A Review of Biomimetic Air Vehicle Research: 1984-2014

Thomas A. Ward[1,*], M. Rezadad[1], Christopher J. Fearday[2] and Rubentheren Viyapuri[1]
[1]Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[2]Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ABSTRACT
Biomimetic air vehicles (BAV) are a class of unmanned aircraft that mimic the flapping wing kinematics of flying organisms (e.g. birds, bats, and insects). Research into BAV has rapidly expanded over the last 30 years. In this paper, we present a comprehensive bibliometric review of engineering and biology journal articles that were published on this subject between 1984 and 2014. These articles are organized into five topical categories: aerodynamics, guidance and control, mechanisms, structures and materials, and system design. All of the articles are compartmented into one of these categories based on their primary focus. Several aspects of these articles are examined: publication year, number of citations, journal, authoring organization and country, non-academic funding sources, and the flying organism focused upon for bio-mimicry. This review provides useful information on the state of the art of BAV research and insight on potential future directions. Our intention is that this will serve as a resource for those already engaged in BAV research and enable insight that promotes further research interest.

Keywords: flapping wing, micro air vehicle, biomimetic, nano air vehicle, ornithopter, unmanned air vehicle

1. INTRODUCTION
Research into aircraft that mimic flying biological organisms (e.g. birds, bats, and insects) by flapping their wings to achieve lift and thrust has occurred for centuries. Historically, this type of aircraft is called an ornithopter[i]. Perhaps the most famous early design was created by Leonardo da Vinci in 1485. Early devices were only capable of gliding. The first ornithopters capable of powered flight were not built until the 20th century. Despite this long history, the creation of practical biomimetic air vehicles (BAV) that are able to accomplish specific operational air missions was not possible until modern times. Modern BAV primarily consist of small unmanned systems. Much of the early work focused on bird-like biomimetic ornithopter vehicles (BOAV). While advances in BOAV are progressing, perhaps the most promising new class of BAV is called biomimetic micro air vehicles (BMAV). This type of micro-scaled aircraft mimics the flapping wing motion of insects or very small birds (e.g. hummingbirds). The additional lift gained by rapidly oscillating its wings, allows BMAV to attain lift with a very small wing surface area. The US Defense Advanced Research Projects Agency (DARPA) released a Broad Agency Announcement (BAA 97-29) in 1997, defining micro air vehicles to be less than 15 cm in any dimension. Later in 2005, DARPA defined nano air vehicles (BAA 06-06) as being no larger than 7.5 cm or heavier than 10 g (carrying a 2 g payload). (In this review we group both biomimetic micro and nano air vehicles as BMAV.) The primary payloads envisioned for a BMAV are ultra-lightweight, compact electronic and surveillance detection equipment. Their miniature physical size makes them difficult to detect, easy to quickly deploy by a single operator, and relatively inexpensive to fabricate. Their size offers the potential to fly them inside buildings or compact spaces. BMAVs are envisioned for use on civil and military missions that are of a limited duration, such as: remote sensing of hazard sites (e.g. chemical spill, radiation, high voltage area etc.), indoor video mapping, and police and military surveillance (Michelson et al, 2002 [1]).

*Corresponding author. Tel: +603-7967-4455; Fax: +603-7967-5317 Email: DrTomWard@um.edu.my
[i]From the Greek words: ornithos (meaning bird) and pteron (meaning wing)

BMAV are also desirable for their potential to be highly agile. Insects generally steer and maneuver by altering wing motion. However, they also use their legs or abdomens as control surfaces during flight (Götz et al, 1979 [2], Lorez, 1995 [3]). Thus, a central challenge in understanding how insects steer and maneuver is determining how modifications in wing stroke kinematics alters the forces and moments being generated. Organisms studied include: hawk moths, dragonflies, beetles, and variety of others. The wing trajectories of these models can be different depending on the thorax-wing connections and their muscles.

Several comprehensive review articles have been published on biological (e.g. insect or bird) aerodynamics (Maxworthy, 1981 [4], Sane, 2003 [5], Wang, 2005 [6], Wu, 2011 [7]). One article surveyed literature published before 2006 and made an assessment on the primary challenges facing future MAV development (Pines et al, 2006 [8]). These challenges included: operation in the very sensitive Reynolds number regime; lack of analysis tools to accurately model the steady and unsteady environments that MAV encounter while in flight; ultra-lightweight adaptive and biologically inspired materials and structures; micropropulsion systems and power sources; miniaturized flight navigation and control; and a lack of system engineering tools. As will be shown in this article, progress has been made in some of these research areas since 2006 (e.g. aerodynamic modeling, materials, and structures) but relatively little has been done in other areas (e.g. micropropulsion systems, power sources, flight navigation, and control). Four other review articles have been written that focus on a specific aspect of BAV. The first compares the aerodynamic efficiency of different hover-capable BAV to helicopters (Mayo et al, 2010 [9]). Another reviews the flapping wing mechanisms of BAV designs that are inspired by birds (Gerdes et al, 2012 [10]). One analyzes the stability of different aerodynamic flapping wing models presented in past publications (Karásek et al, 2012 [11]). Lastly the power electronic topologies of several past MAV designs are reviewed and compared (Chen et al, 2013 [12]).

This article presents a comprehensive, bibliometric review of existing research and literature examining flapping wing devices from 1984 to April 2014. It is a broad-based review that is not limited to one particular design aspect. Specifically the objectives of this article are:

1. Develop a framework that categorizes research on BAV.
2. Broadly summarize what has been discovered and the challenges that still lie ahead.
3. Analyze the international focus of this research (publications, citations, authoring organizations, funding sources, and biological organisms being studied) to discover who is engaged in BAV research, what is being done, and where it is moving.
4. Guide further research in a way that is useful for future practical applications.

The overall intention of this article is to highlight the important potential of BAV technology and provide insight to both academic researchers and industry designers, as they strive to determine the next step forward in implementing the advances being discovered.

2. RESEARCH METHODOLOGY

The quantitative synthesis done in this bibliometric review is based on investigating a number of journal articles that are directly related to BAV technology. The process used to identify, screen, and determine the eligibility of these articles is shown in Figure 1. The first 30+ years (1984 until 2013, plus the first four months in the present year of 2014) were selected as the publication date range under consideration. Although ornithopters are not a new research area, BAV have only just become popular within the last few decades. So the 30+ year time range of this study is reasonably complete.

An initial comprehensive search for articles was performed using multiple databases (e.g. Web of Science, Science Direct, IEEE Xplore, and Microsoft Academic Search). This initial search was done using broad common descriptor phrases such as: flapping wing, insect flight, bird flight, biomimetic, flapping flight, and robotic flight. The search engine matched these phrases with terms stored in the metadata for each document. This initial search yielded 797 potential publications, which was extracted from the database into Endnote and then loaded into a Microsoft Excel spreadsheet. An extensive manual examination of these publications enabled the authors to redefine an improved list common descriptor phrases (listed in Figure 1). A new, refined search was then done on the Web of Science database (Thomson-Reuters) using the improved descriptors. This narrowed the number down to 537 potential publications. Since journals are the most reliably vetted resource to find information on new discoveries, other publications (e.g. conference papers, master theses, doctoral dissertations, text books,

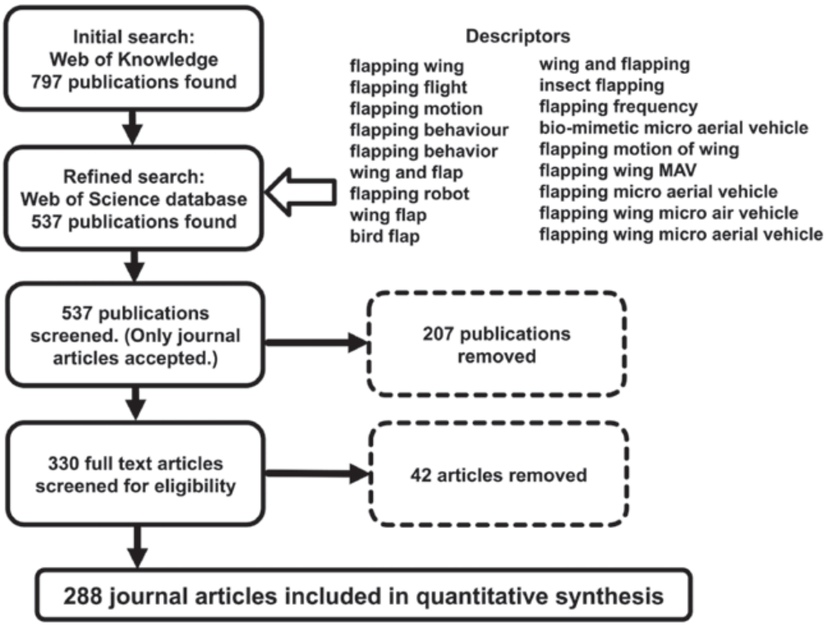


Figure 1 Article identification and screening process for quantitative synthesis

etc.) were screened out, eliminating 207 publications. Although conference papers were screened out of our bibliometric analysis, it must be noted that many describe functioning BAV. Some examples include: the Georgia Institute of Technology Entomopter (Michelson et al, 1998 [13]), the Harvard University Microrobotic Fly (Wood, 2007 [14]), and the AeroVironment Nano Hummingbird (Keennon et al, 2012 [15]).

