting the tail assembly at a large angle of attack and using the servo to create rotation, a yaw force turns the MAV. In both the Small Bird and Big Bird, the tail creates a torque that keeps the nose of the bird up and allows for stable flight.

The toy and hobby market has produced some very successful fliers that fall into this category of tail style. I-fly sells a line of MAVs called the Wingsmaster Ornithopters that use a tail rudder actuated with a small servo for steering control. Another entry from the toy market is Wowwee's Flytech Dragonfly MAV. Instead of the usual method of using an actuated control surface to provide yaw, the Flytech Dragonfly draws its inspiration from a helicopter tail rotor. A small motor is mounted in the tail that is capable of variable speed rotation in both directions. This provides a thrust force that yaws the MAV left and right to provide steering. The hobbyist market has produced some very lightweight fliers, with one of the lightest in the world coming from the Osaka Slow Fliers Club. The ornithopter shown in figure 6 weighs 1.54 grams and has a rudder capable of steering the ornithopter.

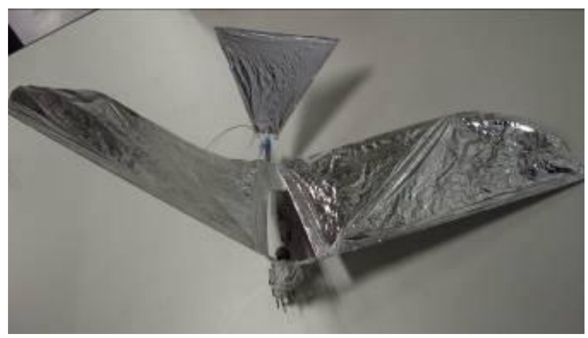

Figure 5: University of Maryland Big Bird

The Technical University of Delft in the Netherlands has created a miniaturized version of its Delfly MAV, called the Delfly Micro, figure 7.

The tail design uses a magnetic coil rudder actuator for light weight. This MAV has the very noteworthy feature of vision-based stabilization. By mounting a camera onboard, the optical flow is used to determine the attitude of the MAV, and apply corrective control inputs to the tail and wings to maintain better stability during flight. This allows the Delfly Micro to be more controllable than most fliers at the size, where steering becomes difficult for a human operator due to rapid changes in flight characteristics.

The Naval Postgraduate School has created a non-traditional MAV shown in figure 8 that also uses the magnetic coil actuator to steer a tail rudder [10].

This choice of actuation is popular at small size scales because flight speeds tend to be slower, therefore the load is not so large that a servomotor is required for steering, which would be a much heavier option. The NPS flier uses a flying wing style body with the rudder mounted towards the rear in the center of the MAV. Steering control is separate from altitude control, which is accomplished with variation in flapping speed. This flier has the unique benefit of being practically impervious to stall, since its flapping wings draw air in with a suction effect. Control is improved through this phenomenon and this makes the NPS flier one of the most maneuverable MAVs in this category.

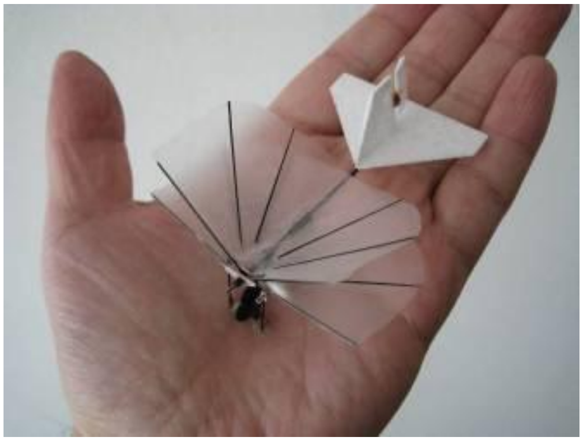

Figure 6: Osaka Slow Fliers Club MAV [11]

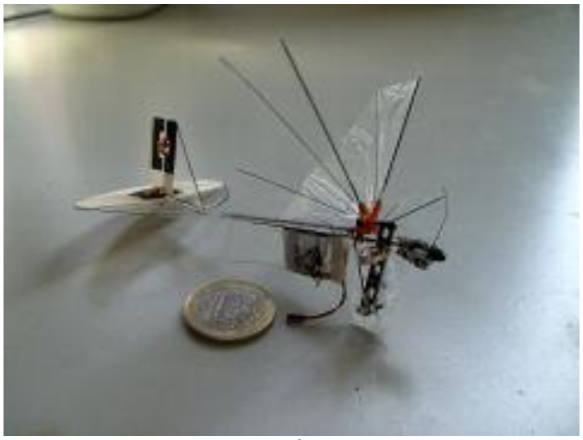

Figure 7: Delfly Micro [12]

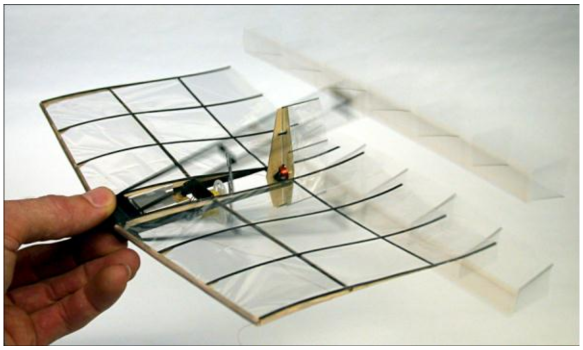

Figure 8: NPS Flier [9]

2.3 Ruddervator Tails

The ruddervator tails category refers to a control layout that is not easily classified with the more traditional schemes. This configuration uses surfaces called ruddervators, more commonly known as a v-tail. The general idea is that instead of using a vertical rudder arranged perpendicular to a left and right elevator fin, as with most aircraft, two fins are arranged at an intermediary angle between vertical and horizontal. By mixing the two control surfaces, it is possible to achieve both the rudder and elevator degrees of freedom. There are two MAVs we discuss that make use of this configuration, both versions of the Delfly from the Technical University of Delft. The original Delfly, shown in figure 9, uses ruddervators angled downward so that the mechanism will be protected during landing.

