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Challenges Facing Future Micro-Air-Vehicle Development

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Nomenclature

A_r = rotor disk area
C_D = sectional drag coefficient
C_{D0} = zero-lift drag coefficient
$C_{l\alpha}$ = lift-curve slope
C_P = power coefficient
C_{Pi} = induced power coefficient
C_{P0} = profile power coefficient
C_T = thrust coefficient
c = chord length
D = drag force
$D.L.$ = disk loading
L = lift force
m = mass
$P.L.$ = power loading
SF = separated flow
T = rotor thrust
V = local wind velocity perceived by flap
W = weight
W_f = final weight
W_o = gross takeoff weight
α = blade section angle of attack
η = efficiency
μ = dynamic viscosity
ρ = air density
σ = rotor solidity
Φ = flapping amplitude (peak to peak)

I. Introduction

ONE-HUNDRED years after the Wright Brother's first powered historic flight at Kitty Hawk, North Carolina, on 17 December 1903, aerospace engineers still face challenges in understanding and harnessing the physics of flight. Whereas the 20th century ushered in the era of manned atmospheric and spaceflight, it is likely that the 21st century will be characterized by the emergence of autonomous computer-controlled uninhabited flight. Driven by a host of civilian, homeland security, and military objectives, uninhabited air vehicles (UAVs) have emerged as the platform of choice for warfighters conducting survelliance and reconnaissance operations in hostile environments.

Because of their relatively low cost and propensity for providing accurate survelliance information, numerous UAV development programs have been initiated worldwide.[1,2] As indicated in Fig. 1, typical UAVs have wing spans greater than 1 m and gross takeoff weights (GTOW) greater than 5 kg. However, in the past decade a new class of UAV has emerged, which is at least an order of magnitude smaller in length and two orders of magnitude lighter in weight than previously developed aircraft. This new class of UAV is called a micro air vehicle (MAV) or sometimes referred to as a μUAV. These vehicles have been defined to have no length dimension greater than 6 in. with gross takeoff weights of approximately 200 g or less.

As a new class of air vehicle, these systems face many unique challenges that make their design and development difficult. For example, micro air vehicles operate in a very sensitive Reynolds-number regime. In this regime, many complex flow phenomena take place within the boundary layer. Separation, transition, and reattachment can all occur within a short distance along the chordline of a wing or rotor and can dramatically affect the performance of the lifting surface. Hence, designing vehicles that can efficiently fly in this flight regime represents an entirely new challenge to aerospace design engineers. In fact because of the lack of knowledge about the fundamental flow physics in this regime, the development of small-scale flying vehicles parallels the development of the practical powered aircraft developed by the Wright Brothers in 1903. After the initial development of the Wright Flyer, engineers and scientists struggled to develop analytical tools as well as gather enough experimental wind-tunnel and flight-test data to help develop better design tools that would improve the performance of fixed-wing aircraft. A similar trend is evolving in the development of small-scale mechanical flying machines. There are few if any analysis tools to help MAV designers accurately model the steady and unsteady environment that MAVs encounter while in flight.

Fortunately, the development of larger-scale UAVs over the past 30 years provides some insight and guidance into the anticipated performance of microscale fixed-wing and rotary-wing MAV designs. For instance, using data from previously developed UAVs, it is possible to extrapolate performance parameters such as endurance, wing span, payload mass, and range to much smaller scale lengths. Figure 2 illustrates such scaling trends for UAV payload weight and endurance vs GTOW. Surprisingly, over a broad range of UAV GTOW, the payload mass scales linearly on a log-log scale. Extending this linear scaling trend to a micro air vehicle with a weight of approximately 100 g provides a first guess of the potential payload weights for a small-scale fixed-wing mechanical

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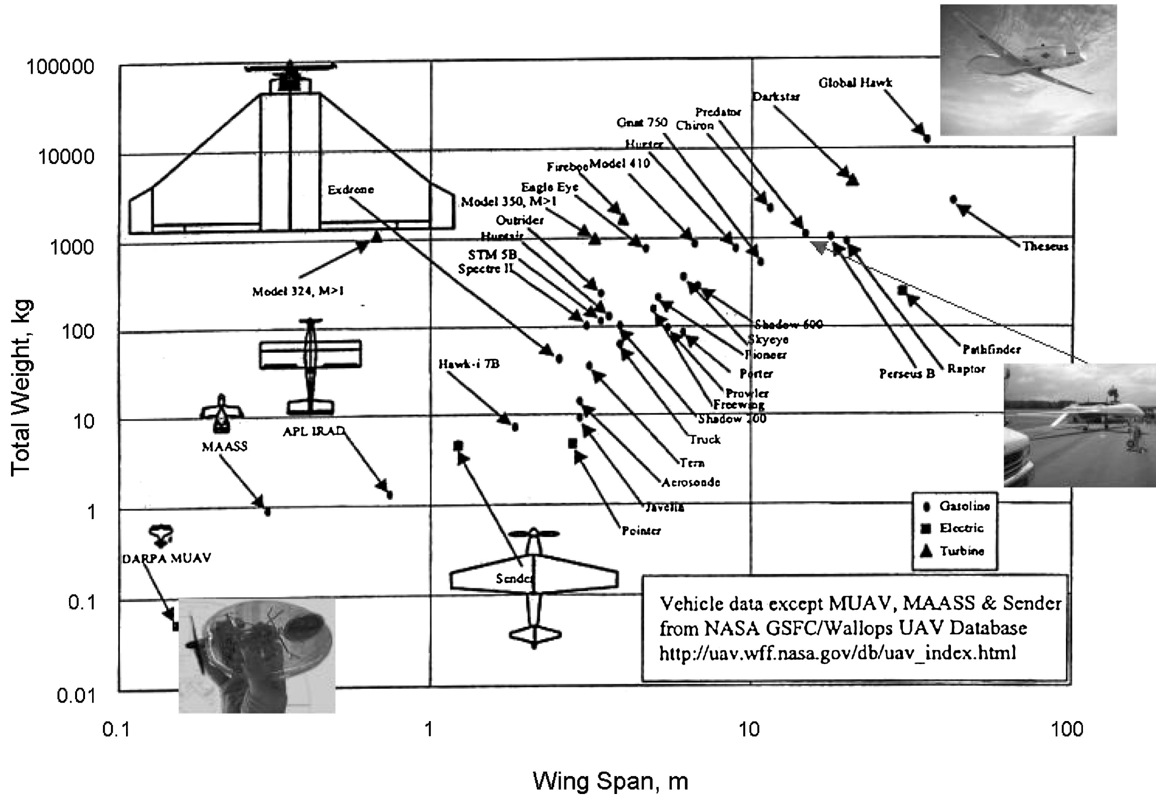


Fig. 1 Scale of uninhabited air vehicles.[2]

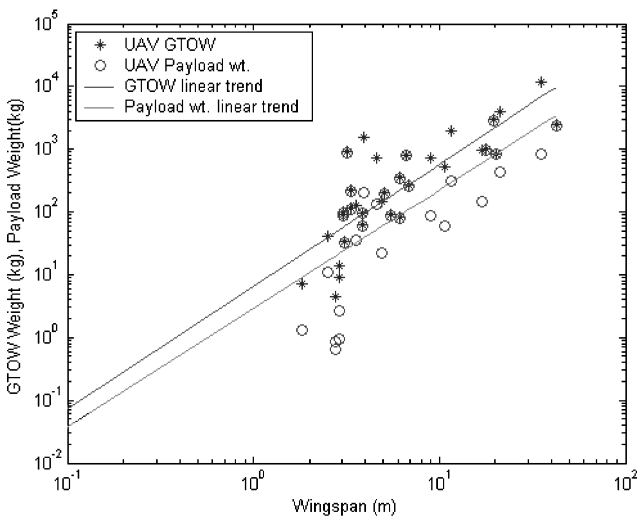


Fig. 2 UAV GTOW and payload weight vs wing span.

flyer. This scaling suggests an approximate payload weight of 10 g. Similarly, extending the linear curve fit for endurance provides some insight into expectations for the endurance of small-scale length fixed-wing UAVs. Fixed-wing UAV endurance data have a much greater scatter as efficiencies in propulsion and aerodynamics become more uncertain as size and weight decrease.

Although these scaling trends offer some insight into expected performance, data and design tools for small-scale aircraft [Wing spans <6 in. (15.24 cm)] are sparse. But aerospace scientists and engineers are not at a complete loss because nature has produced numerous biological flying machines that have evolved over millions of years to efficiently fly in the low-Reynolds-number regime (see the "Great Flight Diagram" in Fig. 3). However, achieving or exceeding the efficiency, maneuverability, and autonomous operation found in nature will be quite a challenge. This paper attempts to review the status in the development of this new class of air vehicle and discusses some emerging trends in technology that can lead to more efficient small-scale flying machines. In the next section the performance of fixed-wing and rotary-wing MAVs is reviewed. Section III discusses the three fundamental technical barriers that limit the performance of many of the MAVs discussed in Sec. II. Finally, Sec. IV discusses some emerging research trends that can improve the development of the next generation of autonomous small-scale flying machines.

II. Status of and Performance of Current MAVs

A. Evolution of Micro-Air-Vehicle Development

In the United States, the development of MAVs has been spearheaded by the Department of Defense's (DoD) need to develop autonomous, lightweight, small-scale flying machines that are appropriate for a variety of missions including reconnaissance over land, in buildings and tunnels, and other confined spaces. Of particular interest is the ability of these vehicles to operate in the urban environment[4–7] and perch on buildings to provide situational awareness to the warfighter. Following DoD's lead,* numerous national and international government agencies have initiated activities to develop small autonomous flying vehicles.

To establish guidelines for vehicle designs, an urban mission was assumed, and a set of baseline requirements was developed. These vehicle and mission performance requirements are summarized in Table 1. In addition to the requirements listed in this table, vehicles had to be compact, efficient, and simple to design and operate. To better understand these challenges, the next section attempts to compare the performance of various integrated micro-air-vehicle designs flying under their own power that have been developed under government-sponsored research programs.

*Data available online at http://www.aero.ufl.edu/~issmo/mav/info.htm.