The abstract of each journal article was then manually reviewed to eliminate papers that were irrelevant to BAV research. Some of these abstracts were written in a clear manner that enabled confident screening. However, about one-third of the articles required that the full text be rigorously reviewed in order to remove any doubt. Biological articles were included if the focus was on some aspect of flapping wing mechanics that could be exploited in a BAV. Engineering articles were included only if the authors specifically stated a BAV application as an objective.

Although the bibliometric approach used in this paper is both conservative and inclusive, no method is perfect and without risk. The relevancy of an article was determined by the objectives and results stated in it, eliminating any bias of the authors of this article. The only potential source of error is excluding relevant BAV publications in the screening process. Articles not listed in the Web of Science database were not considered. All publications except journal articles were screened out. Engineering articles that did not mention a BAV application were excluded. Given the vast number of publications, it was necessary to rigorously screen these in order to obtain a high confidence in the qualitative and quantitative synthesis of the resultant articles. So the 288 articles analyzed provide a good overall assessment of BAV research with a minimal risk of error. An exhaustive list of all these articles is not included in this paper, simply because there are too many. However, a representative sample of articles (about 25%) is referenced in the sections that follow.

Figure 2 shows that no articles were published the first two years (1984-1985) and very few (3 or less per year) were published afterwards until 2001. (This proves that the 30+ year range is reasonably complete as we had assumed.) Publications continued to fluctuate at a low level until 2005, after which the numbers of articles begin to rapidly increase, reaching a peak in 2013 of 43 articles. (As of 30 April 2014, 7 articles have been published so far in 2014. This number is expected to grow throughout the year.)

Figure 3 shows the number of citations per year since 1984. This analysis is based on the Citations per Publications (CPP) listed in the Journal Citation Reports (JCR) on the Web of Science. CPP is defined as the ratio of the number of citations the publication has received to the length of time since publication. It is used to assess the impact of a journal relative to current publications on similar topics. These results show that the interest in BAV research has grown rapidly over the last two decades with

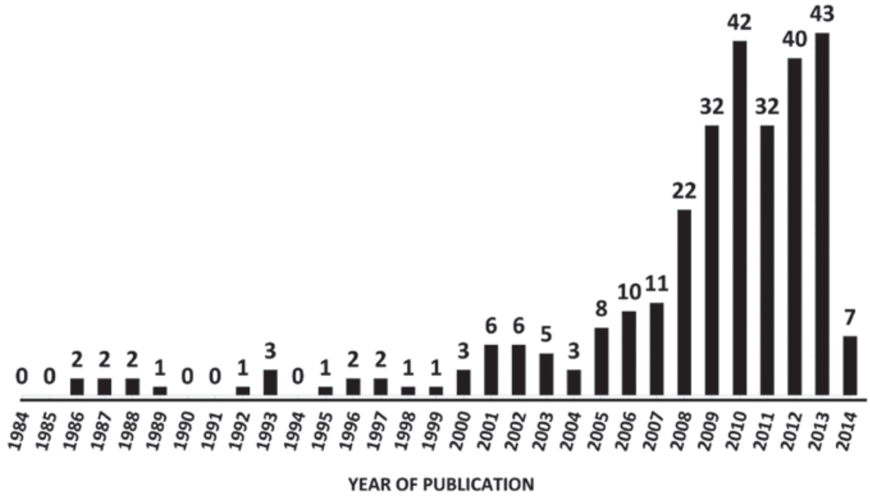


Figure 2 Number of journal article publications per year

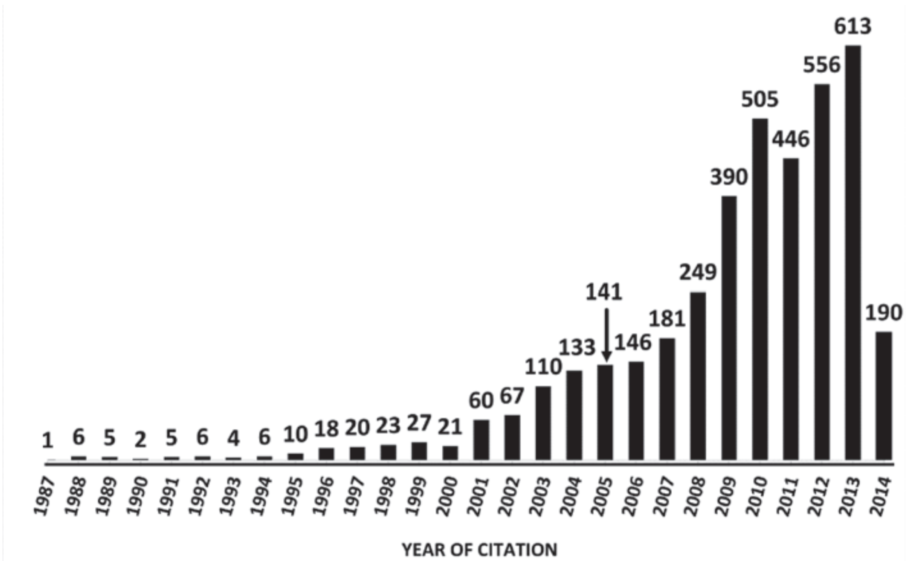


Figure 3 Number of BAV journal article citations per year

no signs of abatement. Although the number of citations started with a low amount, they rapidly began to increase in 2001 and grew to a peak of 613 in 2013. By the end of April 2014 there were 190 citations of BAV articles.

The 288 journal articles on BAV can be further classified into specific topical categories. This was done by (once again) reviewing the content of all the journal articles (shown in Figure 2) and determining the primary focus of research in each article. In a small number of cases, when uncertainties in categorizing an article occurred, inquiries were made from other experts until a consensus on categorization was made. The primary categories determined from this analysis are: (i) aerodynamics; (ii) guidance and control systems; (iii) mechanisms; (iv) structures and materials; and (v) system design. Some of these categories can be further divided into subcategories. The percentages of articles associated with each category are shown in Figure 4.

A summary review of the articles in each of the categories is discussed in Sections 2.1 to 2.5. Due to the large number of papers, it is impractical to systematically discuss each of the 288 articles individually. Therefore only a representative sample of articles is referenced (spanning across the entire 30+ year range) in order to give the readers an understanding of the progress and state of the art of research in these categories.

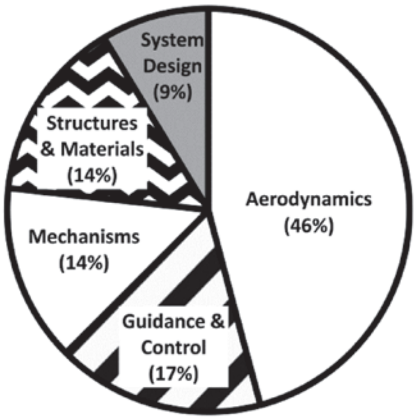


Figure 4 Subject categorization of BAV journal publications

2.1 Aerodynamics

This is the most popular category, with 46% of the journal articles primarily focused on elements of BAV (flapping wing) aerodynamics. As the popularity of this category suggests, it is a critical research area for the development of BAV and many challenges are involved. Conventional steady state aerodynamic theories are insufficient to predict the physical phenomenon of flapping wings. Also experimental studies of the complex vortices and flow patterns associated with flapping wings are less understood and more difficult to measure than traditional fixed wing or rotor propelled aircraft. The publications can be divided into four subtopics (Figure 5): theory; experimental analysis; computational modeling (e.g. computational fluid dynamics), combined experimentation and modeling, and propulsive performance analysis.

The objective of many early researchers was to explain the aerodynamic phenomena governing the flight of birds (Berg et al, 1995 [16], Spedding, 1996 [17]). Measurement of wing motion was generally obtained from stereophotogrammetry of multiple still photographs using a high speed camera. It was discovered that birds flex, bend, and rotate their wings in complex maneuvers throughout flight to adapt to changing conditions. Birds and bats generally operate in the $10^4 < Re < 10^6$ flight regime range, where slight disturbances have a great effect on flow separation and turbulence transition. Vortex induced unsteady flows dominate this regime. In one article, Particle Image Velocimetry (PIV) measurements were used to identify three distinct types of vortices generated across the chord length of a flapping wing. These were the leading edge vortex (which occurs at the leading edge of the wing) and the translational and rotational stopping vortices which both occurred at the trailing edge of the wing (Kurtulus et al, 2008 [18]).