The Delfly is similar to its Micro version in that it uses camera vision-based stabilization to maintain stability in flight. This is similar to fly-by-wire technology that many modern aircraft use, which allows for stable flight in aircraft that are inherently unstable. With small magnetic actuators, the ruddervators can be moved both in the same direction for turning, or both in the opposite direction for elevation. Any combination of the two commands allows for a full flight envelope, just as a MAV with a separate elevator and rudder could achieve.

Figure 9: Delfly [13]

2.4 Independent Wing Control

An alternative to using the tail for control is to alter the phase of the wings to achieve force imbalance. The resulting turning is achieved without the aid of a separate devoted control surface for that degree of freedom. Such examples are very rare in the field of miniature air vehicles, due to the typically rapid flapping rates required to sustain flight. This creates a complicated control problem that requires a non-traditional flapping mechanism. One example that achieves the force balance needed for steering but not successful MAV flight is shown in figure 10.

The four bar linkage mechanism is flapped with a piezoelectric unimorph, figure 11. Such a configuration avoids the weight penalty associated with an electric motor, and offers the ability to control the magnitude and speed of the flapping motion. This is a key benefit as compared to a motor with a mechanism, because a motor cannot offer the ability to vary the flapping range of the wing, only the speed.

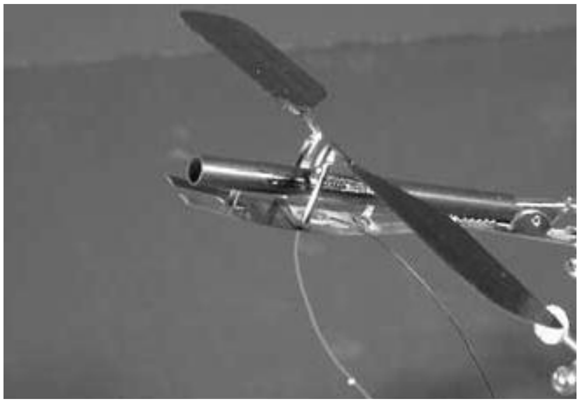

Figure 10: Unimorph actuated independently controlled wings [14]

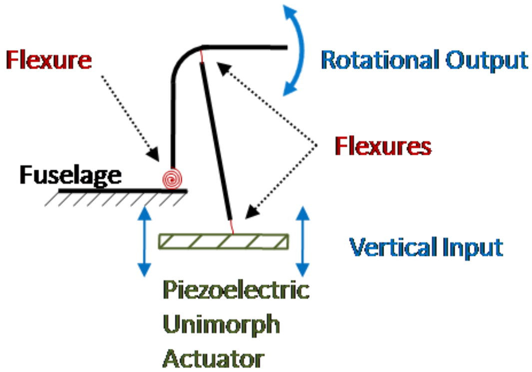

Figure 11: Functional schematic for four-bar unimorph actuation [14]

By using actuators with slightly different resonant frequencies, it is possible to create asymmetry in the flapping for steering purposes. While this MAV has not successfully completed a flight, the technology employed shows great promise for future designs. Independent wing control coupled with fast flapping rates is a key step towards realizing the same level of maneuverability that is present in flying animals, and if successfully implemented in a flying prototype this would be a noteworthy advancement of the MAV field.

3 WING DESIGNS

MAVs generate the lift and thrust forces necessary for flight using flapping wings. The performance of wings depends upon the shape and compliance of the wings and the wing movement modes. The average and instantaneous thrust and lift generation strongly depends on how wings change their shapes during the flapping cycle. Several studies have been conducted to investigate aerodynamic performance of flapping wings and construct models to predict wing flight performance [48-52]. These models can be used to optimize wing performance by changing spar arrangement on wings to control the wing compliance and changing the cross section shape to control lift coefficient. This area has attracted significant research attention. To keep this paper focused on the mechanical design aspects, we will not discuss aerodynamic aspects of wing design.

Several different wing movement modes have been investigated to achieve flight. The most traditional functionality is with flapping wings, where flight is achieved with two flapping wings. Alternatively, four wings can be used where each side of the fuselage has a pair of wings flapping in opposite phase. This arrangement cancels out the vertical oscillations associated with two wings, resulting in more stable flight, at the expense of greater energy consumption to drive more wings. Within each category, there are variations on the basic design, such as folding wing spars, or wings that use clap-and-fling to boost lift production. Each wing style will be discussed in more detail to clarify the relative strengths and weaknesses.