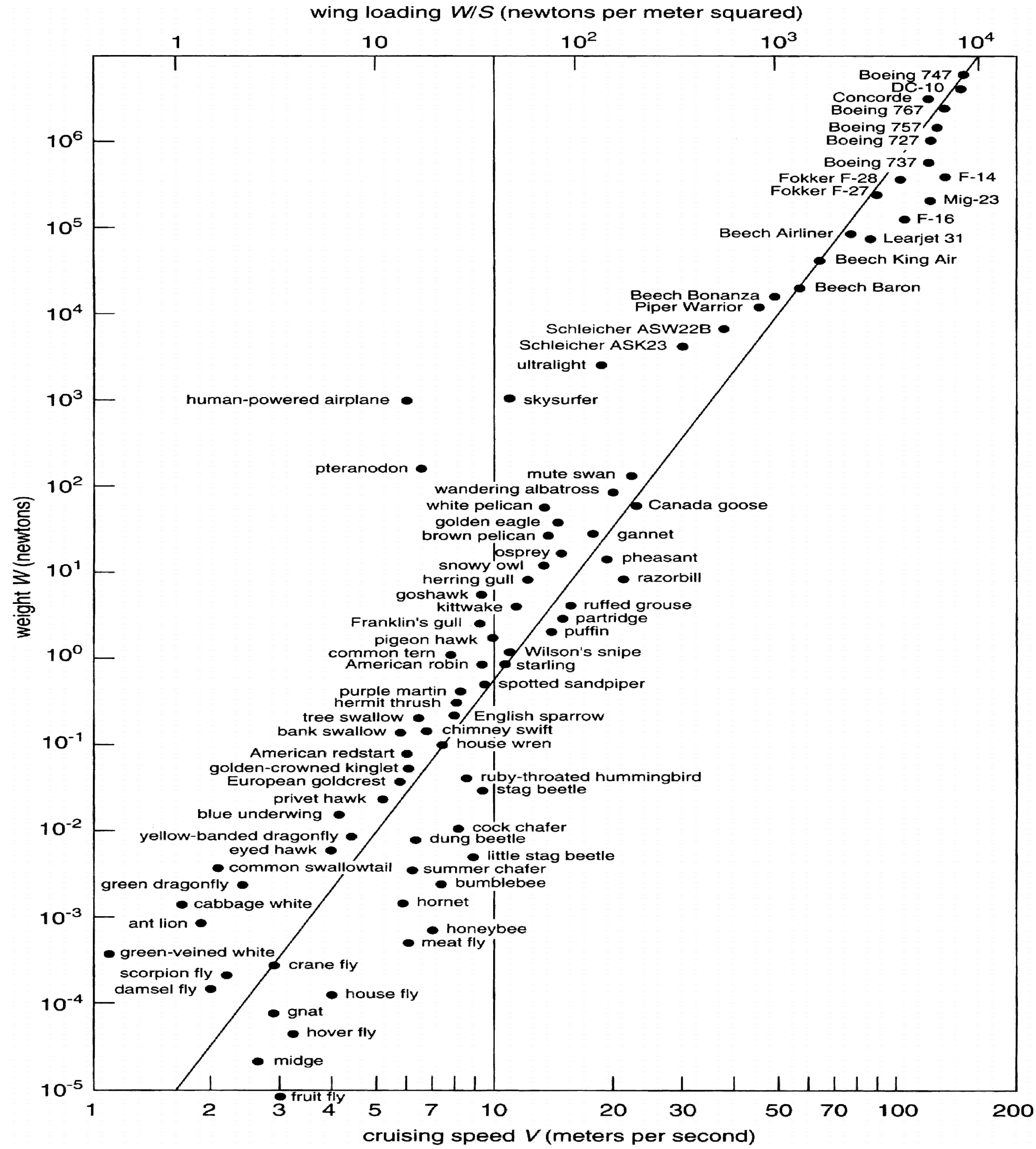


Fig. 3 Great Flight diagram.

Table 1 MAV design requirements

Specification	Requirements	Details
Size	<15.24 cm	Maximum dimension
Weight	~100 g	Objective GTOW
Range	1 to 10 km	Operational range
Endurance	60 min	Loiter time on station
Altitude	<150 m	Operational ceiling
Speed	15 m/s	Maximum flight speed
Payload	20 g	Mission dependent
Cost	$1500	Maximum cost

B. Performance of Micro-Air-Vehicle Designs

Table 2 summarizes some of the size, weight, and performance parameters of recent MAV designs flying under their own power (i.e., no tethered power). Data appearing in this table have been either estimated by the author or has been obtained from the literature.[8–15] A glance at this table reveals that the majority of current fixed-wing and rotary-wing designs rely on battery power for energy, conventional airfoil shapes for achieving lift, and propellers or rotors for achieving thrust. All, with the exception of Microbat, rely on conventional steady-state aerodynamic principles for generating thrust and lift. Similar to small insects and birds, CalTech/Aerovironment's Microbat uses flapping of its wings via an electric motor to generate thrust and lift, suggesting possibly a new paradigm shift in the design and development of future micro air vehicles. However, before we discuss this paradigm shift it is instructive to compare the performance of current MAV designs to their full-scale counterparts. Metrics of interest include fixed-wing vehicle endurance, vertical-takeoff-and-landing (VTOL) hover performance, and vehicle subsystem mass fractions.

1. *Fixed-Wing Endurance Performance*

The endurance for steady cruising flight of fixed-wing MAV designs powered by an internal combustion engine is given by

$$E = (\eta/c_f)\left(C_L^{\frac{3}{2}}/C_D\right)\sqrt{2\rho_\infty S}\left(1/\sqrt{W_f} - 1/\sqrt{W_o}\right) \qquad (1)$$

where S is the wing surface area, η is the propeller efficiency, c_f is specific fuel consumption, and C_L and C_D are the vehicle's lift and drag coefficients, respectively. Because the endurance of a vehicle is inversely proportional to the power required to maintain steady level

Table 2 Design and performance parameters of some representative MAVs[8–15]

Vehicle properties	Black Widow (Aerovironment)	Hoverfly (Aerovironment)	LUMAV (Auburn Univ.)	MicroStar (Lockheed-Martin)	Microbat (CalTech)	MICOR (UMD)
GTOW, g	80	180	440	110	10.5	103
Cruise speed, m/s	13.4	15–20	5	13.4–15.6	5	2
Wing loading, N/m^2	40.3	——	——	70.9	40	——
Disk loading, N/m^2	——	70	185	——	——	25
Wing span or rotor diameter, cm	15.24	18	15.24	22.86	15.24	15.24
Max L/D	6	N/A[a]	N/A	6	N/A	5
Endurance, min	30	13.2	20	25	2 min 16 s	3
Hover endurance	N/A	7.3	N/A	N/A	N/A	3
Power source	Lithium-ion batteries	Lithium-ion batteries	2-stroke IC engine	Lithium-ion batteries	Sanyo NiCad N-50 cells	Lithium-ion batteries
Energy density, W-h/kg	140	140	5500 methanol	150	100	150
Hover power, W	N/A	24.5	70	N/A	N/A	11
Hover FM	N/A	0.39	0.41	N/A	N/A	0.55

[a]N/A = not available.

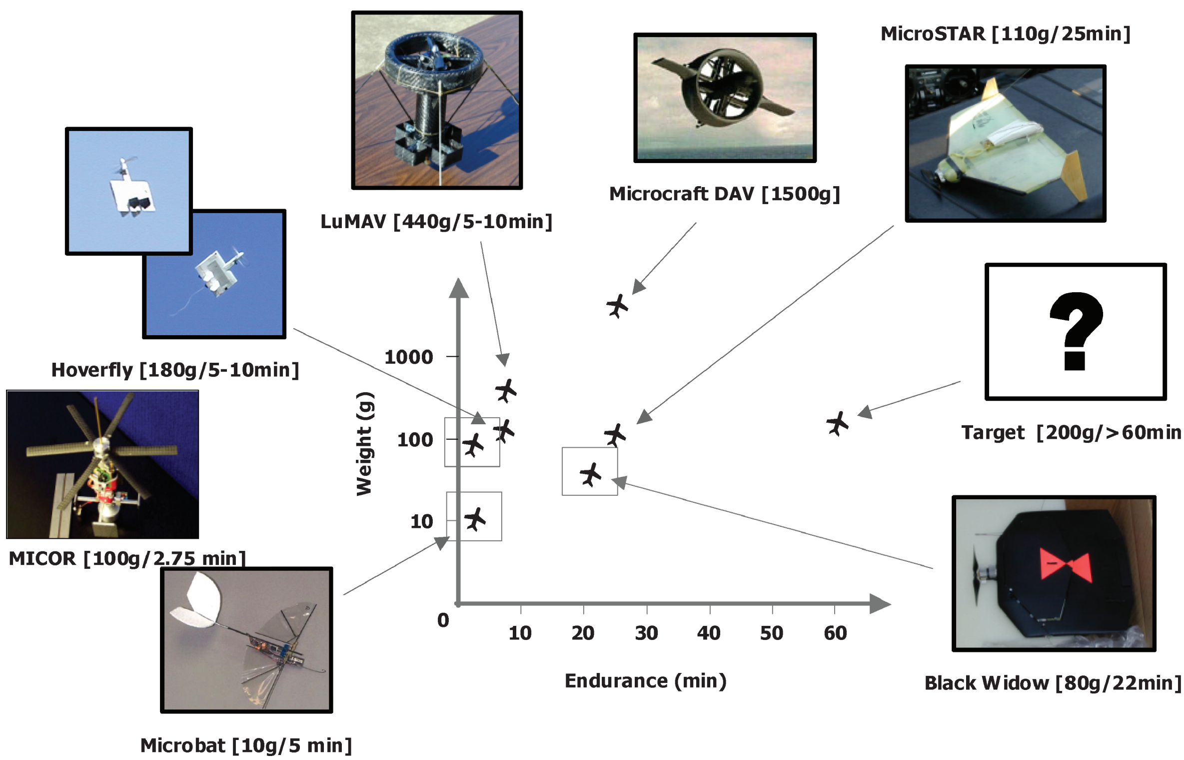


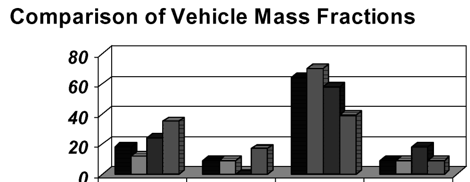
Fig. 4 Endurance or hover time of current MAVs.

flight, it is important to minimize the power required to increase the endurance. This suggests that from Eq. (1) one would like to have high wing loading, high lift coefficient, low drag coefficient, high propeller efficiency, and fly as low as possible. Although it is difficult to find all of these parameters for existing fixed-wing MAV designs, it is still possible to compare the endurance performance based on measured flight times. Figure 4 displays the GTOW weight of various MAV designs vs endurance or maximum hover time. Although these represent substantial progress in the field, the fact that none has been able to achieve true long-loiter times (>60 min) or efficient hovering flight is a testament to the difficulty of flying extended missions with small vehicles. Careful inspection of these vehicle designs reveals a variety of technical challenges for aerospace design engineers. For example, a detailed breakdown of the mass fractions of three of these vehicles reveals a number of shortcomings when compared to full-scale systems. Figure 5 displays the mass fractions of three microflyers compared to a full-scale Boeing 767 commercial jetliner. Notice that for the small-scale flyers the mass fraction of the propulsion system (batteries/power and motor/transmission) is in excess of 60% of the total vehicle mass. In contrast a jetliner has a propulsion/fuel system mass fraction of approximately 40%. It appears that this 20% savings at full scale is used entirely for payload because the payload mass fraction is 29% for the 767 and just 9% for the University of Maryland's MICOR (Micro Coaxial Rotorcraft) and CalTech/Aerovironment's Microbat, respectively. Additionally, there is a wide variation in the mass fraction of the structure required to support flight of the three small-scale vehicles compared in Fig. 5.