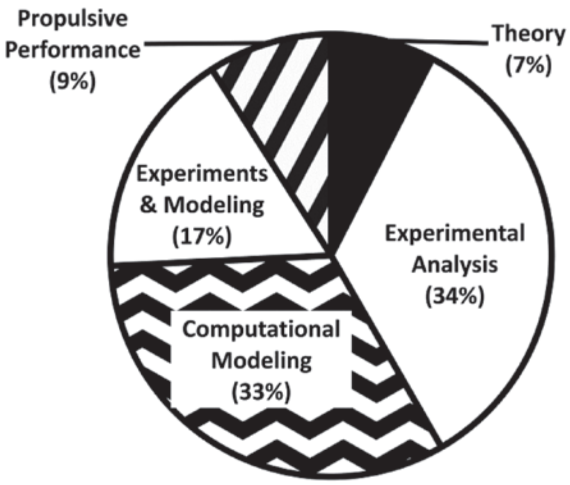


Figure 5 Aerodynamic subcategories

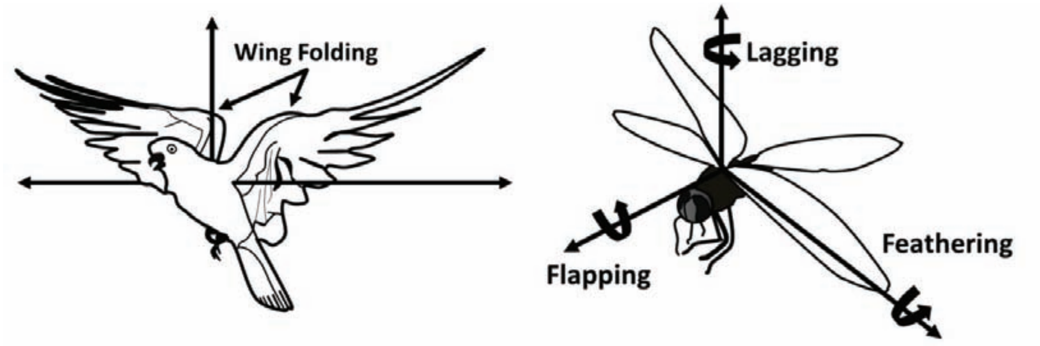
This complex flow is very difficult to model. Because of this, early work (some predating our 1984 cut-off date) used a quasi-steady model in which the wing flapping frequency was assumed to be slow enough to avoid shedding large wakes (Weis-Fogh et al, (1959) [19], Weis-Fogh (1973) [20], Lighthill, (1973) [21], Betteridge et al, 1974 [22]); Norberg, 1985 [23]). While a slow wing beat frequency may be a reasonable approximation for some (generally large) birds; it is an inaccurate assumption for insects, small birds (e.g. hummingbirds), or BMAV. They fully operate in an unsteady state flow regime that cannot be predicted by quasi-steady models (Karpelson et al, 2010 [24]). Several articles show the heavy dependence that the leading edge vortex has in generating lift and thrust. One article proposed a method of estimating the aerodynamic forces by adding the mass of the vortex wake sheets, similar to Prandtl's momentum theory for a fixed wing (Sunada, 2001 [25]). Another example, involving the flight of fruit flies, showed that these forces depend only on five non-dimensional parameters: Reynolds number, flapping stroke amplitude, flapping mid-stroke angle of attack, wing rotation duration, and a rotation timing (Wu, 2004 [26]). In another article, flow is modeled by numerically solving the Navier Stokes equation for incompressible flow. The algorithm uses the artificial compressibility method, employing a third-order flux difference splitting technique for the convective terms and a second-order central difference for the viscous terms (Tang, 2001 [27]).

Figure 5 shows that of the 288 articles examined about one-third (34%) focus solely on flapping wing aerodynamics experimentation (Hu et al, 2010 [28], Phillips et al, 2013 [29]). This percentage rises to approximately half (51%), when considering the articles (17%) that contain both experimental analysis and computational modeling. A few articles (7%) present analytical theories that can be used to model unsteady flows (Wang et al, 2010 [30]). Approximately one-third of the articles (33%) present computational models that account for unsteady flow effects (DeLaurier, 1993 [31]; Smith, 1996 [32], Zhu et al, 2014 [33]). These articles employ a variety of analytical and numerical methods to do this. As already mentioned, many of these articles (17%) also present experimental measurements as a means of assessing the accuracy of their computational models (Tuyen et al, 2013 [34]). When these are considered, the percentage of computational model articles is approximately half of the total number of aerodynamics articles (50%). A few articles (9%) specifically examine the aerodynamic effects of flapping wings on propulsive performance (e.g., lift, thrust, and drag) (Mueller et al, 2010 [35], Mahardika et al, 2011 [36]).

The aerodynamics of flapping wings is clearly a mature category of research. Over the three decades examined, many researchers have made critical contributions to the worldwide body of knowledge on this topic. Articles have been published from many different analysis perspectives (e.g. experimentation, theory, computational modeling, etc.), creating a rich source of knowledge that is expanding each year. Even so, more research is needed because the topic is very complex. It can be expected that more breakthroughs will result, as diagnostic equipment and computational tools advance.

2.2 Guidance and control systems

The second most popular category of articles (17%) is guidance and control (Figure 5). Flight stability and maneuverability of flying organisms depend primarily on wing motion and secondly on the motion of other body parts (e.g. tail, legs, abdomen, thorax, etc.) (Yates, 1986 [37], Sane et al, 2001 [38], Taylor, 2002 [39]). These control surfaces give the organism the ability to perform precise aerodynamic maneuvers. Wing movement can generally be defined by four degrees of freedom (DOF): spanning, lagging, feathering, and flapping. Spanning involves the span-wise folding of the wings during flapping (Figure 6a). This reduces the wing span on the upstroke and expands it on the downstroke. Therefore the induced forces (e.g. lift and drag) on each upstroke are reduced relative to the downstroke, giving a positive net lifting (and thrusting) force for each complete flapping cycle (downstroke plus upstroke). Although some insects, with relatively low wing beat frequencies (about 20 Hz) are capable of restricted spanning, this motion is generally limited to bird or bat flight (Lewitowicz et al, 2008 [40]). The other three wing DOF are applicable to all flying organisms (Figure 6b). Flapping and feathering are the primary motions that allow flight, although it has been shown that some butterflies use only flapping (Tanaka, 2010 [41]). Flapping creates the large aerodynamic pressure differentials that generate lift and thrust. Feathering movements change the pitch of the wing. Lagging movements enable specialized maneuvering, such as hovering.



(a) Spanning in bird flight (b) Common rotational wing DOF

Figure 6 Degrees of freedom for the wings of flying organisms

The types of control systems applied to each wing DOF on a BAV are defined as: active, passive or semi-active. Active control directly moves a control surface (e.g. by an actuator) using energy extracted from an onboard power source. Birds and bats are vertebrates with muscles connected to a wing bone structure, allowing them to actively control their wing span and rotational wing DOF. This enables them to simultaneously obtain lift and thrust during the flapping downstrokes. In contrast, insects are invertebrates with muscles attached to an external skeleton. This allows them to actively control flapping and feathering during upstrokes and downstrokes. Insects use many different and complex wing motions that widely vary between species.

Although flying organisms commonly employ active control of their wing DOF, this is not possible for most BAV (Dickingson, 2007 [42]). Living organisms derive energy from complex and integrated sets of natural biological systems that rely upon food digestion and air respiration as their raw feed sources. In contrast, all current BAV designs must rely upon non-biological onboard power supplies. Most of these (especially BMAV) use electrical power sources (e.g. battery, chemical reaction systems, etc.). These sources have a much lower power-to-weight ratio than natural biological systems. This places comparatively higher size and weight restrictions on BAV designs.

BAV generally operate by actively controlling the flapping DOF. The other DOF (spanning, feathering, and lagging) may be passively or semi-actively controlled to reduce power consumption. Passive control does not require any energy extraction from a power source. It is achieved by coupling motion of one DOF with another that is being actively controlled. This means that passive control cannot be utilized independently on each DOF like active control (Arabagi, 2013 [43]). Semi-active control is also not utilized independently. However, some aspects can be controlled independent of the active controlled DOF to which it is coupled. One example that has been investigated involves first passively coupling the wing's feathering DOF to the active controlled flapping DOF, then varying the wing joint's stiffness using a tunable impedance system. The feathering DOF is semi-actively controlled by adjusting the impedance without any effect on the flapping DOF (Byl, 2010 [44]).

Several articles experimentally analyze or mathematically model the flight dynamics of a BAV in order to design an automatic control system (Krashanitsa et al, 2009 [45], Sunata et al, 2010 [46]). Several articles examine flapping kinematics to optimize the induced forces (lift and thrust) (Rakotomamonjy et al, 2007 [47], Gopalakrishnan et al, 2009 [48]). Insects generally flap their wings at the resonance frequency of their wing-body system to maximize energy efficiency. Articles have been written applying this phenomenon to a BAV (Isogai et al, 2009, [49]).