3.1 Flapping Wings

The category of flapping wing locomotion is the most well known, and is often seen as the traditional method of flapping flight. Flapping wings are used by a wide variety of animals including birds, bats, and a variety of insects. The general principle of operation is that two wings are flapped to produce both lift and thrust, thus overcoming gravity and drag to provide sustained flight. Generally, flapping fliers can most easily be distinguished based on their respective size scale and flight speed or the Reynolds number experienced in flight, and therefore flight style. By observing nature, one can see the difference in flight style between a large soaring bird such as an albatross, and a hummingbird, which must flap its wings very rapidly to stay aloft. A similar relationship holds for man-made flapping wing fliers. At larger size scales, higher Reynolds numbers are encountered and therefore slower flapping and soaring are the most effective modes of flight. Fliers in the centimeter scale however, experience very different aerodynamic effects, with less favorable lift to drag ratios. The general trend is that as the flier decreases in size, the wings must flap faster to produce the necessary lift and thrust to support flight. This creates a unique challenge for miniature MAV designers, because traditional aerodynamics break down with such small wings. However an interesting trade-off is that with higher rates of flapping comes the opportunity to realize greater control resolution, and some impressive acrobatic maneuvers become possible. In this section, we will discuss a number of successful flapping wing miniature fliers, both commercially available, as well as research platforms.

One of the design goals of the Microbat was to create wings using Micro Electrical Mechanical Systems (MEMS) technology. Several MEMS wings were constructed, with variation in parameters such as chord and spar width, membrane thickness, number of spars, and sweep angles. Wing materials chosen were titanium-alloy metal (Ti-6Al-4V) as the structure, and poly-monochloro-para-xylelene (parylene-C) as the membrane. The wings were designed to make use of unsteady-aerodynamics to achieve a high lift coefficient, relative to a fixed wing of similar size. One of the key benefits of MEMS-based wings is that the wings can be created exactly the same every time, using a template style of construction. With such lightweight MAVs, the small variations present in hand-made parts translate to large differences in performance from one version to another. The Microbat has a very short wingspan, with the current version measuring 9 inches from wingtip to wingtip.

Another MAV using MEMS technology to produce wings is shown in figure 13.

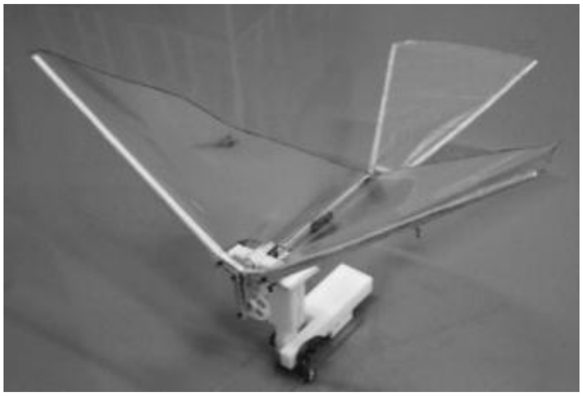

Figure 13: MEMS wings with PVDF sensing capability [15]

By creating one wing with a PVDF skin as a smart wing, it acts as a real time lift sensor. Comparison of its results to a load cell mounted to the MAV shows that it is a viable means of determining performance in flight [16]. Such a feedback system is a key difference separating man-made MAVs from flying animals, and incorporation of this style of distributed sensing technology gives great promise for the future of MAVs.

Wings do not necessarily have to be constructed with MEMS technology at this size scale. They can be constructed by hand using traditional materials as well. The University of Maryland Small Bird and Big Bird and the University of Delaware ornithopter all use flapping wings constructed in a similar manner. The wings use lightweight and stiff rods to provide structure, much like a bird's skeleton. The rods serve to strengthen the wings and help them to achieve an airfoil shape during flapping. The wing surface is made of a thin mylar film, stretched over the stiffeners. As the wings flap, the configuration of the stiffeners combined with aerodynamic loading causes the wings to create a rounded airfoil shape, providing lift. Since these wings are handmade, construction repeatability becomes an issue due to the small difference between sets of wings created.

The I-fly Vamp and Wasp also use a thin foil skin stretched over front and rear wing spars to provide stiffness. The front spars of the wings are mounted into the flapping mechanism, providing the power for flight. The rear section of the wings is mounted into a surface that can be tilted left and right along the body of the MAV. By shifting the angle of the entire flapping plane of the wings, steering is achieved. Due to the economical nature of the flier, the MAV is somewhat underpowered, so steering results in altitude losses. However, if a more advanced MAV were to incorporate skewing wings into a system that also has a rudder, redundant control would be possible, thus safeguarding against system failures. For this reason the research community could draw inspiration from the toy market for a technology that can improve the robustness of their MAVs.

3.2 Four Clapping Wings

This category includes any MAV that uses one or two pairs of wings flapping opposite each other, such that the vertical inertial oscillations present in a two-winged flier are cancelled out. This style of flight offers the key benefit of greater stability, which could allow for more delicate sensors and payloads to be carried successfully.

In this category, there are a variety of examples that use generally the same principle of operation. The Osaka Slow Fliers Club 1.5g ornithopter is one of the lightest that has completed a successful flight. The toy market has contributed models such as the Wowwee Flytech Dragonfly, and Wingsmaster Ornithopters all use a pair of wings constructed of thin film with stiffener ribs, flapping in opposing phase. The Delfly, Delfly II, and Delfly Micro all use a similar style of wings, with the added benefit of their vision-stabilization system. This makes these MAVs more suited to outdoor flights, and capable of more advanced maneuvers. The Delfly II is the most capable of the three, with the ability to fly forward, hover, and even fly backward at low speed.