2. *Rotary-Wing/VTOL MAV Hover Performance*

In the case of rotary-wing/VTOL designs, another metric of interest is hover efficiency. Although the hover performance of more conventional full-scale rotorcraft configurations is well documented in the literature, the hover performance of micro "hovering" air vehicles in hover at low Reynolds numbers is relatively unknown.[16,17,†]

[†]Data available online at http://www.faulhaber.de.



	Structure	Payload	Fuel/Propulsion	Electronics/Avionics
Black Widow	18	9	64	9
MICOR	12	9	70	9
Microbat	24	0	58	18
Boeing 767	35	17	39	9

Fig. 5 Mass fraction of MAVs compared against a Boeing 767.

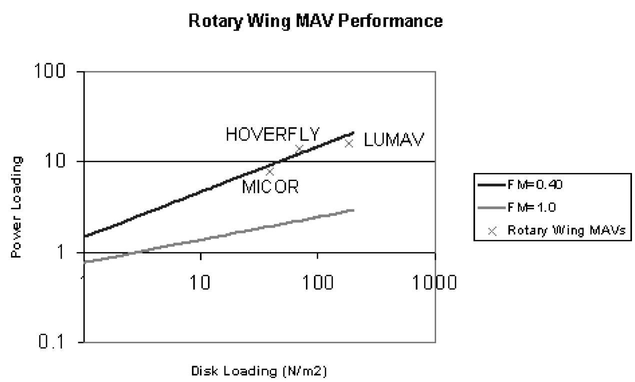


Fig. 6 Rotary-wing MAV performance.

To compare the hover performance of various rotary-wing and VTOL MAV designs, it is important to examine the metric for comparing hover efficiency. This is accomplished by comparing the actual power required to hover with the ideal power required to hover.[18] This leads to the rotor figure of Merit (FM) given by

$$\mathrm{FM} = \frac{\text{ideal power}}{\text{actual power}} = \frac{Tv}{P} \tag{2}$$

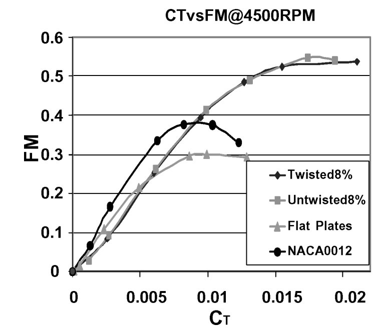
where P is power supplied to the rotor and v is the rotor induced velocity. The larger the value of FM, the smaller the power required to produce a given thrust, or the larger the thrust per unit power. For an ideal rotor FM should equal 1. By rearranging Eq. (3), it is not difficult to derive the following equation relating power loading to rotor disk loading from simple momentum theory:

$$P.L. = 0.638\left(\sqrt{D.L.}\middle/\mathrm{FM}\right) \tag{3}$$

where $P.L.$ (Power/Thrust) is power loading and $D.L.$ (Thrust/Disk Area) is disk loading. This expression measures the aerodynamic and power efficiency of hovering vehicles.

Figure 6 plots $P.L.$ vs $D.L.$ for the three hovering MAV configurations (Kolibri, Hoverfly, MICOR) listed in Table 2. Upper- and lower-bound limits are illustrated for figure-of-merit values of 0.40 and 1.0. Those vehicle designs lying above the curve for a FM = 0.40 require more power to stay aloft and are therefore less efficient than other hovering designs. For the designs considered in this study, it appears that MICOR has the lowest power loading for a given disk loading at this scale length. However, it is instructive to examine the vehicle's figure of merit vs various thrust coefficients. This is displayed in Fig. 7. Notice that in comparison to full-scale rotorcraft, MICOR's 8% cambered airfoils achieve at best a FM value of 0.55 (Ref. 19). Full-scale rotors achieve FM values in the range from 0.65 to 0.85. In a full-scale rotor 30% of the power is consumed by the profile losses and 70% by the induced losses. However, at low Reynolds numbers the profile power has a much larger influence over the total power required by the rotor. At high

Fig. 7 Figure of merit vs thrust coefficient.



thrust coefficients the contribution of profile power goes up to 45%. In addition, section lift-to-drag ratios for typical airfoil geometries tend to range from 2 to 8. Thus, scale size, airfoil design, thickness, and surface roughness appear to have a significant effect on the hover perform-ance of micro rotary wing designs. Hence, MAV designers are faced with significant challenges as length scale decreases.

In terms of efficient MAV design, several technical questions remain unanswered. For example, is it possible that MAV designers can improve the overall efficiency and performance of MAVs? Are there lessons to be learned by studying the efficiency of biological flyers? Unlike subsonic fixed-wing aircraft with their steady, almost inviscid flow dynamics, biological flyers such as insects and small birds fly in a sea of vortices when they flap their wings. These vortices can be used to keep MAVs aloft, especially in the case of hovering flight. Recently, it has been demonstrated by computational-fluid-dynamics (CFD) analysis[20] that bumblebees flap their wings in a complex kinematic figure-eight pattern to generate lift and thrust. Similarly, hummingbirds are well-known masters of hovering flight by flapping their wings in excess of 20 Hz.

Closer examination of biological fliers reveals that existing MAV designs cannot match the aerodynamic performance (stability, maneuverability, and efficiency) of insects and small birds. This should come as no surprise because design tools at this scale of flight are not available. In addition, the underlying physics that are responsible for the achievements of nature's great flyers is still not well understood. For example, how an insect can take off backwards, fly sideways, and land upside down[21] cannot be explained using conventional aerodynamic theory. It appears that insect wings produce lift more efficiently than one would expect based on conventional steady-state aerodynamic theory.[22–25]

III. Fundamental Physics Limiting MAV Performance

One of the greatest challenges for researchers is determining how insects and small birds can generate forces that can range from 2 to 12 times their body weight. Conventional steady-state aerodynamic theory is unable to explain this phenomenon. Thus, something about the complexity of the wing pitching/plunging/lagging motion increases the lift produced by a wing above and beyond that which it could generate under steady flow conditions or that can be predicted by conventional steady-state aerodynamic theory. The reasons for this remain research topics, but some conclusions are emerging. Recent work by experimental biologists indicates that the pitching/plunging motion of the insect wing can improve efficiency by enabling the recovery of wake vorticity.[26] Other studies indicate that birds can increase their aerodynamic efficiency via large-scale morphing of their wing geometries.[27] A remarkably wide range of changes can be affected including variations in anhedral, dihedral, planform, camber, aspect ratio, wing sweep, and wing warping.

Given that the performance of the current generation of MAVs is vastly inferior to that of birds, insects, and even full-scale UAVs, it seems logical that subsequent generations of MAVs could improve their performance by mimicking at least some aspects of biological flight. Thus, if MAVs are to approach and possibly exceed the performance of biological flyers, advances are required in several fundamental areas including 1) low-Reynolds-number aerodynamics ($<4 \times 10^4$), 2) lightweight and adaptive wing structures, 3) energy storage/conversion to useful power/propulsion, and 4) insect-like flight navigation, guidance, and control. The status of the first three areas is reviewed next.

A. Low-Reynolds-Number Aerodynamics

The aerodynamics of MAV flight is affected by the scaling of the Reynolds number Re, which is the ratio of inertial to viscous forces in a fluid. For conventional steady-state aerodynamics, Re is defined as the product of a characteristic airfoil chord length and velocity divided by the dynamic viscosity μ of the fluid and is defined by the following relationship:

$$Re = \rho V c / \mu \tag{4}$$

The Reynolds number characterizes the nature of the flow conditions over a body immersed in a fluid. To understand this important relationship, one simply needs to examine the range of Reynolds number that applies to biological systems. Nachtigall[28] postulated that the flow properties of biological creatures might be divided into three regimes. The first regime is dominated by viscous forces, as small organism attempt to propel themselves by wiggling through the fluid. The third regime is dominated by inertial effects that lead to the characteristic wake of a body moving through a fluid. The second regime is the most difficult as insects and small birds tend to generate vortices to stay aloft and move through a fluid. This is the same flight regime in which most micro-air-vehicle designs reside. Thus, for a given wing at a given Mach number, one is interested in maximizing the lift-to-drag ratio (L/D). This is often taken as a measure of a wing's overall aerodynamic efficiency. This ratio is highly dependent on not just wing geometry, but also the given flow conditions over the airfoil. Thus, for any airfoil the lift-to-drag ratio can be written as a nonlinear function of Reynolds number given by

$$L/D = f(Re) \tag{5}$$

In 1980 McMasters and Henderson[29] found that the maximum lift-to-drag performance of various airfoils vs Reynolds numbers dramatically changed for $Re < 10^5$. In their studies they found that at low Reynolds-numbers (in the flight regime of birds, insects, and MAVs), smooth airfoils perform worse than rough airfoils (see Fig. 8). However, at $Re > 10^5$ the performance of smooth airfoils greatly improves. This was primarily because of the underlying highly viscous laminar flow physics present at low Reynolds numbers.[30] A more recent study by Baxter and East[31] in this Reynolds-number regime, steady-state aerodynamic analysis reveals that as the Reynolds number decreases the minimum power condition for straight and level cruising flight can be approximated by

$$C^2_{L\,\mathrm{min\,Power}} = \left(3C_{d_o}/b\right)(Re_{\mathrm{ref}}/Re)^{0.5} \tag{6}$$

where Re_{ref} is the reference Reynolds number value of 10^5. Thus, it can be seen from this expression that as the Reynolds number decreases the profile drag increases. Baxter concluded that the minimum drag-minimum power configuration of MAVs requires vehicles with lift coefficients in excess of three. These results indicate that as the profile drag coefficient increases relative to the induced drag coefficient, the operating C_L at which minimum drag and minimum power are obtained are significantly higher than those required at more conventional flight Reynolds numbers ($>10^5$). Similar to fixed-wing airfoil studies, rotary-wing rotor aerodynamics suffer from the same flow physics that limit the performance of fixed-wing MAVs. In a recent study by Bohorquez et al.,[19] blade element momentum theory (BEMT) coupled with a uniform inflow model was used to determine the two-dimensional lift and drag properties of several simple airfoil shapes at a tip $Re = 3 \times 10^4$. They found that estimated maximum rotor lift-to-drag ratios ranged from 4 to 10 (see Fig. 9). In addition, they found that the profile drag for rotor blades at $Re < 3 \times 10^4$ constitutes a higher percentage of the total power required to hover than found in full-scale rotors. Preliminary CFD and fluorescent oil-based flow-visualization experiments (see Fig. 10) revealed large-scale flow separation with only a fraction of the rotor having attached flow. This is largely because the flow in this regime is laminar, but also unstable and tends to separate easily from the surface of airfoils. This is because the low inertial forces in the fluid boundary layer render it unable to stay attached

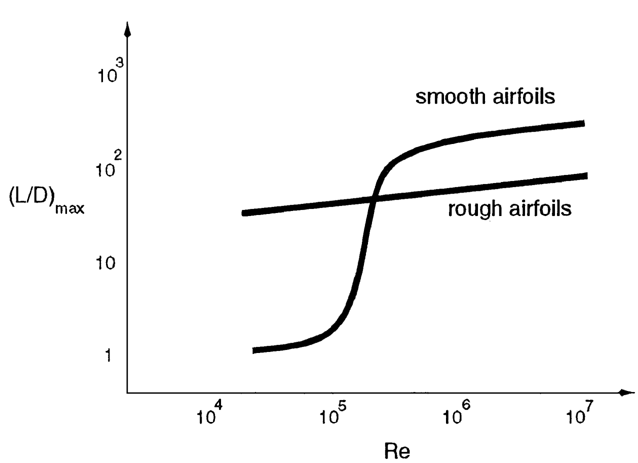


Fig. 8 L/D$_{max}$ vs Reynolds number for smooth and rough airfoils (McMasters and Henderson).