Although a few articles discuss using onboard sensors for altitude, position, or orientation feedback (Duhamel, 2013 [50], Rifaïa, 2013 [51]), there are very few articles on guidance, as compared to control. This is an area that will require more research as BAV development continues to progress.

2.3 Mechanisms

BAV mechanisms include the mechanical power source and the linkages to transmit this power to move the wings. This is a growing research category that accounts for 14% of the 288 publications considered. Most of the early work focused on BOAV and many biological studies of bird and bat mechanics have been done (Muijres et al, 2011 [52]; Nudds et al, 2009 [53]). However, BMAV research

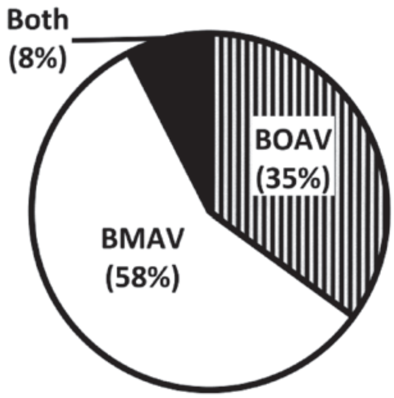


Figure 7 Mechanism articles subcategorized by vehicle type

has greatly expanded (especially over the past decade) and now constitutes the majority of the articles published (Figure 7).

Figure 8 shows six subcategories of mechanisms: biological mechanics studies, motor and micromotor, piezoelectric wings, piezoelectric actuator, power enhancing, and other miscellaneous topics. Biological mechanics studies are the largest subcategory of with 43%. The majority of these studies examine how the flapping wing mechanics of organisms can be applied to BAV mechanisms (Zhang et al, 2008 [54]; Vazquez, 1992 [55]). Others study specific BAV mechanisms with the intention of bio-mimicking bird and insect wing joints. (DeLaurier et al, 1993 [56]; Galiński et al, 2005 [57]).

The second most popular subcategory (28%) is related to motors or micromotors. Motors are used primarily for large-scaled BAV mock-ups designed to study wing joint kinematics (George et al, 2012 [58]). Most of the articles on BOAV and some large BMAVs (less than 10 grams), examine the use of micromotors in the design of flyable systems (Gerdes et al, 2012 [9]; Hines et al, 2014 [59]; Yang et al, 2009 [60]). These motors are similar to those commonly used in mobile phones to make them vibrate. However, since insects have sub-gram masses bio-mimicking them necessitates a much lighter piezoelectric like mechanical power sources (Mateti et al, 2013 [61]). Figure 8 shows that 23% of the articles focus on either piezoelectric actuated wing mechanisms or wings that include piezoelectric material themselves (Chung et al, 2008 [62]; Kummari et al, 2010 [63]). Piezoelectric actuators provide compact and lightweight mechanical power, but require mechanical amplification due their small displacement output (Chung et al, 2009 [64]; Truong, 2011 [65]).

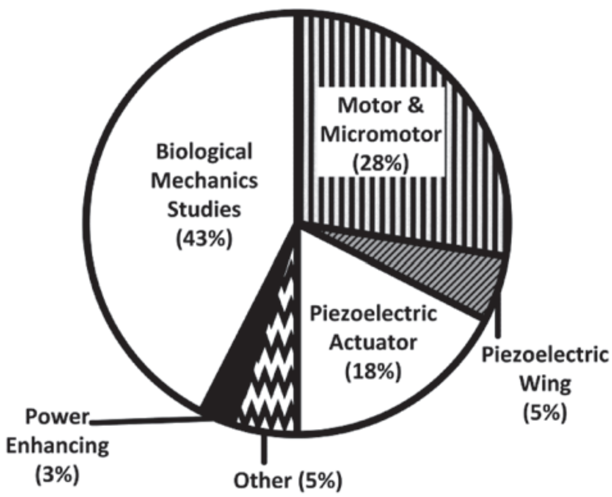


Figure 8 Mechanism articles subcategorized by mechanical power source

Specialized electronics are required to provide the high voltage piezoelectric input. Many insects store energy in their exoskeleton or other body parts which can be used to enhance the wing's propulsive efficiency. Mechanisms that can incorporate power-enhancing materials (typically elastic) account for 3% of the articles. These articles give further insight into how to use these materials effectively (Hollenbeck, 2012 [66]). Although there are several conference papers on mechanisms powered by thermoelectric materials or a capacitive muscle-like power source, few journal articles deal with them (Karpelson, 2008 [67]). It is expected that journal article publications will follow within the next few years, as these technologies produce more substantial research.

As mechanisms become smaller and require greater precision, it is expected that new techniques will be employed. The "Others" subcategory (which accounts for 5% of the articles) encompasses this broad area of research. Microelectromechanical System (MEMS) techniques are especially attractive as a means to obtain miniaturized, precision components. MEMS techniques, such as patterning precise structures out of SU-8, allow implementation of small insect parts (like a thorax joint) or fine structures (like an insect wing) (Dargent, 2009 [68]). As new ultra-lightweight mechanical power sources such as electro active polymers (Mukherjee et al, 2010 [69]) become available, it is expected that more research will focus on the electrical and mechanical subsystems needed to implement these power sources.

2.4 Structures and materials

Research on new lightweight wing materials and structures is critical for BAV. This category accounts for 14% of the 288 publications considered. It is important to note that this list only accounts for structures or materials articles that specifically state application to BAV as the objective of the research. Additional articles may have the potential for BAV application (even though this is not the stated objective of the article), but quantifying these articles is outside the scope of this review. For example, research on materials is normally published in journals that cover a wide range of applications rather than solely BAV. This explains why only 2 of the 42 articles in this category can be subcategorized as primarily focusing on material aspects.

The first article in this category was not published until 1995. It examined the flapping wings of diving birds, establishing a proportional relationship between wing mass, size, and the torque needed for a desired angular acceleration (Vandenberg et al, 1995 [70]). Later articles studied how the bones and tissues of bird wings are able to cope with the torsional loads caused by flapping wings (DeMargerie, 2002 [71]).

Research on the wing structures of insects have primarily focused on dragonfly species. The effect of wing morphology and flapping kinematics on the aerodynamics of flight has been studied (Sudo et al, 1999 [72]). One article examined the flexibility of a dragonfly's wing as it passively deformed. This is regarded as one of the important mechanisms on improving BMAV flight. Data from stress relaxation experiments was used to characterize the biomaterial properties of insect wings (Bao et al, 2006 [73]). Another article studied the effect of spanwise flexibility on the thrust, lift and propulsive efficiency of an oscillating rectangular wing. It was discovered that a limited degree of flexibility improves these parameters, but too much will cause the wing tip to move out of phase with the root thereby diminishing the thrust (Heathcote et al, 2007 [74]). Researchers have successfully bio-mimicked several different artificial insect wings (less than 2 cm in length). Complex wing structures have been fabricated using photolithography to create a positive relief (Shang et al, 2009 [75]).

BAV materials research is relatively new and novel materials based on biopolymers are being studied in various institutions around the world. Design studies were performed on a four bar linkage mechanism that was used to drive a BMAV test article. A wing spar made from a carbon epoxy composite, was shown to be capable of dissipating inertial stress caused by high flapping frequencies. (Galinski et al, 2005 [76]). Another study used rubber-based flexures in the joints of their linkage system. This incorporated spring stiffness in the joints, which acted like energy storage elements to reduce the input power required to produce thrust (Sahai et al, 2013 [77]).

Unlike aerodynamics, research into structures or materials specifically for BAV is still at an early stage. Like the other categories, the subject of research has shifted from BOAV in the early years to BMAV in modern times. Breakthroughs have been made on structural designs that will improve the efficiency of BMAV wings. Photolithography methods have been developed to fabricate flexible insect-sized wings. It is expected that research on developing new bio-inspired wing membranes and frames will progress as new materials are synthesized.