The Naval Postgraduate School MAV is an unusual entry into this class, however due to the manner of its wing flapping, it has been classified as a clapping wing MAV. The NPS MAV uses a flying wing fuselage shape with a pair of wings that flap in a vertical plane mounted to the rear. These wings flap in counterphase, thus thrusting the wing through the air and providing lift. The design and operation of this MAV is unlike any of the others discussed, however the performance of this MAV offers some interesting performance tradeoffs. The speed is controlled by trimming the pitch of the flapping wings, pre-flight, and the altitude is controlled by varying the flapping rate. This is an unusual configuration for an MAV, however the maneuverability is very good. The key benefit of this style of flight is related to the energy expenditure during flight. In many two-winged MAVs, the wings flap and the body will oscillate opposite the wings' motion. This means that valuable battery power is being wasted performing the work of accelerating a massive body up and down. Or in four-winged MAVs, the wings are mounted to a body that functionally does not contribute to the flight capability, it just provides a structural support for flight systems. In the NPS flier, all energy expended by the motor is directed into the flapping wings that drive a wing into the air. Therefore, the entirety of the MAV is being used for the beneficial purposes of thrust and lift generation.

A new concept for clapping wings is the use of 3-way clap and fling, to augment lift. Clap and fling has been shown to produce extra lift in the literature [17-22] [23]with small winged fliers, however, the idea of 3-way clap and fling is relatively new. By exploiting the effect at the left and right sides where the wing pairs meet, as well at the top of the MAV where the opposing wing pairs meet, figure 14, the effect is magnified, thus improving lift.

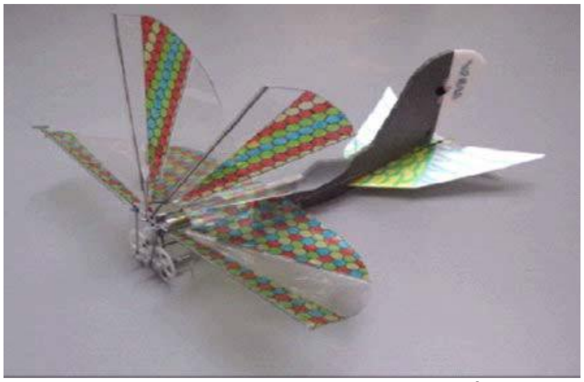

Figure 14: WSU MAV wings exploit clap and fling at the sides and the top of the wingbeat [24]

In a similar manner as the Delfly II, the MAV shown in figure 15 uses passive stability to achieve hovering flight.

This MAV is designed to mimic insect-style flight, with a Reynolds number of about 8000. It maintains its stability in much the same manner as a damped pendulum that returns to rest when disturbed, by creating a balance of forces that tends to keep the MAV upright and centered. The sails act as dampers to prevent unstable or oscillatory motions from taking over during flight.

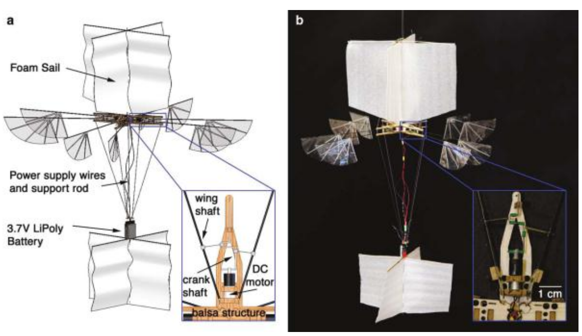

Figure 15: Passively stable hovering MAV [25]

3.3 Folding Wings

Observation of larger birds in nature reveals that wing flapping is tailored to the requirements and conditions faced at the time. When a bird is taking off, the wings are flapped differently than during cruising flight. Since the bird does not have the airstream flowing over their wings from the static position, lift must be somehow augmented, since aerodynamic lift is lacking in this condition. Therefore, birds will flap their wings downward, fold them in towards their body, during the upward flap, and then re-extend their wings during the downward flap. This results in maximum wing area during the down flap, which is producing helpful upward lift. During the up flap, the area is minimized, thus reducing the magnitude of harmful negative lift. By using this style of flapping, the bird is able to get airborne and then transition to standard flight. For a MAV to recreate this style of flapping, passive wing folding is an attractive option due to the excessive weight of actuators that would be needed. In [26] the authors describe a successfully flying MAV that uses wings with one-way compliance to accomplish the desired folding effect, figure 16.

Figure 16: Wings with one-way compliance

The result is that the wings can lift the same amount of weight, but with slower forward velocity. Thus, a behavior much like the bird during takeoff is accomplished with folding wings. In [27, 28], the authors attempt a similar style of wings, resulting in augmented lift production in non-moving air. However, flight was not achieved probably due to the extreme amount of folding used by the wings disturbing the balance of forces in flight. The ornithopter used in this particular experiment is too large to be considered a miniature air vehicle, however.