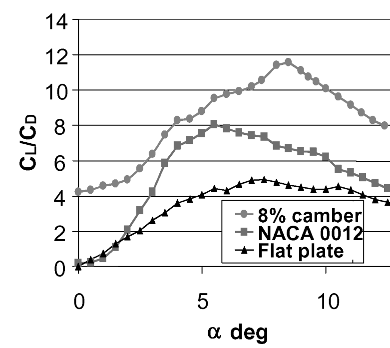


Fig. 9 Lift-to-drag ratio for several rotors with aspect ratio of 6 at a tip $Re = 3 \times 10^4$ calculated using BEMT.

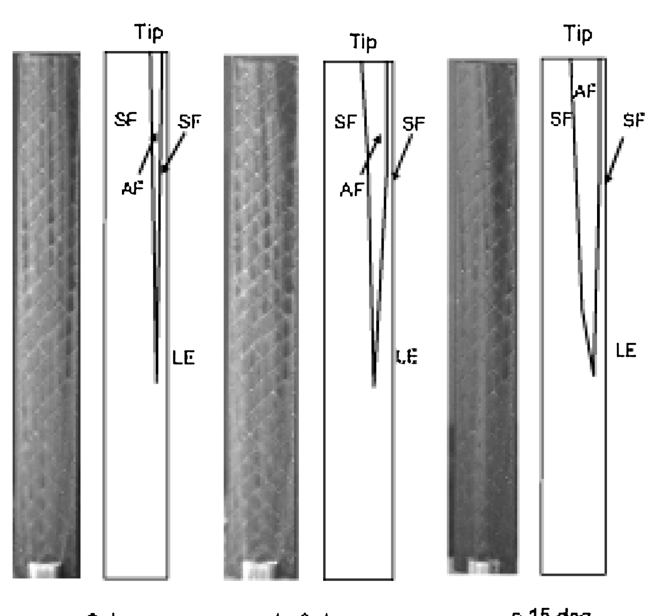


Fig. 10 Oil flow-visualization Results on 6-in. rotors with tip $Re = 3 \times 10^4$ and 8% curvature.

in the face of the adverse pressure gradients after the suction peak. Under certain conditions, the separated shear layer can reattach to the surface, forming a laminar separation bubble (LSB).[32−35] More commonly, the shear layer can transition to turbulent flow and only then have the kinetic energy to be able to reattach thereby forming a transitional separation bubble.

In addition, a number of complex and nonlinear flow phenomena can cause the LSB to move back and forth over the airfoil as well as increase and decrease in size. Although the discussion of these flow physics is beyond the scope of the present paper, there have been numerous techniques used to mitigate the effects of the LSB on the airfoil's aerodynamic performance. These techniques include both passive and active flow control methods to inject disturbances into the boundary layer at the proper scale length. A summary of these techniques is presented in a recent paper by Gad-el-Hak.[36] The goal of flow control is to improve the overall aerodynamic efficiency of airfoils and to transition laminar flow to turbulent flow as a means of reducing the skin-friction drag and causing the flow to reattach over an airfoil.

This limit in aerodynamic efficiency using conventional steady-state aerodynamic theory has prompted many researchers to search for the unsteady aerodynamic mechanisms that might explain the high forces produced by insects and small birds.[33−44] Pioneering research by Lighthill,[37] Rayner,[38,39] and Pennycuick[40,41] has provided some insight into avian flight. However, until recently little was known regarding the complex kinematics of insect flight. Biologists Ellington and Dickinson have made significant advances in understanding the aerodynamic physics of insects. According to Ellington[42] (see Fig. 11), the wing stroke of an insect is typically divided into four kinematic portions: two translational phases (upstroke and downstroke), when the wings sweep through the air with a high angle of attack, and two rotational phases (pronation and supination), when the wings rapidly rotate and reverse direction. For comparative purposes, flap-ping flight of insects in hovering mode is characterized by wing-beat frequency and mean Reynolds number. Ellington[42] approximates mean Reynolds number as

$$Re = 4\Phi f R^2/\upsilon \mathcal{AR} \tag{7}$$

where $\mathcal{AR}$ is the aspect ratio, f is the wing-beat frequency, R is the wing length/span, and Φ is the wingbeat amplitude (peak to peak). Using geometrical similarity and scaling relationships for wing-beat frequency, researchers discovered that the Reynolds number increases as a function of mass $m^{0.42}$. For various sized insects, Reynolds number varies from 10 to 10^4. Over this wide range of Reynolds number for flapping flight, the flow regime is primarily laminar with several unsteady mechanisms contributing to the elevated performance of insect flight. The unsteady mechanisms that have been proposed to explain the elevated performance of insect wings typically emphasize either the translational or rotational phases of wing motion. However, the first unsteady effect to be identified was a flapping mechanism termed the "clap and fling,"[43] which is a close apposition of the two wings preceding pronation that accelerates the development of circulation during the downstroke.[44] Although the clap and fling can be important, especially in small species, it is not used by all insects and thus cannot represent a general solution to the phenomenon of force production. Recent studies by Dickinson and colleagues[45−48] and Liu et al.[49] suggest that several unsteady mechanisms might explain how insect wings generate such large aerodynamic forces over a complete wing-beat cycle.

A more detailed look at these aerodynamic mechanisms can be explained by examining the flow physics associated with any airfoil with increasing angle of attack. The high adverse pressure gradients that build up near the leading edge under dynamic translating (flapping) conditions cause flow separation to occur there. Experimental evidence suggests the formation of a shear layer that forms just downstream of the leading edge, which quickly rolls up and forms a vortex. Not long after it is formed, this vortex leaves the leading-edge region and begins to convect over the upper surface of the airfoil. This induces a pressure wave that sustains lift and produces airloads well in excess of those obtained under steady conditions. Although delayed stall might account for enough lift to keep an insect aloft, it cannot easily explain how many insects can generate aerodynamic forces that exceed twice their body weight while carrying loads. Several additional unsteady mechanisms have been proposed, mostly based on wing rotation. Depending on the Reynolds number (see Fig. 12), these mechanisms include delayed stall, wake capture,[50] rotational circulation, and bound circulation. Dickinson et al.[46] have proposed that the flight of a drosophilia fly relies on complex kinematic motion of the insect's wings. This kinematic motion gives rise to unsteady lift and drag forces that exceed lift forces under steady aerodynamic loads at the same Reynolds number. Although these recent advances in understanding aerodynamic physics have given researchers a clearer picture of low-Reynolds-number flight, researchers still have not been able to demonstrate a direct connection between mechanisms and the forces generated in flight.

Thus, the major obstacle in realizing truly efficient micro air vehicles in the <100–200-g class are the complex unsteady aerodynamic mechanisms that contribute to the efficient lift and flight maneuvering capability of insects and small birds in the Reynolds number

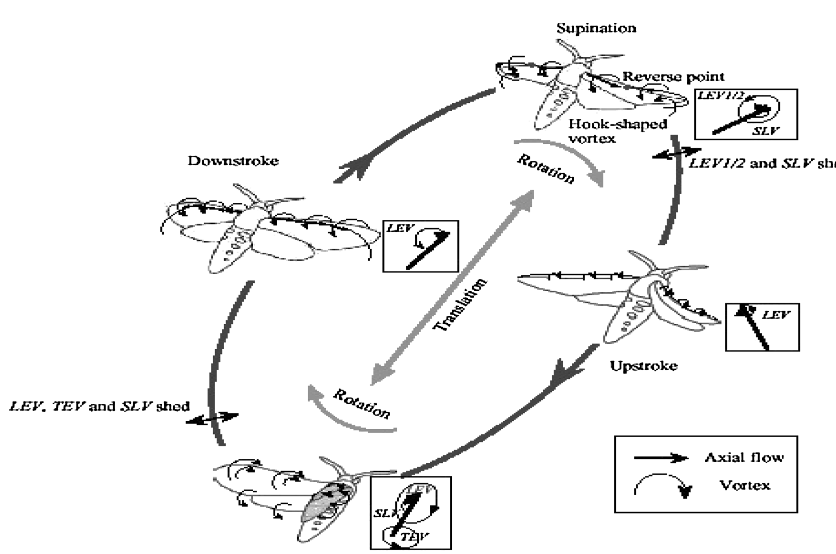


Fig. 11 Diagram of the vortex system during the complete wing-beat cycle. The shaded area at pronation denotes the morphological lower wing surface on the insect diagram (insets). A large leading-edge vortex (LEV) with strong axial flow is observed during the downstroke. This LEV is still present during supination, but turns into a hook-shaped vortex. A small LEV is also detected during the early upstroke and gradually grows into a large vortex in the latter half of the upstroke. This LEV is still observed closely attached to the wing during the subsequent pronation, where a trailing-edge vortex (TEV) and a shear-layer vortex (SLV) are also formed, together forming a complicated vortex system (Ref. 42, 99).

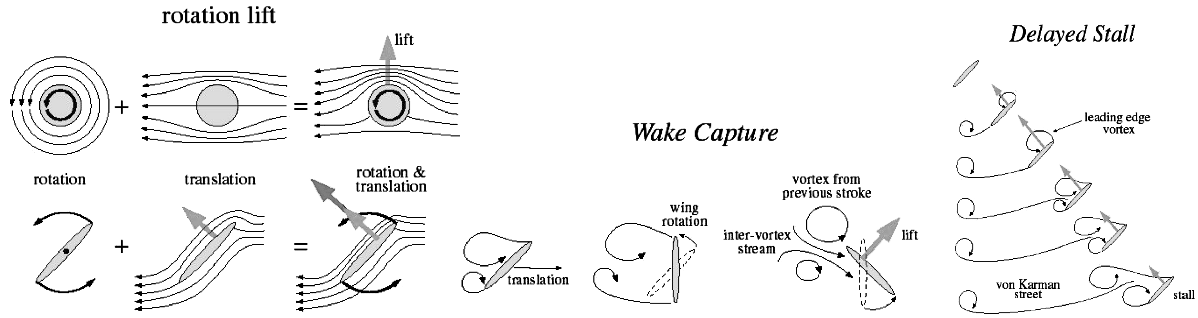


Fig. 12 Summary of unsteady aerodynamic mechanisms governing the flight regime of insects and small birds (http://socrates.berkeley.edu/flymanmd/).