2.5 System Design

System design accounts for the last 9% of the articles surveyed. There are a great number of approaches to the journal articles in this category. By using cameras to track selected points on the wings, multiple cameras can create a three dimensional reconstruction of the flight path, including wing deformations. Combining motion capture with a load cell measuring thrust, allows the flight to be characterized (Gerdes et al, 2013 [78]). 3D printing is a novel technology that allows the generation of biologically inspired thorax and hinge mechanisms from computer concepts (Bejgerowski et al, 2009 [79]). With 3D printing, numerous wing designs can be generated and modified while working toward an optimal system design (Richter et al, 2011 [80]). MEMS allow the incorporation of silicon wafer technologies to develop precise components such as joints (Meng et al, 2012 [81]). The most common approach to system design is to lay out a new design or upgrade an existing design based upon numerical analysis, like finite element analysis (FEA) (Tsai et al, 2009 [82]). A series of articles examines a mechanism that sandwiches a fixed wing surface in between two flapping wings (above and below). This mechanism is used to compare the air flow over fixed wings to the complex flows caused by adding the biologically inspired flapping wings (Jones et al, 2009 [83]). Gradient-based optimization of non-linear flapping wing structures allows for better tradeoffs between accuracy and computational efficiency when using finite element analysis to perform system design (Stanford et al, 2011 [84]). A simplifying approach of developing figures of merit can be very useful to aerospace engineers when they are trying to compare competing designs. A figure of merit that allows comparison of mechanical system efficiency to their biological counterparts is of great interest (Whitney et al, 2012 [85]). While a figure of merit that compares mechanical and biological flapping wing systems is very useful, it would also useful to compare BAV to other more established aerodynamic systems. As fully functional BAV systems are completed, the number of articles on system design will continue to increase.

3. RESULTS OF ANALYSIS

The 288 identified journal articles were analyzed by: publication year, journal, author (identifying organization and nation), funding source, number of citations, authorship specifications, topic category, and the biological organism studied (if specifically stated). This analysis shows the chronological growth of BAV research and the technological challenges which still remain. It can be used as guide toward future BAV research and its applications.

3.1 Distribution of articles by journal

The distribution of articles by journal is shown in Table 1. Only the top ten journals by percentage of total publications (288 articles) are shown. The top journal with 29% of the articles on BAV is the *American Institute of Aeronautics and Astronautics (AIAA) Journal*. An AIAA journal (*Journal of Aircraft*) also places third with 16% (tied with *Experiments in Fluids*). Both of these journals publish

Table 1 Distribution of articles by journal

	Article (%)	Journal
1)	29 %	*AIAA Journal*
2)	20 %	*Journal of Experimental Biology*
3)	16 %	*Experiments in Fluids*
	16 %	*Journal of Aircraft*
4)	11 %	*Bioinspiration & Biomimetics*
5)	10 %	*International Journal of Micro Air Vehicles*
6)	8 %	*Aeronautical Journal*
	8 %	*IEEE Transactions on Robotics*
	8 %	*Journal of Bionic Engineering*
	8 %	*Journal of Fluid Mechanics*

‡ *Thomson Reuters ISI Web of Science quartile journal ranking*

aerospace engineering related articles. The *Journal of Experimental Biology* is second with 20%. The combination of engineering and biology journals in this table shows the diversity of perspective analysis of BAV articles. The table also shows the Institute for Scientific Information (ISI) Thomson-Reuters quartile ranking of each of these journals as listed in the Web of Science. This quartile ranking is based on the SCImago Journal Rank (SJR) which calculates the prestige of each journal (on a three year cycle).

3.2 Distribution of articles by authoring organization

The distribution of journal article publications by the submitting author organization is partially shown in Table 2. (It is important to note that some articles include co-authors with multiple affiliations; however this table considers only the submitting organization listed in the Web of Science.) A complete

Table 2 Distribution by submitting author organization

No. Articles	Authoring Institution	Country
19	• United States Air Force	• United States
15	• Konkuk University	• South Korea
13	• Cranfield University	• United Kingdom
11	• University of Maryland	• United States
10	• Harvard University	• United States
9	• University of Delaware • Virginia Polytechnic Institute and State University	• United States • United States
8	• Beihang University • Seoul National University	• China • South Korea
7	• University California Berkeley • University of Michigan	• United States • United States
5	• Cornell University • Delft University of Technology • Nanyang Technological University • Nippon Bunri University • Shanghai Jiao Tong University • United States Navy • University of Poitiers	• United States • Netherlands • Singapore • Japan • China • United States • France
4	• Brown University • Carnegie Mellon University • Chinese Academy of Science • Korea Advanced Institute of Science and Technology • Kyoto University • New York University • Pierre-and-Marie-Curie University • Sungkyunkwan University • Tohoku University • University of Cambridge • University of London • University of Science and Technology of China • University of Tokyo • University of Toronto	• United States • United States • China • South Korea • Japan • United States • France • South Korea • Japan • United Kingdom • United Kingdom • China • Japan • Canada

list consists of 92 organizations, so for brevity only those with four or more publications are shown in this table. This table shows that the largest numbers of articles were authored by a non-academic organization: the US Air Force (primarily by the US Air Force Research Laboratory). The most productive academic organization was Konkuk University in South Korea, followed by Cranfield University in the United Kingdom. The University of Maryland and Harvard University have produced the largest number of academic articles in the United States.

The complete list of 92 authoring organizations was used to generate Figure 9. This figure shows the distribution of the countries of the authoring organizations. This figure shows that authoring organizations from the United States produced 40% of all the articles on BAV. Organizations from Japan, South Korea, and the United Kingdom each produced 11% of the articles. Organizations from China produced 8% and France produced 4%. The remaining 15% of the articles were authored by: Germany, Singapore, Netherlands, India, Canada, Australia, Turkey, Iran, Sweden, Russia, Italy, and Poland.

Figure 9 Countries of authoring organizations

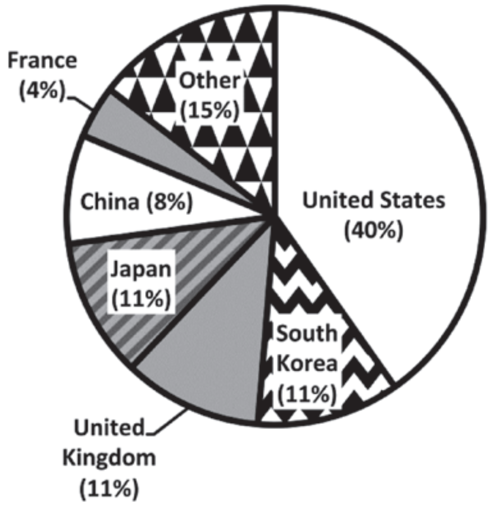


Table 3 shows the academic organizations that have authored recent article publications (2012-2014). Figure 2 shows that there are a total of 90 articles in this year range. Only the top ten organizations by percentage of publications authored within the year range are shown. This percentage is compared to the overall percentage (out of 288 articles) covering the entire 30+ year range (1984-2014). A comparison of Tables 2 and 3 indicates that some past prolific authors (e.g. University of Delaware, Virginia Polytechnic Institute and State University, Beihang University, Seoul National University, etc.), have regressed in recent years. A high percentage for both recent and overall articles in Table 3 (e.g. Konkuk University, University of Maryland, Harvard University), indicates a mature ongoing research program that consistently publishes articles. A high percentage of recent articles but low percentage overall (e.g. Carnegie Mellon University, Kyoto University, Delft University of Technology), implies that the research program is either new or has undergone a recent increase in output. There are a number of possible reasons that could account for this increase (higher prioritization, research breakthroughs, more postgraduate students, increased funding, new sponsorship etc.), but it is impossible to identify these unique reasons from the data available.

Table 3 Top authoring academic organizations for recent publications (2012-2014)

Rank	Articles (%) 2012 - 2014	1984 - 2014	University	Country
1)	7.6 %	5.1 %	Konkuk University	South Korea
2)	5.4 %	3.8%	University of Maryland	United States
3)	4.3 %	3.4 %	Harvard University	United States
4)	4.3 %	1.4 %	Carnegie Mellon University	United States
	4.3 %	1.4 %	Kyoto University	Japan
5)	3.3 %	2.4 %	University of Michigan	United States
6)	3.3 %	1.7 %	Delft University of Technology	Netherlands
7)	3.3 %	1.4 %	Drexel University	United States
	3.3 %	1.4 %	Sungkyunkwan University	South Korea
8)	2.2 %	4.4 %	Cranfield University	United Kingdom

3.3 Distribution by non-academic funding sources

The distribution of journal article publications by non-academic funding sources (e.g. research grants) is shown in Table 3. This list excludes internal funding from the colleges, academies or universities (where the academic research may have been performed). The table shows that the split between government and private research funding is evenly divided. Government funding sources account for 51% (46) and private funding 49% (44).

Sources from the United States made the largest impact with 41 articles (46%). The US Department of Defense (DoD) sponsored a total of 22 (25%) articles. These articles were sponsored by the Air Force Office of Scientific Research, Army Research Laboratory, and the Office of Naval Research. Additionally, two articles were funding by the American Society for Engineering Education under the Science, Mathematics and Research for Transformation (SMART) scholarship for service program. This program aims to increase the number of civilian scientists and engineers working at DoD laboratories. Thus of all non-academic sources listed in Table 4, the US military has made the largest single impact in BAV research. The US-based National Science Foundation and the Wyss Research Institute also made significant impacts.