4 DRIVE MECHANISM DESIGNS

There are four primary classifications of drive mechanisms used by the MAVs discussed: (1) double pushrod, (2) double crank, (3) single pushrod, and (3) side-mounted crank. Each of these four mechanisms presents a tradeoff of multiple important performance attributes. Some of the considerations for selecting a mechanism layout include the particular geometry and weight constraints for the MAV, as well as the required forces to be transmitted and the rate of flapping. Other concerns include the manufacturability of the selected design, especially with very small and light MAVs. As the size of mechanisms grows ever-smaller, the human limitation becomes a factor in the construction of more complex mechanism layouts. Due to the reduced stability of MAV platforms, a durable mechanism is desired, due to a variety of damaging factors including dirt contamination, crashes, assembly stresses, and the fatigue effects of high flapping rates.

4.1 Front Mounted Double Pushrod

The first style of mechanism discussed is a front-mounted double pushrod mechanism, shown in figure 17 [6].

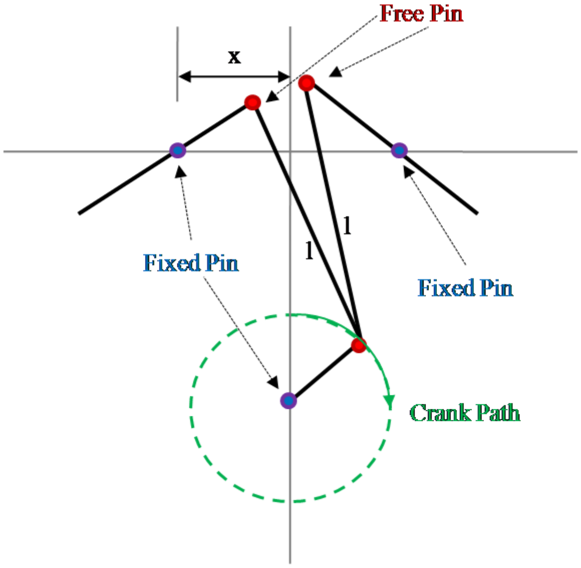

Figure 17: Double pushrod flapping mechanism [6]

This mechanism uses a motor connected to a system of gears that increase flapping force while reducing flapping rate. Pushrods connect to each flapping spar, thus driving the wing motion up and down through pinned connections. Due to the pinned connections, the vertical translation is the only component of motion that is transferred from the drive gear. Since each wing spar has its fulcrum located at a fixed distance x from the central axis of the mechanism, and the pushrods are of fixed length l, a problem arises. The two pushrods are never exactly in the same vertical location, except for the apex and the nadir of the flapping motion. This creates a phase lag between the two wings, resulting in slightly asymmetric flapping of the wings. At the miniature size scale, this is an undesirable situation, where control is already difficult due to the low inertia of the fliers relative to their large wing and fin surface area. This style of mechanism is used in the Microbat, figure 18, the Chung Hua University MAV, figure 19, and the University of Delaware ornithopter, figure 2 on the right.

Despite its inherent limitations, this configuration is popular due to its simple construction, light weight, and ease of part replacement. If the MAV is very small and has a sufficiently high flapping rate, it is possible that the asymmetry of the wings can be masked during the overall flap motion. If the throttle is reduced however, the MAV will begin to exhibit noticeable oscillations and be more difficult to control.

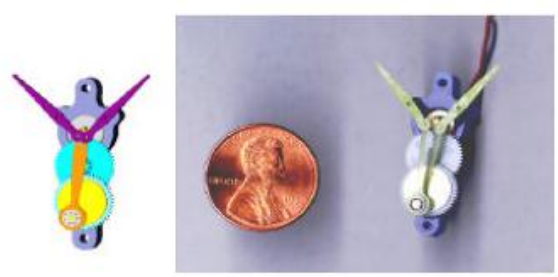

Figure 18: Double pushrod from Microbat [6]

Figure 19: Chung Hua University MAV double pushrod mechanism [29]

4.2 Front Mounted Double Crank

A variation of the double pushrod design is the double crank. This design is similar in functionality, except that the two pushrods no longer share a common mounting point on the crank. The Delfly uses this style mechanism, shown in figure 20.

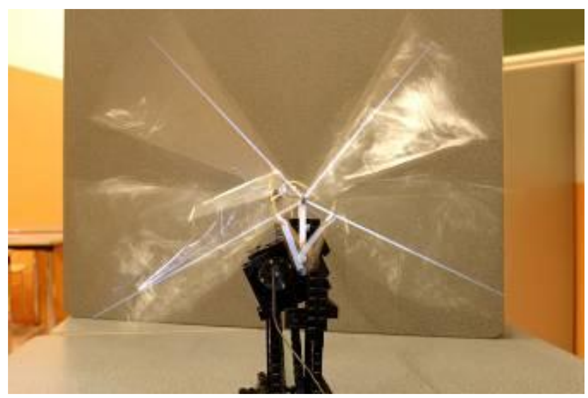

Figure 20: Delfly I front mounted double crank

The benefit of this change is that the asymmetry in wing flapping can be reduced, thus improving the stability of the MAV.

4.3 Front Mounted Single Pushrod

The single pushrod mechanism drives the two wings' motion together with a common pushrod, mounted to the crank in a central pinned connection, shown in figure 21.