Table 3 Proposed microengines[58]

Properties	MIT	UCB	UMICH1	UMICH2
Mass, g	4	22.1	54.4	39.3
Power, w	10	30	21.1	22.3
Type: gas turbine	Wankel	Swing engine	Swing engine	——

range $50 < Re < 3 \times 10^4$. Thus, it will be necessary to develop a new set of analytical and computational tools to compliment experimental investigations to study the complex steady and unsteady aerodynamic flow behavior at low Reynolds numbers for biological flyers. Fortunately, aerospace researchers at the University of Florida,[51] Notre Dame,[52] Naval Postgraduate School,[53] and at Cranfield University[54–56] are making progress in trying to computationally and analytically model the complex aerodynamic mechanisms harnessed by biological flyers to complement experimental investigations by Dickinson and Ellington. However, these efforts are only in their early stages because data at low Reynolds ($<3 \times 10^4$) are relatively scarce for typical airfoil crosssections. Although Selig et al.[57] at the University of Illinois have conducted extensive experimental investigations on air foil sections at Reynolds numbers greater than 3×10^4, there is still much to be understood in regards to flow physics and parameters at much lower Reynolds numbers. For such low Reynolds numbers there is a degree of uncertainty in the value of the average profile drag coefficient CD_o. Some experimental studies suggest that CD_o at low Reynolds number for conventional NACA series airfoils can range from 0.05 to 0.0084 (at $Re = 1 \times 10^4$ and 3×10^5, respectively) and for curved plates can range from 0.17 to 0.08 (at $Re = 10^4$ and 6×10^4, respectively).[58–62] The actual value depends on the viscous drag effects, geometry, and surface roughness of the manufactured airfoils. Lift-to-drag ratios of characteristic airfoils range from 2 to 8, depending on the Reynolds number. These low lift-to-drag ratios make flight at this scale extremely challenging.

B. Lightweight, Flexible and Adaptive Wing Structures

Although it is important to understand the flow physics associated with small-scale flight, one must not neglect the contribution of lightweight, flexible, and adaptive/morphing wing structures to the overall system performance and mass fractions. Once again, geometric similarity provides a means for comparing the structural efficiency of current MAV designs with those found in nature. Therefore, it is useful to compare MAV structural design parameters such as wing span, aspect ratio, and wing loading to biological flyers. To enable this comparison, Rayner[38,39] has developed a number of geometric scaling relationships for birds. These approximate relationships are given next as a function of total body mass m:

$$\text{Wing span} = 1.17m^{0.39} \quad (8)$$

$$\text{Aspect Ratio} = 8.56m^{0.06} \quad (9)$$

$$\text{Wing Loading} = 62.2m^{0.28} \quad (10)$$

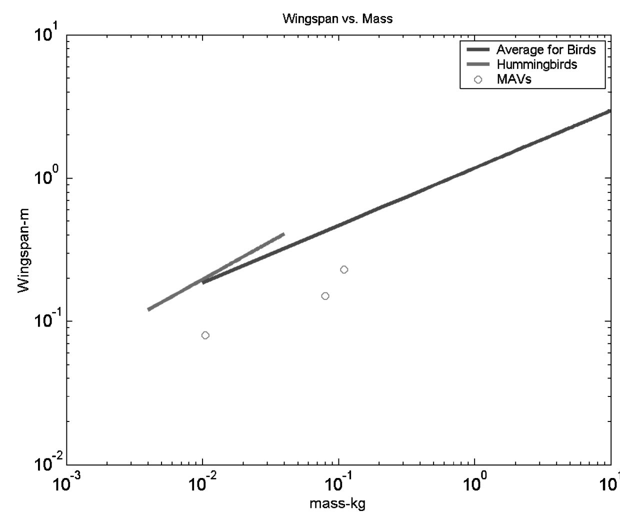


Fig. 13 Wing span vs mass.

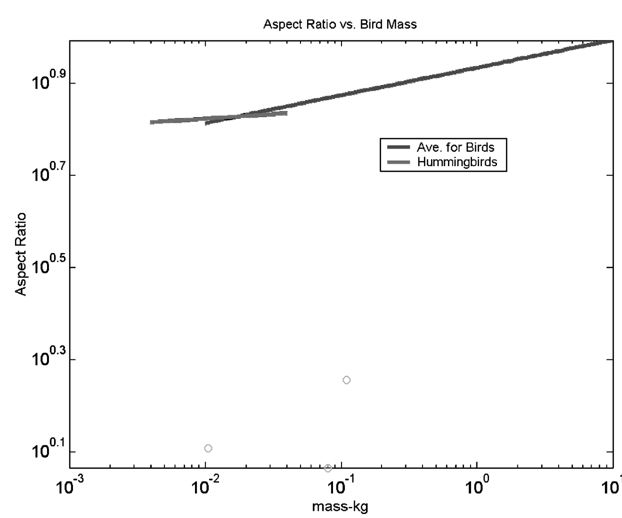


Fig. 14 Aspect ratio vs mass.

1. Geometric Wing Scaling: Wing Span, Aspect Ratio and Wing Loading

Figures 13–15 illustrate these geometric scaling relationships for small birds and how they compare to three of the current fixed-wing MAV designs listed in Table 3. Although approximate, these scaling relationships illustrate that most MAV designs have shorter wing spans and lower aspect ratios than their biological counterparts, suggesting more stringent control system requirements for MAVs at the same cruise condition than a bird of comparable weight. This implies higher bandwidth control is required for MAVs with the same GTOW. Another important property of wing span and aspect ratio is its connection to the aerodynamic properties of an aircraft.

As the wing span and aspect ratio increase, the lift-to-drag ratio tend to increase, affecting the glide ratio of the aircraft. Thus, birds with long wing spans and high aspect ratios are more akin to dynamic soaring. Because most MAVs have short wing spans and low aspect ratios, one would not expect for these vehicles to have great glide or soaring properties. These performance limitations are a result of span requirements imposed under the original Defense Advanced Research Projects Agency (DARPA) MAV program that limited the wing span to 15.24 cm (6 in.).

Figure 15 displays the average wing loading (N/m^2) values for birds as a function of body mass. Specific birds are displayed by the "x" symbol. The wing loading for three MAVs is also displayed in this figure with the "o" symbol. Notice that the wing loading for MAVs is significantly higher than the equivalent size bird. This suggests that MAVs must fly faster in comparison to birds of comparable geometric size, aerodynamic properties and weight to stay aloft. To accomplish this goal, MAVs must expend more power to overcome the induced aerodynamic drag. In addition, a higher wing loading means lower agility and maneuverability. Finally, the more loaded the vehicle the less efficient it is because more power is needed to carry the same unit load.

2. Wing Design

Most fixed-wing MAV designs are based on rigid-wing technology (see Fig. 16) consisting of conventional rib/spar elements to support aerodynamic and structural loads. These structural elements have been constructed from a number of different types of materials including basal wood, foam core, and fiberglass skin combinations. In full-scale aircraft, rigid composite wings are used to support the air loads and to minimize structural dynamic effects so as to avoid unstable aeroelastic interactions. Material for these types of wings must consist of properties with high tensile strength and stiffness, but low structural weight. More importantly, wings at full scale do not flap. However, for small-scale vehicles it is clear that nature suggests that flapping flexible wings may be advantageous to enhance the performance of small-scale microflight. The advantages of the use of flexible wings include passive adaptive washout control that extends the range of the aerodynamic lifting surface. Such wings have the effect of suppressing wind gusts and restoring constant thrust and lift over the airfoil. Researchers at the University of Florida[63] have developed numerous flexible fixed-wing designs and manufacturing methods to understand the performance enhancements of flexible wings for fixed-wing MAVs.

To further understand the potential benefits of thin flexible wings for small-scale flight, one simply has to examine the form and function of insect wing designs.[64] Insect wings are comp. of thin cuticular structures supported by a series of veins filled with insect blood to provide a level of structural rigidity and flexibility to the wing. Patterns of wing venation are often highly complex. For a typical insect wing (see Fig. 17),[65] the major veins originate at the axillary apparatus, running distally and toward the trailing edge of the wing. As displayed in Fig. 17, the median flexion line represents a radial groove or region of increased flexibility along which the wing can deform to achieve variable camber. Two other flexion lines, the claval furrow and jugal fold, help to achieve wing folding against the body.

Thus, MAV wing design represents one of the major challenges to efficient flight in the low-Reynolds-number regime. In the case of flapping flight, it is important that mechanical wing designs have features of high specific strength, low specific modulus, and low elastic modulus. The actual design choices will depend on the specific wing kinematics and dynamics that are desired for the flapping air vehicle. However, researchers at Cranfield (Shrivenham)[54]

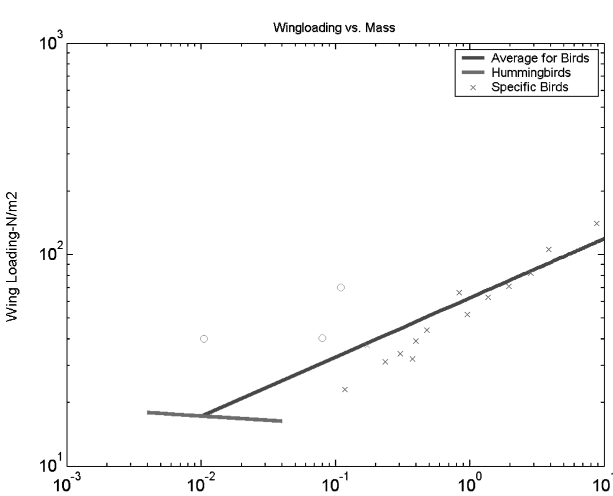


Fig. 15 Wing loading vs mass.

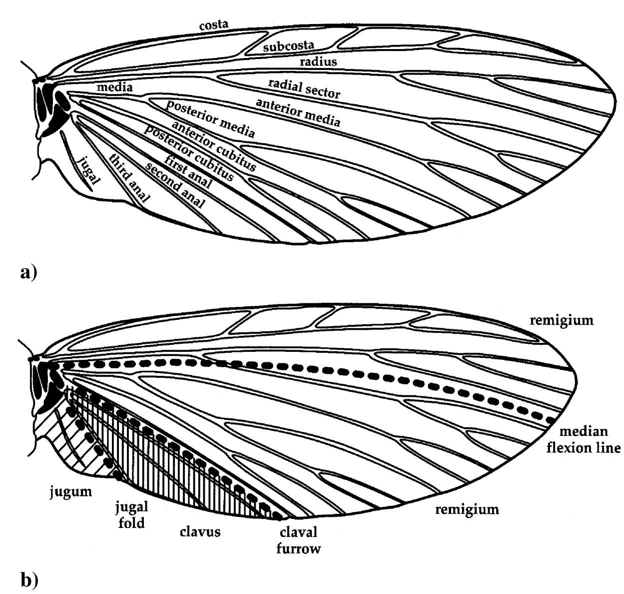


Fig. 17 Detailed wing morphology illustrating veins and folding lines.