Funding from South Korean sources has made the second largest impact with 31 articles (34%). Two government ministries within the South Korean government sponsored most of these journal article publications. The National Research Foundation of Korea also made a considerable impact. Other funding sources come from Japan, the United Kingdom, Sweden, and China.

Table 4 Distribution by non-academic funding sources

Articles	Funding Source	Type	Country	Years
17	• National Science Foundation • Air Force Office of Scientific Research • Ministry of Education, Science and Technology	• Foundation • Military • Government	• United States • United States • South Korea	• 2008-14 • 2010-13 • 2010-13
12	• National Research Foundation of Korea	• Foundation	• South Korea	• 2011-14
5	• Ministry of Education, Science, Culture and Sports • Engineering and Physical Sciences Research Council	• Government • Research Council	• Japan • United Kingdom	• 2010-12 • 2008-12
3	• US Army Research Laboratory	• Military	• United States	• 2009-10
2	• American Society for Engineering Education - SMART program • Knut and Alice Wallenberg Foundation • Ministry of Trade, Industry and Energy • National Natural Science Foundation of China • US Office of Naval Research • Swedish Research Council • Wyss Institute	• Non-profit • Foundation • Government • Foundation • Military • Research Council • Research Institute	• United States • Sweden • South Korea • China • United States • Sweden • United States	• 2013 • 2011 • 2011 • 2012-14 • 2009-13 • 2011 • 2012-13

3.4 Distribution by flying biological organism

Many of the journal articles focus on studying a particular bird, bat, or insect. The biological journal articles focus on gaining an understanding of the anatomical mechanisms necessary for flapping wing flight. Therefore they were included and appropriately categorized in Figure 4. All of the engineering articles examined directly relate to some aspect of the BAV categorizations. Many of these articles attempt to mimic a particular flying organism. So it is important to examine which organisms are being studied and this is shown in Figure 10. [Note: there are also many articles that do not specify a particular organism, but instead look at a broad class of flying organisms in which to biomimic. Because they are not specific, these articles are not included in Figure 10.]

Figure 10 shows that insects are the most popular organisms studied (in 89.6% of the articles examined). Birds account for only 6.6% and bats only 3.8% of the articles examined. Of all the insects, hawk moths (also called Sphingidae) account for 44% of the articles. Hawk moths are a popular subject of study because they are readily accessible, with 1,450 species scattered throughout the world. They are known for their flying speed and endurance. Bio-mimicry of hawk moths is of interest because they are relatively large, so have a capacity to carry a lot of weight due to their large wing surface areas. They are also popular because there is a rich resource of studies of them in which to draw upon (Hollenbeck et al, 2012 [66]).

Dragonflies are the focus of 23% of the articles. They are characterized by two pairs of long wings and an elongated body. They are of interest because of their versatility in being able to either hover or fly at high speeds. They have a relatively high wing beat frequency (50-60 Hz) enabling them to be one

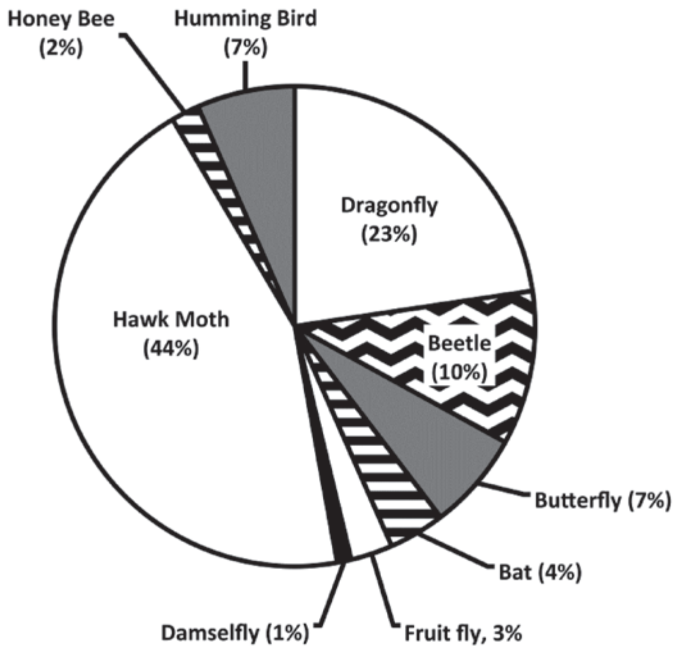


Figure 10 Flying organisms studied

of the fastest flying insects in the world (Wakeling et al, 1997 [86]). Bio-mimicry of these abilities into a BMAV is highly desired. Also damselflies, which account for 1% of the articles, have many similarities to dragonflies.

Although beetles are not as active at flying as moths or dragonflies, they have been the subject of 10% of the articles. This is because they are large and heavy and therefore more akin to the size and weight limitations imposed on many BMAV researchers. For example, the *Allomyrina dichotoma* beetles generally weigh between 6 to 10 grams and have a wingspan of 13 cm (Nguyen et al, 2010 [87]). Fruit flies and bees have been studied and modeled in order to understand the unsteady aerodynamics that allows them to maneuver and hover [Wu et al, 2004 [26]; Zhang et al, 2008 [54]). Bees are of particular interest due to their very high lift-to-weight ratio; which is due to their ultra-high wing beat frequency (about 200 Hz).

The primary vertebrates examined are hummingbirds and bats. Hummingbirds are of interest due to their small size and high wing beat frequency (40-50 Hz), which enables them to hover. In contrast, bats are of interest due to their low wing beat frequency (10 Hz) and short wing span (low aspect ratio) giving them superb maneuverability (Furst et al, 2012 [88]).

As can be observed from this review, these organisms were selected for bio-mimicry study either due to desired qualities such as velocity or maneuverability; or to account for BAV limitations such as size, weight, or low wing beat frequencies. Therefore the numbers and variety of bio-mimicry species can be expected to increase as technological challenges are overcome and research expands to new regions of the world to encompass new species.

CONCLUSIONS

This comprehensive bibliometric review clearly shows that research into BAV have greatly expanded in the past 30+ years. In the early years, the focus was primarily on understanding how organisms fly from a biological research perspective. However as research interest in BAV grows and develops the focus is shifting to biomimetic engineering analysis. The number of research publications began to increase in 2005 and is rapidly growing today. The general focus of these articles can be categorized as: aerodynamics, guidance and control, mechanics, structures and materials, and system design. Aerodynamics accounts for the vast majority of the articles. The primary challenge is the complexity of dealing with unsteady flows. Researchers focused on guidance and control are faced with the difficulties of bio-mimicking organisms that primarily use active control, with less energy demanding semi-active and passive controls. Mechanisms are becoming more miniaturized as MEMS processes are applied. Structures research has focused on examining the mass, torque, and flexibility of wing designs. New biomaterials are being studied to create lightweight and flexible wings. System engineers are studying a variety of new methods to design and fabricate BAV. Figures of merit are being developed in order to compare and optimize these designs.

BAV research is now being done at universities around the world. Currently most of this research is occurring in the United States, South Korea, Japan, the United Kingdom, and China. The top authoring universities are: Konkuk University in South Korea; Cranfield University in the United Kingdom; and the University of Maryland and Harvard University, which are both in the United States. Research is funded by several sources including: the National Science Foundation; the US Air Force Office of Scientific Research; the South Korean Ministry of Education, Science and Technology; and the National Research Foundation of Korea. Although most of the articles are authored by university based researchers, there are a large number of articles authored by the US DoD (primarily at the US Air Force Research Laboratories). Although many flying organisms have been studied as the subjects of bio-mimicry, hawk moths and dragonflies remain the most popular for application into BMAV. However, this may change as BAV research continues to expand throughout the world.

ACKNOWLEDGMENTS

This article was written under the auspices of the Center for Transportation Research at the Faculty of Engineering, University of Malaya. The authors are thankful to University of Malaya for financial support under the High Impact Research MoE Grant: UM.C/625/1/HIR/MoE/ENG/53 (D000053-16001) from the Ministry of Education, Malaysia and the University of Malaya Research Grant: RG155-12AET.

REFERENCES

[1] Michelson, R., (2002) Chapter 24 in Ayers, J., Davis, J., and Rudolph, A. (Eds.), Neurotechnology for Biomimetic Robots, Massachusetts Institute of Technology

[2] Götz, K. G., Hengstenberg, B., and Biesinger, R., (1979) Optomotor control of wing beat and body posture in drosophila, *Biological Cybernetics*, 1979, 35, 101-112.

[3] Lorez, M., (1995) Neural control of hindleg steering in flight in the locust. Journal of Experimental Biology, 198, 869-875.