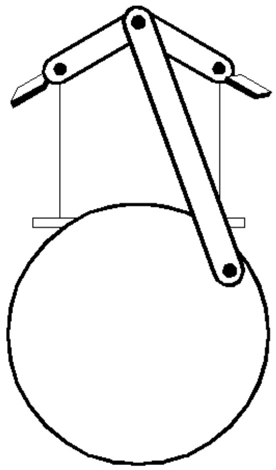

Figure 21: Single crank functional schematic [30]

The key difference between the single crank as compared to the double crank is the wing flapping can be made always symmetric, thus improving the low-speed stability of the MAV. A performance tradeoff with this mechanism is that the stresses will be much higher in the single pushrod, since it must drive both wings at the same time, in phase. In addition, the stress on the electronics components including the motor and electronic speed controller will be greater, since the wing flapping is exactly in phase. With the double crank, the wing flapping was slightly out of phase, thus distributing the load of a single flap cycle over a larger time period. While the overall work required is equivalent, the spike in loading is more focused in the single crank mechanism. It is possible to adapt the single crank mechanism to have a phase lag as with the double crank mechanism, by incorporating sliding hinges to support each wing spar [30]. As the wings flap, the hinges that provide a fulcrum for the wings are free to move so that the motion is not jammed up at any point during the flapping motion.

As a method of reducing the loading spike, a compliant frame can be used. The general principle of operation is that by incorporating elastic links into the mechanism, spring energy can be stored and released during the flap cycle. By designing the geometry and stiffness of the system to optimize the energy storage and release, the loading range, i.e. the difference between the largest and smallest load can be reduced. Reduction in the loading range has been shown to improve the efficiency of the mechanism, thus prolonging battery life and improving the reliability of the electronics components [5] [8]. This style of mechanism is used in newer versions of the University of Maryland Small Bird and Big Bird, figure 22.

Figure 22: UMD single crank mechanism

Due to the layout of the mechanism, it is possible for both of the compliant links in the mechanism to deflect simultaneously in the same direction, a degree of freedom that can be thought of as 'sway'. Causes for the sway effect include driving wings that are too large for the mechanism, driving wings too rapidly, or large wind gusting or other external loads of the mechanism that remove it from its design range. This effect serves to reduce the distance from the pushrod to the pinned connection that drives the wings up and down, thus altering the designed-in flapping range and causing undesired dynamic effects. For these reasons, it is important to ensure the single pushrod is staying within its designed limits. This behavior can be alleviated with the addition of a pin and slider joint in the center of the mechanism, resulting in always symmetric deflections by the compliant links

One variation on the single crank mechanism concept is shown in figure 23.

Figure 23: Parallel single cranks [24]

With a pair of front-mounted single cranks, some of the problems of this mechanism style are solved. The mechanism is set up to flap the wings in phase, with a pair of equally sized cranking gears attached to the drive motor. Assembly is made easier with the use of multi jet modeling rapid prototyping machines. The gears are deposited with a removable wax that is dissolved during post processing, so that the mechanism is assembled automatically.

4.4 Side Mounted Crank

Some of the MAVs discussed use another style of single crank mechanism, the sideways pushrod layout. In this configuration, the axis of gear rotation is shifted 90 degrees to be perpendicular to the direction of flight and coincident with the MAV elevation axis. There is one pushrod used to drive each wing in this mechanism layout. Each pushrod is attached to the slowest-moving gear, with one on both the left and right side of the MAV that moves vertically with the gear using a pinned connection. The vertical movement of the pushrods is transmitted to the wing spars at a mounting point, thus driving the wings up and down. In the Delfly II, figure 24, Delfly Micro, figure 25, and Osaka Slow Flier's Club MAV, figure 26, a sideways pushrod mechanism is used.