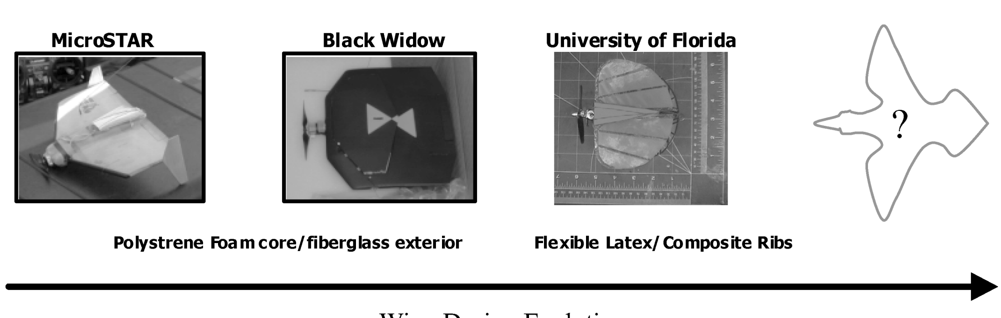
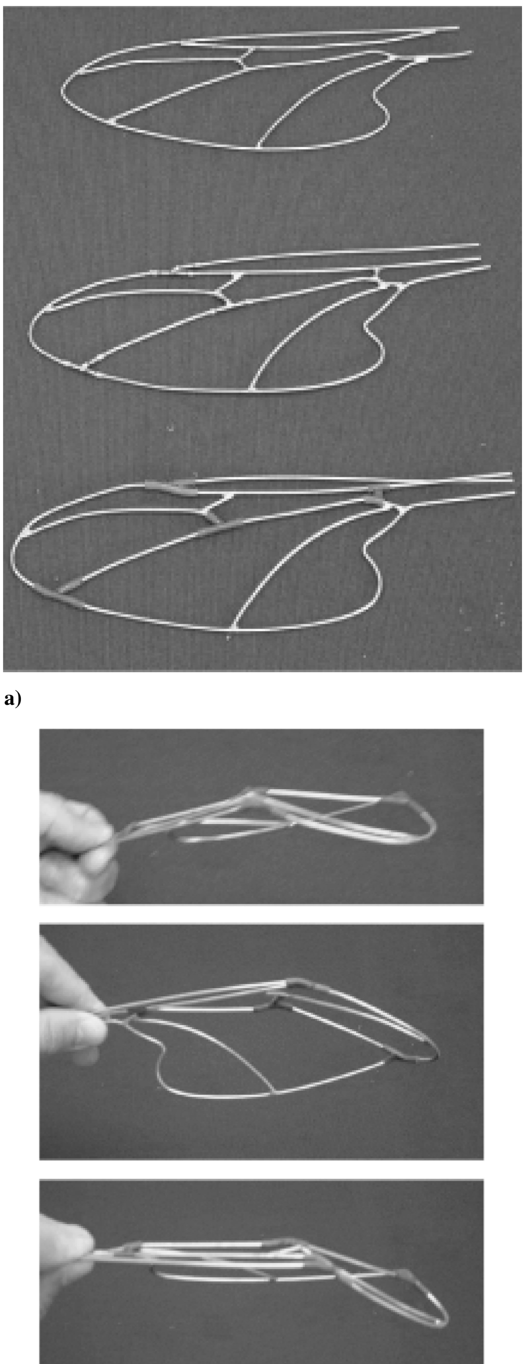


Fig. 16 MAV fixed-wing design evolution.

have developed novel lightweight and stiff wing designs that mimic the morphology of an insect wing involving elastic membranes with supporting strut-like wing spars. Figure 18 displays this strut-like wing concept that consists of five spars wrapped in a membrane. Rather than subject spars and membrane to high loads, hinges have been used to create preferred directions of high deformations.

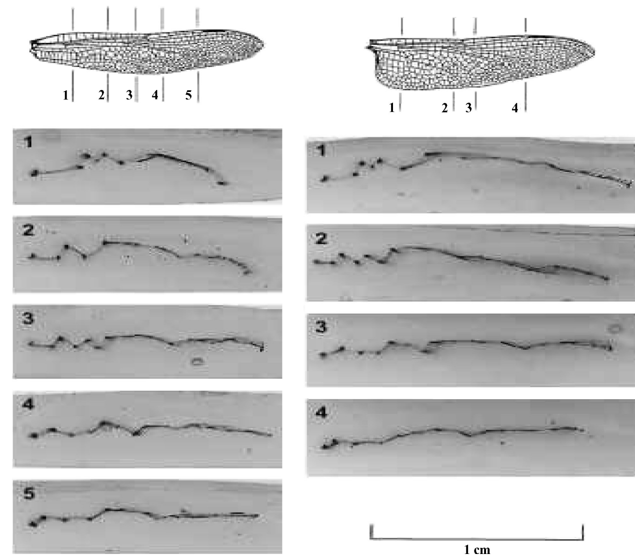
This approach offers a practical solution to inducing passive wing twisting under high flapping frequencies. Active wing deformations can occur by exploiting directional properties of membranes and actuator strategies associated wing warping. Although promising, the performance of this concept has not been evaluated.



a)

b)

Fig. 18 Metal wire wings: a) three models of five-spar metal wire wings,[53] where top, a rigid structure with no hinges; middle, hinges made of metal springs; bottom, hinges made by joining the spars with heat shrinking polypropylene "sleeves"; and b) effect of hinges on deformation pattern.



a) b)

Fig. 19 Morphological camber shape changes along the span of dragonfly wing.[65]

Finally, the most intriguing aspect of small-scale wing design is the fact that it has been observed that both insects and birds undergo significant morphological shape change in the geometry/stiffness (compliance) of their wings during flapping flight. This morphological shape change for some species is believed to occur passively as a built-in mechanism that enables the animal to reduce its drag profile during the upstroke motion of its wing. To illustrate this phenomenon, Fig. 19 displays the cross sections of a dragon fly wing undergoing flapping flight.[66] Notice that the chord dimension reduces during the upstroke. In addition, one can also see some changes in wing camber at various cross sections. Similarly, birds[67] such as falcons use wing geometric shape change to loiter on station in a high-aspect-ratio configuration using air currents and thermals to circle above until they detect their prey. Upon detection, the bird morphs into a strike configuration to swoop down on unsuspecting prey. This ability to change the nature of lift and drag over the wing using geometric changes expands the flight envelope of nature's great flyers. Currently, none of the MAVs displayed in Fig. 4 undergo morphological shape change to improve their lift, thrust, maneuverability, or resistance against wind gusts.

C. Energy Storage/Conversion to Useful Power/Propulsion

Although maximizing the power-to-weight ratio is important for all aerospace power systems, two factors make it absolutely critical to micro air vehicles. First, the overall aerodynamic efficiencies of conventional fixed-wing vehicles using steady-state analysis tools decreases with size. This difference is reflected in the fact that the Reynolds numbers associated with micro-air-vehicle flight are several orders of magnitude smaller than those associated with conventional flight making the aerodynamic efficiency of lift-generating systems for micro air vehicles substantially less than their conventional-scale counterparts. Finally, the efficiency of the power/propulsion system appears to degrade with decreasing size. Together, these factors conspire to make the power/weight ratio and efficiency of the power system critical and enabling for hovering as well as fixed-wing mechanical flying vehicles. Moreover, although improving efficiency at small scale is important, one must also achieve mass fractions (subsystem mass to total mass) of the propulsion that are less than 50% of the total MAV mass. As stated earlier, current MAVs exhibit propulsion system mass fractions of approximately 60% with respect to GTOW.

In contrast, a large fraction of the weight of small biological flyers is concentrated in muscle matter used to generate large-scale complex translational (flapping) kinematics. Rayner[38,39] found that approximately 16% of the bird's mass is comprised of the pectoral and supracoracoideus muscles. The pectoral muscle is used for the downstroke of a bird's wing and is significantly larger in mass fraction than the supracoracoideus muscle that is used for the upstroke motion of the wing. In comparison, birds have approximately three times the mass fraction of muscle found in humans. Thus, this large muscle mass fraction coupled with the elasticity/flexibility and low inertia of a bird's wing provides the necessary power and lift-to-weight ratios required for efficient low-Reynolds-number flight.

Although there is at least one example of a truly biomimetic power system that converts chemical energy in ATP to mechanical work, practical biomimetic devices for converting stored energy to mechanical work are at least a decade away. However, there is a variety of energy conversion and propulsion systems that can deliver 10 to 15 W of power to MAVs. These include microengines, battery/electric motor technology, micro fuel cells, and internal combustion engines. The status of some of these areas as they relate to MAV propulsion is discussed next.

1. *Microengines*

A promising, but technically challenging propulsion and/or power source is the micro turbine engine. These devices are capable of producing 10 to 50 W of power in a volume less than 1 cm^3 while consuming only 7 grams of fuel per hour. Towards this goal, the Massachusetts Institute of Technology (MIT)[68] Gas Turbine Laboratory has been developing a microelectromechanical-systems (MEMS) scale device under DoD funding, which consists of a 1-cm-diam engine with a centrifugal compressor and radial inflow turbine, separated by a hollow shaft for thermal isolation, and supported on air bearings. A working combustor has been built, but the compressor, generator, and bearings have yet to be perfected at the microscales. The program goal is to produce 13 g of thrust with thrust-to-weight ratios approaching 100:1 (compared to 10:1 for today's modern jet fighter).

The United Kingdom's Defense Evaluation and Research Agency has also successfully produced and demonstrated their own variant of a turbine engine at small scale. The device is 1.3 cm by 0.5 cm and weighs less than 2 g. It uses a hydrogen-peroxide-kerosene fuel mixture and has achieved 6.4 g of thrust for up to an hour of operation.

Other proposed microengines include those under development at University of California, Berkeley and the University of Michigan. Cadou et al.[69,70] summarize the expected performance parameters of various microengines in Table 3.

2. *Battery/Electric Motors*

Many of the MAVs listed in Table 3 have relied on battery power to drive efficient electric motors. Compared to a rechargeable Nicad battery of the same weight, a lithium ion or polymer batteries deliver several times more energy. However, lithium ion and polymer batteries suffer from low discharge rates and insufficient energy density (150 W · hr per kg) to sustain long-duration MAV flight. Recent advances include the development of thin flexible/conformal sheets of lihium ion battery technology. This new development enables the battery to double as a multifunctional structure supporting aerodynamic lift and as a source of energy. This can enable the next generation of MAVs to stay aloft longer.