[4] Maxworthy, A., (1981) The fluid dynamics of insect flight, *Annual Review of Fluid Mechanics*, 13, 329-350

[5] Sane, S., (2003) The aerodynamics of insect flight, *Journal of Experimental Biology*, 206, 4191-4208

[6] Wang, Z., (2005) Dissecting insect flight, *Annual Review of Fluid Mechanics*, 37, 183-210

[7] Wu, T., (2011) Fish swimming and bird/insect flight, *Annual Review of Fluid Mechanics*, 43, 25-58

[8] Pines, D. J. and Bohorquez, F., (2006) Challenges Facing Future Micro-Air-Vehicle Development, *Journal of Aircraft*, 43, 290-305

[9] Mayo, D. and Leishman, J., (2010) Comparison of the Hovering Efficiency of Rotating Wing and Flapping Wing Micro Air Vehicles, *Journal of the American Helicopter Society*, 55, 25001

[10] Gerdes, J., Gupta, S., and Wilkerson, S., (2012) A Review of Bird-Inspired Flapping Wing Miniature Air Vehicle Designs, *Journal of Mechanisms and Robotics*, 4, 021003

[11] Karásek, M. and Preumont, A., (2012), Flapping Flight Stability in Hover: A Comparison of Various Aerodynamic Models, *International Journal of Micro Air Vehicles*, 4, 203-226

[12] Chen, C. Tang, Y., Wang, H. and Wang Y., A Review of Fabrication Options and Power Electronics for Flapping-Wing Robotic Insects, *International Journal of Advanced Robotic Systems*, 10, 1-12

[13] Michelson, R. and Reece, S., (1998) Update on flapping wing micro air vehicle research, Ongoing work to develop a flapping wing, crawling "Entomopter", 13th Bristol International RPV Conference, Bristol, United Kingdom

[14] Wood, R. (2007), Liftoff of a 60mg flapping-wing MAV, Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, CA, USA

[15] Keennon, M., Klingebiel, K., Won, H., and Andriukov, A., (2012) Development of the Nano Hummingbird: A tailless flapping wing micro air vehicle, 50^{th} Aerospace Sciences Meeting, Nashville, TN, USA, AIAA 2012-0588

[16] Berg, C. and Rayner, J., (1995) The moment of inertia of bird wings and the inertial power requirement for flapping flight, *Journal of Experimental Biology*, 198, 1655 –1664.

[17] Spedding, G. R., (1996) The Wake of a Kestrel (Falco Tinnunculus) in Flapping Flight, *Journal of Experimental Biology*, 127, 59 –78.

[18] Kurtulus, D. F., David, L., Farcy, A., and Alemdaroglu, N., (2008) Aerodynamic characteristics of flapping motion in hover, *Experiments in Fluids*, 44, 23-36.

[19] Weis-Fogh, T. and Jensen, M., (1956) Biology and physics of locust flight. i. Basic principles in insect flight. A critical review, Philosophical Transactions of the Royal Society B: *Biological Sciences*, 239, 415-458

[20] Weis-Fogh, T., (1973) Quick estimates of flight fitness in hovering animals, including novel methods for lift production, *Journal of Experimental Biology*, 59, 169-230

[21] Lighthill, M., (1973) On the Weis-Fogh mechanism of lift generation, *Journal of Fluid Mechanics*, 60, 1-17

[22] Betteridge, D. S. and Archer, R. D., (1974) A study of the mechanics of flapping wings, *Aeronaut* Q, 129-142.

[23] Norberg, U. M., (1985) Evolution of vertebrae flight, an aerodynamic model for the transition from gliding to active flight, *Am Naturalist*, 126, 303-327

[24] Karpelson, M., Whitney, J. P., Gu-Yeon, W., and Wood, R., J., (2010) Energetics of Flapping-Wing Robotic Insects: Towards Autonomous Hovering Flight, Proceedings from the IEEE/RSJ International Conference on Intelligent Robots and Systems, 1630-1637.

[25] Sunada, S., and Ellington, (2001) A new method for explaining the generation of aerodynamic forces in flapping flight, *Mathematical methods in the applied sciences*, 24, 1377-1386.

[26] Wu, J. H., and Sun, M., (2004) Unsteady aerodynamic forces of a flapping wing. *Journal of Experimental Biology*, 207, 1137-1150.

[27] Tang, J, and Sun, M., (2001) Force and flow structures of a wing performing flapping motion at low Reynolds number, *Acta mechanica*, 152, 35-48.

[28] Hu, H, Kumar, A. G, Abateb, G., and Albertanic, R., (2010) An experimental investigation on the aerodynamic performances of flexible membrane wings in flapping flight, *Aerospace Science and Technology*, 14, 575–586.

[29] Phillips, N., and Knowles, K., (2013) Formation of vortices and spanwise flow on an insect-like flapping wing throughout a flapping half cycle, *The Aeronautical Journal of the Royal Aeronautical Society*, 117, 471-490.

[30] Wang, X. X., and Wu Z., N., (2010) Stroke-averaged lift forces due to vortex rings and their mutual interactions for a flapping flight model, *Journal of Fluid Mechanics*, 654, 453–472.

[31] DeLaurier, J. D., (1993) An aerodynamic model for flapping-wing flight, *The Aeronautical Journal of the Royal Aeronautical Society*, 97, 125-130.

[32] Smith, M., (1996) Simulating Moth Wing Aerodynamics: Towards the Development of Flapping-Wing Technology, *AIAA Journal*, 34, 1348-1355.

[33] Zhu, J. Y. and Zhou, C. Y., (2014) Aerodynamic performance of a two-dimensional flapping wing in asymmetric stroke, *Journal of Aerospace Engineering*, 228, 641-651.

[34] Tuyen Quang Le, Tien Van Truong, Hieu Trung Tran, Soo Hyung Park, Jin Hwan Ko, Hoon Cheol Park, Kwang Joon Yoon, and Doyoung Byun, (2013) Two- and Three-Dimensional Simulations of Beetle Hind Wing Flapping during Free Forward Flight, *Journal of Bionic Engineering*, 10, 316–328.

[35] Mueller, D., Bruck, H. A., and Gupta S. K, (2010) Measurement of thrust and lift forces associated with drag of compliant flapping wing for micro air vehicles using a new test stand design, *Experimental Mechanics*, 50, 725–735.

[36] Mahardika, N., Viet, N. Q., and Park, H. C., (2011) Effect of outer wing separation on lift and thrust generation in a flapping wing system, *Bioinspiration and Biomimetics*, 6, 036006.

[37] Yates, G. T., (1986) Optimum pitching axes in flapping wing propulsion, *Journal of Theoretical Biology*, 120, 255–276.

[38] Sane, S. P. and Dickinson, M. P., (2001) The control of flight force by a flapping wing: lift and drag production, *Journal of Experimental Biology*, 204, 2607-2626.

[39] Taylor, G. K. and Thomas, A. L., (2002) Animal flight dynamics II. Longitudinal stability in flapping flight. *Journal of Theoretical Biology*, 214, 351-70.

[40] Lewitowicz, J., Kowalczyk, G., Sibilski, K., and Zurek J., (2008) Modeling and Simulation of Flapping Wings Micro-Aerial-Vehicles Flight Dynamics, Proceedings from the 26th International Congress of the Aeronautical Sciences, ICAS 2008-5.9.1, 1-24.

[41] Tanaka, H. and Shimoyama, I., (2010) Forward flight of swallowtail butterfly with simple flapping motion, *Bioinspiration and Biomimetics*, 5, 026003.

[42] Dickingson, M., Lehmann, F.-O and Gotz, K. G., (1993) The active control of wing rotation by dorsophila, *Journal of Experimental Biology*, 182, 173-189.

[43] Arabagi, V., Hines, L., and Sitti, M., (2013) A Simulation and Design Tool for a Passive Rotation Flapping Wing Mechanism, IEEE/ASME Transactions on Mechatronics, 18, 787-798.

[44] Byl, K., (2010) A passive dynamic approach for flapping-wing micro-aerial vehicle control, ASME Dynamic Systems and Control Conference. American Society of Mechanical Engineers, DSCC2010-4289, 215-223.

[45] Krashanitsa, R. Y., Silin, D., Shkarayev, S. V., and Abate, G., (2009) Flight Dynamics of a Flapping-Wing Air Vehicle, *International Journal of Micro Air Vehicles*, 1, 35-49.

[46] Sunada, S., Hatayama, Y., and Tokutake, H., (2010) Pitch, Roll, and Yaw Damping of a Flapping Wing, *AIAA Journal*, 48, 1261-1265.

[47] Rakotomamonjy, T., Ouladsine, M., and Le Moing, T., (2007) Modelization and Kinematics Optimization for a Flapping-Wing Microair Vehicle, *Journal of Aircraft*, 44, 217-231.

[48] Gopalakrishnan, P. and Tafti, D., (2009) Effect of Rotation Kinematics and Angle of Attack on Flapping Flight, *AIAA Journal*, 2009, 47, 2505-2519.

[49] Isogai, K., Kamisawa, Y., and Sato, H., (2009) Resonance Type Flapping Wing for Micro Air Vehicle, Transactions of the Japan Society for Aeronautical and Space Sciences, 52, 199-205.