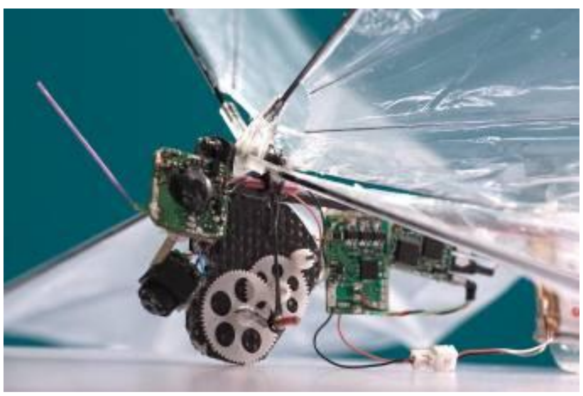

Figure 24: Delfly II side mounted pushrod mechanism

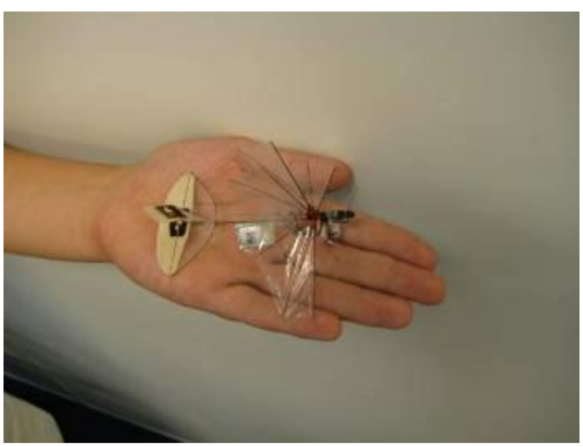

Figure 25: Delfly Micro side mounted pushrod mechanism

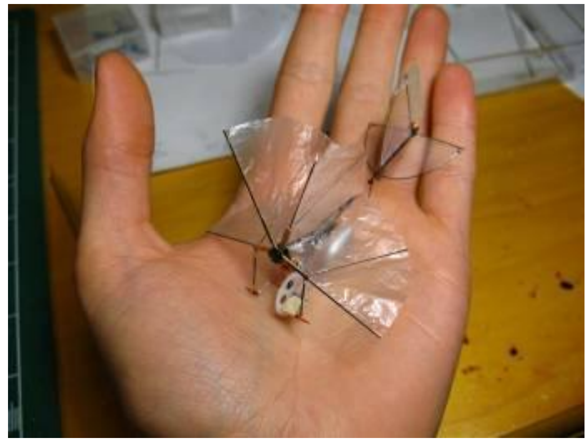

Figure 26: OSFC side mounted pushrod mechanism

This layout transmits crank motion into the elevation axis, instead of the roll axis. For lighter MAVs or MAVs with a large surface area to weight ratio, this configuration is helpful in maintaining stability and controllability during flights. Construction is more complex than the other two layouts; Exposure to crash damage is also greater when using this configuration. Since the pushrods are exposed on both sides of the MAV, it must be shielded from crash damage in a variety of different directions. If a pushrod were bent in a crash, it would probably need replacement since any small difference between the two sides of the mechanism could cause large stresses to arise during high-speed flapping. If the manufacturing and durability limitations can be overcome, the symmetric flapping, light weight, and compact size make this mechanism a good layout for very small MAVs.

4.5 Spherical Mechanism

The spherical mechanism is an attractive alternative in the drive mechanism design area. However, miniature ornithopters have not yet been able to incorporate such a design into a successfully flying example [5, 31-33]. The goal of spherical mechanisms is to recreate the complex flapping motions exhibited by insects in flight, as well as smaller birds such as hummingbirds. This motion consists of a figure-eight pattern inscribed on the surface of a sphere, consisting of translation, rotation, and plunge motions combined into each half-beat of the wings. Such a motion requires the use of spherical mechanisms. The main drawback of the spherical mechanism is that since it is most suitable for the insect or very small bird style of flight, the extra weight associated with a complex structure makes untethered flight very challenging. Currently, research into these mechanisms shows promise [33, 34]. Further development is required to generate the necessary lift for sustained flight.

5 FUTURE RESEARCH DIRECTIONS

At present, flapping ornithopters have achieved an impressive level of sophistication, and through the persistent efforts of researchers and private parties in the last decade, marked progress has been made in small flapping-wing fliers. In this section, we seek to identify certain areas in the field that would be beneficial to further advancement of the state-of-the-art. With improvements in these key areas, flapping-wing MAVs will gain the same kind of consumer acceptance as larger-sized UAVs, which are widely used in a variety of applications.

More research needs to be performed to better understand the properties of flight at the miniature size scale, where unsteady aerodynamics becomes increasingly important. Small fliers tend to flap their wings very rapidly, which creates difficulty in measurement of forces. Therefore, a number of researchers have created tests where wings are aerodynamically scaled, such that the wings are larger or flap in a more viscous fluid [18, 20, 21]. Such devices have given researchers great insight, experimental data, and analytic models about small wing aerodynamics. Researchers have also created tests where a wing is un-scaled that have shown promise, however creating a prototype that can fly using such a wingbeat has proven very difficult, due to the weight of the mechanisms required [33, 34]. Further research into techniques for force measurement will enable future MAVs to achieve greater efficiency by improving our understanding of aerodynamics at the miniature scale.

Flapping-wing fliers generally strive to achieve a biologically-inspired subset of degrees of freedom and wing dynamics, and therefore tend to lack the aerodynamic performance of their organic counterparts. Insects and small birds such as the hummingbird use a very complex wing beat. By altering the timing of the pronation and supination of the wings independently or in unison, natural fliers achieve directional control and improved lift and thrust, respectively [31]. Due to the difficulty of faithfully recreating complex wing motions, man-made fliers tend to lag behind their natural sources of inspiration in terms of payload capacity, maneuverability, and most importantly, flight endurance. Further research into methods for realizing complex wing motions will reduce this performance gap.

At small sizes, faster and more energetic wing flapping is required to maintain flight, and therefore, greater energy density is needed. By making improvements in the energy storage density of batteries or other modes of power used in small MAVs, larger payloads can be carried by smaller flight platforms. Currently, short flight times are a major limiting factor preventing widespread usage of small MAVs. However, with continued research in new power storage technologies, the usefulness of MAVs can be realized in a larger number of applications.

The style of flight exhibited by a particular bird has a strong effect on its body layout, flight control strategy, and the aerodynamics employed. An alternative approach is to improve the cruise behavior of small MAVs. Research into how small birds fly has shown that a hummingbird represents an idealized hover behavior, however a budgerigar offers an effective solution for energy savings during cruising flight [35]. By transitioning between flap-gliding at low to moderate speeds and flap-bounding at fast speeds, energy savings can prolong the duration of flight for a given energy expenditure. If a MAV were capable of altering its physical layout it would be able to realize the benefits offered by multiple styles of flight.

Another technique that could be applied by MAVs at the larger end of the miniature spectrum would be to exploit thermals to boost glide performance, a technique commonly employed by birds. While feathers are not equipped with the ability to sense air currents directly, it is believed that receptors on the follicles of the feathers and changes in pressure distribution on the wing surface are used to provide birds with information about updrafts [36-39].