3. *Micro Fuel Cells*

Although fuel-cell technology[71] is less mature, it is anticipated that progress will result in energy densities that are at least two to four times greater than lithium-ion battery technology. Recently, MTI, Inc, has developed a direct methanol micro fuel cell for the wireless consumer market. These fuels cells have energy densities of approximately 240 W · h/kg. Although the energy density appears to meet the needs of MAV designers, size limits their use in MAV applications. IGR Enterprises, Inc, was funded by DARPA to develop a MAV fuel cell weighing less than 30 g and producing approximately 20 W of power for 1 h. However, this technology is probably a few years from finding itself on MAVs.

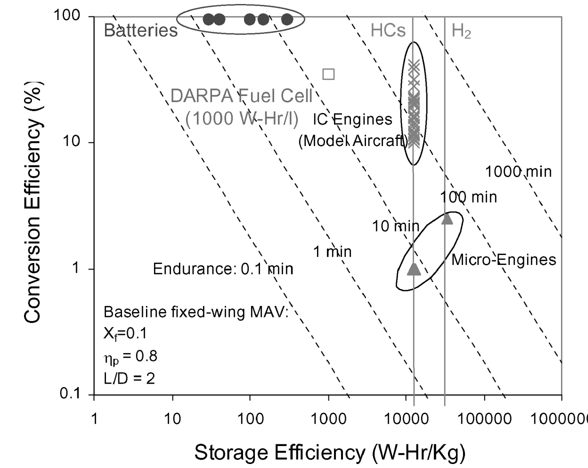


Fig. 20 Comparison of MAV endurance associated with various energy storage/conversion systems.[69]

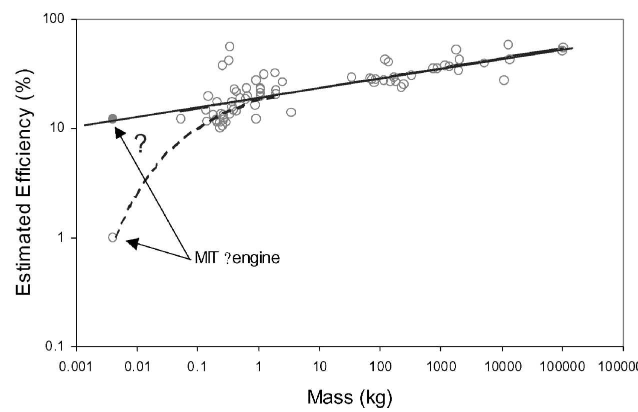


Fig. 21 Estimated efficiency of various hydrocarbon-fueled IC engines.[69]

4. *Internal Combustion Engines*[72,‡]

In the near term, Fig. 20 shows that energy storage and conversion technology based on hydrocarbon fuels and small reciprocating engines that exist today can provide acceptable levels of performance for 200-g class MAVs, that is, if the estimates of engine power and efficiency are correct. Although their thermal efficiencies at MAV scales are low, their power densities are quite high, typically 1 w/g. Such engines have already been developed for the hobby-class community such as the Cox Tee Dee 0.01, which is only 0.01 $in.^3$ in volume but can produce about 20 W of power.

One problem is that these estimates of engine power and efficiency are based on manufacturer's published data,[70] which is rudimentary. Manufacturers usually report only peak power at a particular operating speed, which means that fuel consumption information and efficiency must be estimated. Actual data showing power curves and efficiency (specific fuel consumption) information are never reported because these engines are primarily produced for hobbyists. Moreover, manufacturers' reported data are often highly suspect. There are many reports in the literature about engines with high power whose performance in model aircraft/cars/boats is worse than engines with lower reported power. Although this apparent anomaly could be the result of intentional deception by manufacturers, it could also result from the lack of standardized testing procedures between manufacturers. Cadou shows that efficiency estimates (see Fig. 21) for small reciprocating engines vary widely and seem to show only weak scaling with engine size in comparison to full-scale engines. Clearly, reliable data produced using standardized testing procedures are required to verify the performance capability

‡Data available online at http://www.globalsecurity.org/intell/library/reports/2001/uav0401.htm.

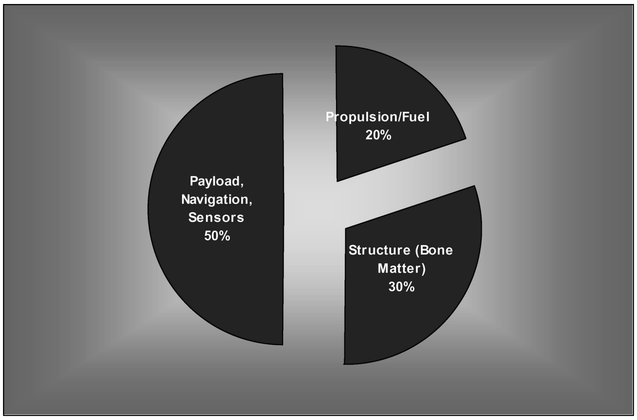


Fig. 22 Estimate of mass fractions computed for birds.

of existing IC engines and to understand how to optimize performance for use in biomimetic MAVs.

Another problem apparent from Fig. 20 is that building efficient IC engines becomes more difficult as engine size is reduced. Thermal and frictional losses scale directly with surface/volume ratio and therefore increase as the size of the engine is reduced. Several research teams building microengines in the 10-Watt/5-g class have recognized this problem but exactly how these losses scale with device size is not well understood. Although this information is critical to designers of MAVs who need to be able to make realistic estimates of the performance capability of a particular size power system before it is actually built, there has been very little work on developing reliable scaling laws.

D. Summary of Status and Performance of Current MAV Development

In summary, it appears that the major reason for the across-the-board failure to achieve true long-loiter, highly maneuverable, and hovering flight in a single configuration is that all of the configurations/designs depicted in Fig. 4 rely on conventional steady-state aerodynamic mechanisms that become inefficient at the low Reynolds numbers associated with smooth airfoils and rotors. The inefficient utilization of aerodynamic lift coupled with relatively inefficient systems for storing and releasing energy (power systems) are the two most significant factors inhibiting the development of efficient miniature mechanical flying machines. From a systems perspective, it appears that biological flyers achieve remarkable mass fractions (Nature's Great Flyers reference) (see Fig. 22) when compared to miniature mechanical flyers. Thus, future MAV designs will undoubtedly take some lessons from nature to achieve efficient operating mechanical flying machines.

IV. Emerging MAV Research and Technology Trends

The next generation of MAV designs that show the greatest promise are the ornithopter configurations. Up to now, there has been little research toward the development of these types of configurations. Researchers at Caltech and Aervironment, with its prototype Microbat, have placed their focus on the wing design, where flexible thin membranes, similar to bat wings are used. Because reproducing the complex kinematics of biological flyers is challenging, one of the primary problems faced when using simplified movements is the increased drag in the upstroke. To reduce this drag, MEMs electrostatic actuator valves have been incorporated to parylene wings in order to control the flow through the membrane.[73,74] Without electrostatic actuation air can move freely from one side of the skin to the other side trough the vent holes. With actuation, these vent holes are sealed, and the airflow is controlled. The membrane behaves as a complete diaphragm. Actuation is done on the downstroke and stopped on the upstroke reducing the drag of the wings over the flapping cycles. To aid the design of ornithopters, one can again examine the characteristics of biological creatures. Studies of birds by Rayner[39] and Norberg[67] have revealed the following scaling relationships characterizing the flapping wingbeat frequency used to acquire thrust and lift:

$$f_{\min} = 2m^{-0.1667} \tag{11}$$

$$f_{\max} = 8m^{-0.333} \tag{12}$$

$$f_{\text{hum min gbird}} = 1.32m^{-0.6} \tag{13}$$

These expressions offer some insight into the potential range of future practical flapping wing MAV designs. For insect-size vehicles in the milligram to tens of grams weight class, wing-beat frequency scales with $m^{-0.24}$, albeit with significant scatter in the data. These flapping frequency scaling relationships offer some guidelines for achieving flapping flight; however, the details lie in the development of efficient lightweight flapping mechanisms that harness similar wing-beat kinematics and unsteady aerodynamics found in insects and small birds.

A. Flapping Mechanisms

To achieve flapping flight, researchers must develop monolithic lightweight devices that can generate large-scale kinematic angular motion with minimal mechanical effort. Insects and small birds accomplish flapping flight in different ways but rely heavily on their anatomy. In the case of an insect, the structural components required for flight derive from the morphological exoskeleton of insect body design. The key element in the insect anatomy is the thorax. Flexibility is essential for the insect thorax, as internal muscular forces cause the thorax to deform and either directly or indirectly transmit forces to the wings. Elastic return of stored energy is also important to minimize the total effort required during a wing-beat cycle. Figure 23 shows a cross-sectional view of the thoracic segment illustrating the intrinsic flight muscles that are used for flapping flight. It is believed that two different sets of thoracic muscles are primarily responsible for complex wing motions. These muscles

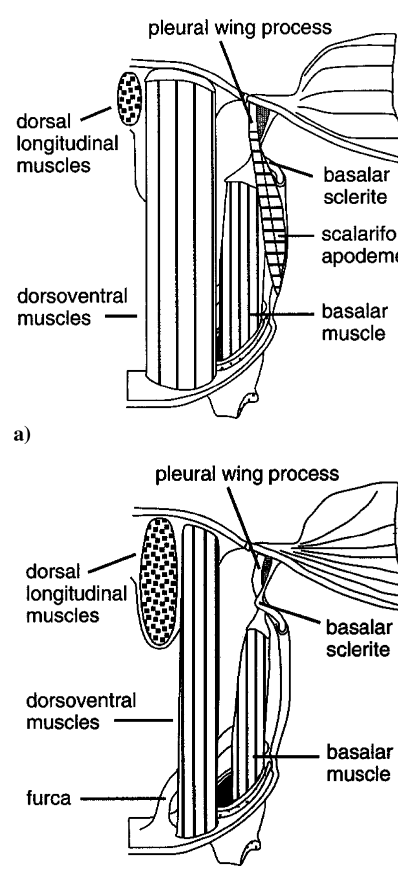
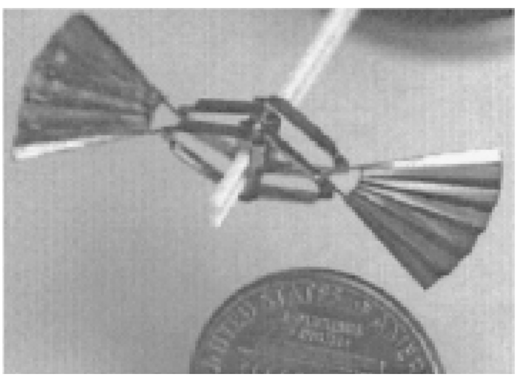


Fig. 23 Cross section of thorax revealing indirect/direct flight muscles responsible for insect flapping flight.

a) Mockup of Robofly



b) 4-bar flapping mechanism

Fig. 24 University of California, Berkeley's Robofly.[74,75]

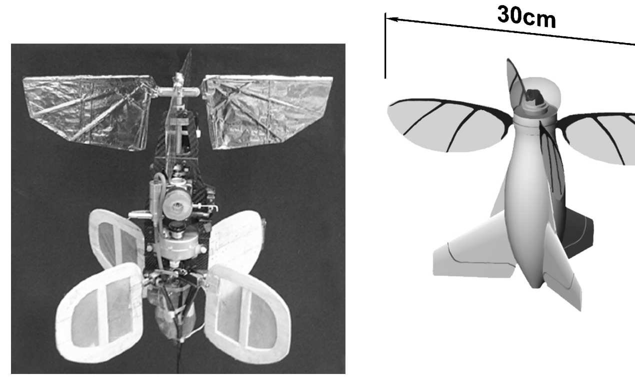


Fig. 25 MENTOR flying vehicle.