[50] Duhamel, P., (2013) Biologically Inspired Optical-Flow Sensing for Altitude Control of Flapping-Wing Microrobots, *IEEE/ASME Transactions on Mechatronics*, 18, 556-568.

[51] Rifaïa, H., Guerrero-Castellanosa, J. F., Marchanda, N. and Poulin-Vittrant, G., (2013) Biomimetic-based output feedback for attitude stabilization of a flapping-wing micro aerial vehicle, *Robotica*, 31, 955-968.

[52] Muijres, F., Spedding, G., Winter, Y. and Hedenström, A., (2001) Actuator disk model and span efficiency of flapping flight in bats based on time-resolved PIV measurements, *Experiments in Fluids*, 51, 511-525.

[53] Nudds, R. and Dyke, G., (2009) Forelimb Posture in Dinosaurs and the Evolution of the Avian Flapping Flight-Stroke, *International Journal of Organic Evolution*, 63, 994-1002.

[54] Zhang, G., Sun, J., Chen, D. and Wang, Y., (2008) Flapping motion measurement of honeybee bilateral wings using four virtual structured-light sensors, Sensors and Actuators A: *Physical*, 148, 19–27.

[55] Vazquez, R. J., (1992) Functional osteology of the avian wrist and the evolution of flapping flight, *Journal of Morphology*, 211, 259-268.

[56] DeLaurier, J. D. and Harris, J. M., (1993) A study of mechanical flapping wing flight, *Aeronautical Journal*, 97, 277-286.

[57] Galiński, C. and Zbikowski, R., (2005) Insect-like flapping wing mechanism based on a double spherical Scotch yoke, *Journal of the Royal Society*, 2, 223–35.

[58] George, R. B., Colton, M. B., Mattson, C. A., and Thomson, S. L., (2012), A Differentially Driven Flapping Wing Mechanism for Force Analysis and Trajectory Optimization, *International Journal of Micro Air Vehicles*, 4, 31-49.

[59] Hines, L., Campolo, D. and Sitti, M., (2014) Liftoff of a Motor-driven, Flapping Wing Micro Aerial Vehicle Capable of Resonance, *IEEE Transactions on Robotics*, 30, 220–232.

[60] Yang, L., Hsu, C., Han, H. and Miao, J., (2009) Light Flapping Micro Aerial Vehicle Using Electrical-Discharge Wire-Cutting Technique, *Journal of Aircraft*, 46, 1866–1874.

[61] Mateti, K., Byrne-Dugan, R., Rahn, C. D. and Tadigadapa S. A., (2013) Monolithic SUEX Flapping Wing Mechanisms for Pico Air Vehicle Applications, *Journal of Microelectromechanical Systems*, 22, 527-535.

[62] Chung, H. and Kummari, K., (2008) Coupled piezoelectric fans with two degree of freedom motion for the application of flapping wing micro aerial vehicles. Sensors and Actuators A: *Physical*, 147, 607-612.

[63] Kummari, K. L., Li, D., Guo, S. and Huang, Z., (2010) Development of piezoelectric actuated mechanism for flapping wing micro-aerial vehicle applications, *Advances in Applied Ceramics*, 109, 175-179.

[64] Chung, H., Kummari, K. L., Croucher, S. J., Lawson, N. J., Guo, S., Whatmore, R. W. and Huang, Z., (2009) Development of piezoelectric fans for flapping wing application, Sensors and Actuators A: *Physical*, 149, 136–142.

[65] Truong, Q., Nguyen, Q., Park, H. C., Byun, D. Y. and Goo, N. S., (2011) Modification of a four-bar linkage system for a higher optimal flapping frequency, *Journal of Intelligent Material Systems and Structures*, 22, 59-66.

[66] Hollenbeck, A. C. and Palazotto, A. N., (2012) Methods Used to Evaluate the Hawkmoth (Manduca Sexta) as a Flapping-Wing Micro Air Vehicle, International *Journal of Micro Air Vehicles*, 4, 119-132.

[67] Karpelson, M., Wei, G. Y. and Wood, R. J., (2008) A review of actuation and power electronics options for flapping-wing robotic insects, IEEE International Conference on Robotics and Automation, 978-1-4244-1647-9/08, 779–786.

[68] Dargent, T., Bao, X., Grondel, S., Le Brun, G. L., Paquet, J. B., Soyer, C. and Cattan, E., (2009) Micromachining of an SU-8 flapping-wing flying micro-electro-mechanical system, *Journal of Microengineering*, 19, 085028.

[69] Mukherjee, S. and Ganguli, R., (2010) A dragonfly inspired flapping wing actuated by electro active polymers, *Structures and Systems*, 6, 867-887.

[70] Van Den Berg, C. and Rayner, J. M. V., (1995) The Moment Of Inertia Of Bird Wings And The Inertial Power Requirement For Flapping Flight, *The Journal of Experimental Biology*, 198, 1655–1664.

[71] DeMargerie, E., (2002) Laminar bone as an adaptation to torsional loads in flapping flight, Anatomical Society of Great Britain and Ireland, *Journal of Anatomy*., 201, 521–526.

[72] Sudo, S., Tsuyuki, K., Ikohagi, T., Ohta, F., Shida, S., and Tani, J., (1999) A Study on the Wing Structure and Flapping Behavior of a Dragonfly, *JSME International Journal*, Series C, 42, 721-729.

[73] Bao, L., Hu J., Yu, Y., Cheng, P., Xu, B., and Tong, B., (2006) Viscoelastic constitutive model related to deformation of insect wing under loading in flapping motion, *Applied Mathematics and Mechanics*, 27, 741-748.

[74] Heathcote, S., Wang, Z., and Gursul, I., (2008) Effect of Spanwise Flexibility on Flapping Wing Propulsion, *Journal of Fluids and Structures*, 24, 183–199.

[75] Shang, J. K., Combes, S. A., Finio, B. M. and Wood, R. J., (2009) Artificial Insect Wings of Diverse Morphology for Flapping-wing MAVs, *Bioinspiration and Biomimetics*, 4, 036002.

[76] Galinski, C. and Zbikowski, R., (2007) Materials challenges in the design of an insect-like flapping wing mechanism based on a four-bar linkage, *Materials and Design*, 28, 783–796.

[77] Sahai, R., Galloway, K. C., and Wood, R. J., (2013) Elastic Element Integration for Improved Flapping-Wing Micro Air Vehicle Performance, 2013, *IEEE Transactions of Robotics*, 29, 32-41.

[78] Gerdes, J., Cellon, K., Bruck, H., and Gupta, S., (2013) Characterization of the mechanics of compliant wing designs for flapping-wing miniature air vehicles, *Experimental Mechanics*, 53, 1561-1571.

[79] Bejgerowski, W., Gupta, S., Ananthanarayanan, A. and Mueller, D., (2009) Integrated product and process design for a flapping wing drive mechanism, *Journal of Mechanical Design*, 131, 061006.

[80] Richter, C. and Lipson, H., (2011) Untethered hovering flapping flight of a 3D-printed mechanical insect, *Artificial Life*, 17, 73-86.

[81] Meng, K., Zhang, W., Chen, W., Li, H., Chi, P., Zou, C., Wu, X., Cui, F., Liu, W, and Chen, J., (2012) The design and micromachining of an electromagnetic MEMS flapping-wing micro air vehicle, *Microsystem Technologies*, 18, 127-136.

[82] Tsai, B. and Fu, Y., (2009) Design and aerodynamic analysis of a flapping-wing micro aerial vehicle, *Aerospace Science and Technology*, 13, 383-392.

[83] Jones, K., and Platzer, M., (2009) Design and development considerations for biologically inspired flapping-wing micro air vehicles. *Experiments in Fluids*, 46, 799-810.

[84] Stanford, B. and Beran, P., (2011) Cost reduction techniques for the design of non-linear flapping wing structures, *International Journal for Numerical Methods in Engineering*, 88, 533-555.

[85] Whitney, J. P. and Wood, R. J., (2012) Conceptual design of flapping-wing micro air vehicles, *Bioinspiration and Biomimetics*, 7, 036001

[86] Wakeling, J. M. and Ellington, C. P., (1997) Dragonfly flight: II. Velocities, accelerations and kinematics of flapping flight, *Journal of Experimental Biology*, 200, 557-582.

[87] Nguyen, Q. V., Park, H. C., Goo, N. M., and Byun, D., (2010) Characteristics of a Beetle's Free Flight and a Flapping-Wing System that Mimics Beetle Flight, *Journal of Bionic Engineering*, 7, 77-86.

[88] Furst, S. J., Bunget, G., and Seelecke, S., (2012) Design and fabrication of a bat-inspired flapping-flight platform using shape memory alloy muscles and joints, *Smart Materials and Structures*, 22, 014011