An area that presents a unique challenge is the creation of flapping MAV systems equipped with autopilots. Achieving autonomous flight becomes increasingly difficult as size is reduced, for a variety of reasons. The high flapping rate and corresponding inertial loading of the wings transmits a fairly strong pitching force to the internal gyroscopic sensors of a typical autopilot, greatly complicating the process of developing suitable control laws. The small size of the flapping MAV platform necessitates that the autopilot used is extremely lightweight, and does not cause undue interference with the flight dynamics or weight distribution. Therefore, any effective autopilot would have to be very fast in terms of processing speed, and also have high resolution sensor inputs and control outputs to provide a sufficient degree of control. This is a much more difficult task in urban or indoor environments, when the margin for error is extremely small and the difference between a successful flight path and a crash is measured in inches.

In order to maximize the versatility of flapping MAVs, a multi-mode locomotion system should be developed. With the ability to land, perch, walk, and even take off nder its own power, the MAV can become an even more versatile platform. For example if power was running low, an MAV could perch on a tree and recharge its battery using an onboard solar cell. Alternatively, if an MAV were tracking a target that became stationary, it could land and await further movement, thus conserving precious battery life. Most importantly, if an MAV could take off and land on its own, it would be separated from the necessity of a human operator nearby to launch and recover the system manually. This has tremendous implications for a large portion of potential consumers who would value persistent flight platforms. Especially in the military, any system that is self-operating is a great addition because it allows the human operator to monitor progress from many vehicles instead of actively controlling a small number of MAVs and devoting all their attention to maintaining simple behaviors.

The dynamics of the wing flapping require improvements, but hardware advances in the areas of battery energy density, small electric motor efficiency, and power transmission efficiency are also required to improve the duration of MAV missions. By making batteries with higher energy density, and optimizing energy usage through the use of elastic energy storage and release, flight endurance can be further improved. If new progress is made in these areas, an entirely new class of flapping fliers can be created that will possess useful and practical flight endurance. Eventually, if MAVs can be created that can remain aloft for up to an hour, then flapping MAV systems will be much more aligned with current objectives typical for unmanned systems.

Research in flapping flight has made great progress in recent years, with some fairly sophisticated examples now being built at low cost. As interest in this area of flight grows, more examples of successful mini-sized MAVs will emerge and continue to advance the state of the art. However, the MAVs are not the only area of research that requires development. At present, the ability to carry payloads on mini-sized fliers is highly limited, so development in miniaturization of sensors, autopilots, and other useful payloads is another area that requires some advances to help fully realize the utility of mini flapping platforms. As part of autopilot development, advances in distributed sensing and actuation will help researchers to create fliers with ever-increasing levels of realism and degrees of freedom.

6 CONCLUSIONS

This paper has presented representative designs of mechanisms and wings found in flapping-wing miniature air vehicles. These MAVs have been classified by the tail, wing, and mechanism functionality. Each MAV has been discussed in detail, and the advantages and disadvantages of each example have been explored. Furthermore, the overall advantages and disadvantages of each general classification have been explored, to determine any general trends that arise. In table 1, values are presented for some of the MAVs discussed to provide a comparison.

The primary conclusions of this review are to identify the progress made so far, and to determine the areas in which further research are needed to advance the state of the art. Flapping wing flight can be used by unmanned aerial vehicles to complete a variety of mission objectives that fixed or rotor wing fliers are unsuited for, but there are a number of practical drawbacks to using flapping style flight at such a small size scale which must be overcome to continue the advancement of the field.

Some areas where future research could help advance the state of the art in MAVs include autonomous flight, including take-off, landing, and perching. In addition, greater sensor carrying abilities would contribute to the goal of autonomous missions. Another area requiring advances is sophisticated wing control. Animals possess many more degrees of freedom than MAVs, a major reason for their advantage in maneuverability, endurance, and effectiveness in adverse weather conditions.

The current field of flapping MAVs displays impressive depth as well as breadth, and has definitely made significant progress since the Microbat first flew in 1998. With the current rate of progress by research groups as well as the ever-increasing level of accessibility to a variety of private groups and consumers, the future of small MAVs should continue to be an exciting field. As research continues in the key areas of research that are lacking, small MAVs will be adopted by many more consumers as a viable flight platform for carrying out missions, as well as by private consumers for entertainment. Eventually, it is expected that MAVs will supplement and even replace larger UAVs in a variety of useful applications where smaller, lighter, disposable aircraft would offer an attractive solution.

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TABLE 1: PHYSICAL DATA [1, 26, 40-48]

Category	Name	DOF	Weight (g)	Span (in)	Length (in)
Clapping Wing MAVs	**Wright State University**	2	12.56	7.9	9
	I-Fly I-bird/fairy/wings (wingsmaster ornithopters)	2	12	10.5	8.25
	Delfly I	3	30	19.69	20
	Delfly II (hover)	3	16.07	11.02	11
	Delfly II (forward)				
	Delfly Micro	3	3.07	3.94	4
	NPS Flier Dr. Jones	2	12.4	10.6	7.09
	OSFC Flier	2	1.47	2.36	2.76
	Flytech Dragonfly	2	28.35	12.3	16.5
Flapping Wing MAVs	**I-Fly Vamp/Wasp**	2	13	10.5	8.5
	Microbat (UF/DARPA)	2	12.5	9.06	6
	UMD small bird	2	9.3	13.5	8
	UMD big bird	2	27.9	22.5	10.5
	UMD jumbo bird	2	38.0	25	11.7