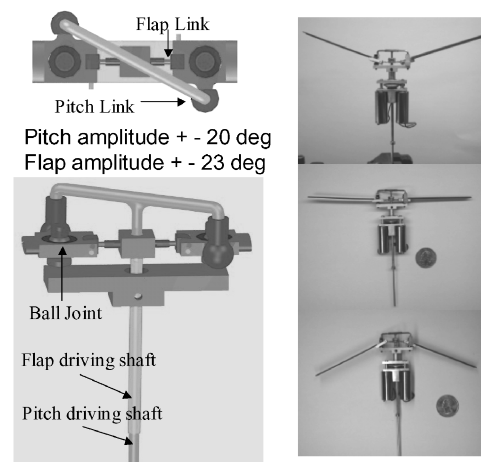


Fig. 26 Biomimetic rotating/flapping/pitching mechanism.§

act either directly on the wing base and sclerites of the auxiliary apparatus[65] or can act indirectly to move the wings via indirect thoracic deformation. Although the details of the interaction of these muscles that enable flapping flight remain a research topic in the biological community, researchers at a number of institutions have either developed or are developing complex mechanical devices that can generate simultaneous pitching, flapping, and translating motion of a small-scale wing.

Recently, a team at the University of California, Berkeley, has developed a piezoelectric wing-driven flap actuation mechanism[75,76] that can generate the kinematic motion required for mimicking the aerodynamic performance of a fruitfly (*Drosophila*). The mechanical equivalent is named "Robofly" and attempts to mimic the kinematics of a fly. A conceptual view of this concept is displayed in Fig. 24a. This vehicle was designed for a Reynolds-number flight regime of 150 and weighs approximately 350 mg. The flapping mechanism was designed using a four- and five-bar linkage schemes driven by piezoelectric actuators. A picture of one of the early mechanism designs is displayed in Fig. 24b. Unfortunately, this concept was never able to achieve enough lift force to support its own weight even with tethered power.

DeLaurier and his students at the University of Toronto working closely with Kornbluh and his colleagues at SR International§ have investigated the clap and fling unsteady aerodynamic mechanism commonly found in insects and small birds to generate lift. Kornbluh attempted to develop a mechanism that generates the unsteady clap-fling motion using electroactive polymer actuators. These elastomeric actuators produce large stroke at reasonable frequencies, but require high voltage to drive them. The high voltage required by the actuators precluded their use in a flapping vehicle design called Mentor. Nevertheless, a larger than MAV scale flapping vehicle ($\sim$500 g) that harnessed the clap-fling flapping motion was developed with both electric and internal combustion-driven power. The MENTOR vehicle was the first of its kind to fully hover under biologically inspired flapping wing propulsion (see Fig. 25).

At the University of Maryland, the author and his students[77] developed a rather unusual flapping, pitching, and rotating device for evaluating the effects of unsteady rotor motion on the hover performance of small-scale rotorcraft designs. In the spirit of generating large-scale kinematic motion, a biomimetic mechanical mechanism has been developed, which rotates like a conventional rotary-wing configuration but is capable of undergoing large angular changes in its pitch and flap degrees of freedom at high frequency. The pitch and flap degrees of freedom can be independently controlled to generate unsteady air loads. A conceptual view of this mechanism is displayed in Fig. 26. Preliminary results of unsteady pitching at 1/4 per rev frequencies show a significant performance gain in the figure of merit near the onset of dynamic stall.

Finally, in the United Kingdom, Zbikowski (personal communication) and his colleagues at Cranfield (Shrivenham) have developed a flapping mechanism for evaluating the wide range of motion associated with flapping insect flight. However, there are little published data on this device and its ability to mimic the unsteady physics that insects and small birds use to acquire efficient aerodynamic lift in hover and forward flight.

Intricate actuation of the flapping mechanism is another potential application for smart material technology; the use of conventional electric motors requires the transformation of rotating motion into a linear reciprocating movement. This involves a certain mechanical complexity, added weight, and more important, a fixed movement pattern, that makes it difficult to change the flapping amplitude and hence restricts the control schemes and experimental degrees of freedom. Smart linear actuators can alleviate these problems by providing controllable stroke amplitude at high frequencies. In addition, the efficient transduction of mechanical power will be essential for achieving long endurance and reliable flapping flight.

§Data available online at http://www.erg.sri.com/automa-tion/actuators.html.

Fig. 27 Aerovironment WASP MAV.[81]

B. Morphological Shape Changes

Although large-scale kinematic flapping motion is of importance, radical shape changes along the span, chord, and thickness directions could also be quite significant to small-scale vehicle performance. For example camber modification along the chord could be used to adapt the airfoil to different flight conditions. In addition wing-tip effects can significantly affect the aerodynamic performance including the wake structure several chord lengths removed from the unsteady vortex interactions. So the simultaneous use of shape transformations could provide enough control authority to command the MAV. Towards this goal, morphing structures technology[78−81] is in its initial stages of development by researchers at NASA Langley Research Center at a much larger length scale; however, such technology might find its way into small-scale flying machines.

C. Multifunctional Structures

Another emerging technology is the integration of additional functionality into a wing structure, for example, including being able to support air loads of an air vehicle wall also providing power, sensing, or communication. Recently, researchers from the Naval Research Laboratory in conjunction with Aerovironment and Telcordia flight tested a multifunctional wing that was integrated with conformal lithium-ion battery technology under DARPA¶ support. The wing while acting as the main lifting surface also served as a source of battery power in the form of conformal lithium-ion battery packs. A picture of the MAV is displayed in Fig. 27. The MAV weighed approximately 150 g and had a wing span of 14 in. The fixed-wing MAV had a measured flight time of 107 min. Thus far, this has exceeded the endurance of all other fixed-wing/ and rotary air vehicles listed in Table 3. Other opportunities for the use of multifunctional structures technology in MAV applications include conformal antennas mounted to the aerodynamic wing or fuselage of an MAV to provide line-of-sight communication to the ground, as well as the use of self-consuming or "autophagous" structures that provide aerodynamic lift but are consumed as power for flight is extracted from the wing material.

D. Emerging Propulsion/Power Technology

Emerging propulsion technologies‡ include the following:

1) Beaming energy to the aircraft for conversion to electricity using either microwaves or lasers eliminates the need to carry propellant onboard, but requires a tremendous transmit-to-receive power ratio (microwaves) or very precise pointing (lasers) and limits flight to within line of sight of the power source (both). Microwave beaming would take 100 kW (134 hp) of transmit power to run just a micro-UAV at a range of 0.6 miles, let alone a more substantially sized aircraft, whereas a laser would only require around 40 W (0.05 hp) of power. Recently, a team of researchers from NASA Marshall Space Flight Center and the University of Alabama demonstrated that a small-scale aircraft can fly under laser power.

2) Reciprocating chemical muscles (RCMs) are regenerative devices that use a chemically actuated mechanical muscle (ionomers) to convert chemical energy into motion through a direct, noncombustive chemical reaction. Power generated via an RCM can be used for both propulsion (via wing flapping) and powering of onboard flight systems. RCM technology could power future generations of MAVs, providing vertical takeoff and landing as well as hover capabilities.

3) Improvements in electric battery technology such as the development of lithium sulfur batteries have higher specific energy (>400 W · h/kg) than lithium ion technology.

¶Data available online at http://www.darpa.mil/body/news.html.

V. Notable Firsts in the MAV Flight Regime

Similar to the 100-year history of powered human flight, there have been several notable firsts that have been achieved by researchers working in the MAV field based on DoD's MAV design requirements. An incomplete, but growing list includes:

1) The first battery-powered electric motor open-loop controlled flapping flight was by Microbat-CalTech/Aerovironment.

2) The longest endurance (<100 g) is >30 min of a fixed-wing MAV by Black Widow Aerovironment.

3) The first autonomous MAV flight (global-positioning-system waypoint navigation) was by Microstar–Lockheed Martin.

4) The first open-loop controlled hovering flight of a biologically inspired flapping vehicle was by MENTOR-SRI.

5) The longest-endurance flapping flight (<100 g) was ∼25 mins by 9-in.-Microbat-Aerovironment.

Although many of these notable firsts are debatable, it is clear that the development of MAV technology is still in its infancy and intersects at the congruence between science and engineering. As new physics is discovered and understood, these ideas will be incorporated in the next generation of MAV designs.[82] New capabilities projected for the next generation of UAVs include the following 1) silent flight as fuel cells and battery technology supplant internal combustion engines; 2) 60% gains in endurance caused by increasingly efficient turbine engines; 3) self-repairing, damage compensating, more survivable UAVs; 4) adaptive MAVs using novel actuator and sensor technology; 5) speedier information availability to users through onboard real-time processing and higher data rates; 6) autonomous operation in open and confined spaces using vision-based image processing; and 7) multimodality UAVs capable of operating in different mediums such as water and air.

VI. Summary

In summary, nature has evolved thousands of insects and small birds that outperform man-made miniature flying machines routinely. Although some of the details underlying the operational success of biological fliers remain a research topic, a general picture is emerging, which indicates that the overwhelming superiority of biological fliers over existing MAVs stems from three fundamental factors: an ability to generate lift more efficiently than existing technologies, an ability to harness morphological shape changes in wing kinematics/structure, and an ability to store and release energy more efficiently. The major obstacle in this endeavor is our limited understanding of the physics of micro-and ultimately nanoflight (<5-cm wing span). The research programs in the United States, as well as others worldwide, have spearheaded a great deal of interest in microscale flight physics that is still evolving. Although significant progress has been made, it is likely that the next generation of small-scale flying machines will be inspired by advances in the following areas: 1) low-Reynolds-number aerodynamics, analytical and computational models; 2) lightweight, adaptive, and biologically inspired multifunctional materials and structures; 3) micropropulsion/power sources; 4) robust flight navigation and control using insect-like optic flow vision; 5) miniaturized navigation and control electronics; and 6) system engineering tools. Assuming that these advances are achieved, it is still difficult to project what these new vehicles will look like. Will nature provide clues? How much will these new vehicles cost? These questions are sure to be answered over the next decade by researchers working at the intersection of biology and engineering. Thus, in order to make future advances in MAV technology it might be wise to heed the words of the Wilbur Wright: "It is possible to fly without motors, but not without knowledge and skill."

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