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Biomimicry in Engineering – Bats and Aviation

Introduction

The field of aviation is a constantly expanding one, and one which still stands to learn a lot from the natural world – and in particular, bats.

For centuries, humans have been fascinated by the concept of flight. And from Daedalus and Icarus' wings bent 'to the shape of birds' [1] in Ancient Greek mythology to the first kites invented during the Chinese Warring States period 2300 years ago shaped like animals [2] or even Leonardo da Vinci's ornithopters [3], engineers have had a clear muse: nature. Now, as we begin exploring the concept of Flapping Wing Micro Aerial Vehicles, (FWMAVs), that focus has not shifted – nor should it.

FWMAVs may be a relatively new development in the aviation field, but there is already a want for them. They have the potential to revolutionise the construction industry, the delivery of supplies, and disaster response, among other applications [4].

As is clear from their name, these drones become airborne through the flapping motion of their wings as opposed to fixed wings or rotors. This technique is used by all 3 extant flying groups in the animal kingdom, meaning a key aspect of their development has involved biomimicry. This has ranged widely from the traditional bird, to insects – and more recently, bats.

Bat Flight

Bats are the only mammal capable of flight [5] and have been doing so for over 50 million years [6], with the smallest, the Kitti's Hog-nosed Bat, measuring only around 30mm long and weighing less than 2g [7]. Due to their mammalian anatomy, their flight mechanism, along with being incredibly distinctive, is also one of the most complex in the animal kingdom – if not the most complex. Consisting of a variety of different joints, bones, and muscles, the mechanism has over 40 degrees of freedom [8] (or 40 possible independent movements [9]) and allows bats to perform a range of impressive manoeuvres. All of this makes bats an exemplary source of inspiration for FWMAVs.

How exactly do they get off the ground though? For a body to fly, there must be 4 forces in a careful balance – weight, drag, lift and thrust [10]. Bats are no different!

Weight acts on a bat because of their mass, and therefore it can't be changed. To fly, a bat must overcome the downward force of weight, which it does by generating lift. The curvature of a bat's wing means it acts like an aerofoil, and therefore air travels at a much greater velocity over the top of the wing than underneath [11]. As shown by Bernoulli's equation, this difference in velocity produces a difference in pressure, with a greater pressure beneath the wing than above it. This in turn leads to the generation of an upward force, known as lift [12].

Drag then occurs when a solid body, like a bat, moves through a fluid, like the air, and is created by the difference in velocity between the two [13]. It must be counteracted for a bat to be able to move forward rather than backwards. Therefore, a bat creates thrust by flapping its wings, forming vortices in the air of its wake, which push them in the right direction [14].

If the lift force is greater in magnitude than the weight, the bat will accelerate upwards; if thrust is greater in magnitude than drag it will accelerate forwards, and vice versa – as in Newton's 2nd law.

So far, this has just been basic flight physics. But there are 3 key differences between a bat's flight mechanism and those of their fellow fliers (birds and insects), and they are found in the wings. These variations are that:

1) Bats have over two dozen independently controllable joints in their wings, compared to only three in a bird's [15].
2) Their bones can adapt and deform during wingbeats.
3) They can vary the stiffness across the skin of their wing membranes [16].

Because their wings are so flexible, they can actively change shape to best suit the needs of the bat at whichever point during the wingbeat. There are four key motions their wings can perform – twisting, cambering, bending and area-changing, shown in Figure 1 – and each adjustment has a different impact on the forces generated by the wing, with the ultimate goal being to maximise the lift and thrust generated.

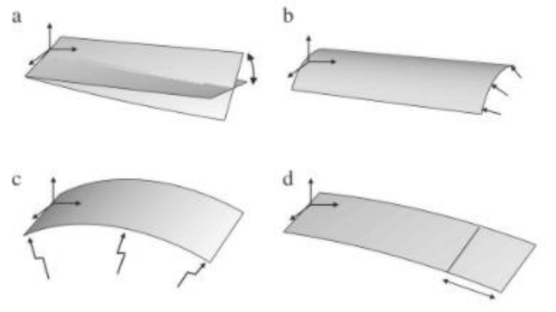

Figure 1 Wing adjustments made by bats. (a) twisting, (b) cambering, (c) bending, (d) area-changing [10].

The twisting of the wing as the bat flies amplifies the lift, while also making the amount of lift generated throughout the wing stroke more stable. Additionally, it allows thrust to be generated in both the upstroke and downstroke. Changing the camber of the wing has a similar role. Bending the wing, again, enhances lift, but more importantly reduces the amount of negative lift and drag produced by the upstroke. Finally, area-changing allows the bat to change the magnitude of forces generated – the larger the area, the larger the force. Therefore, the bat will increase the area on the downstroke, maximising the lift and thrust generated, while decreasing the area on the upstroke, minimising the negative lift and drag generated. Figure 2 shows how the wing is adjusted throughout the wing stroke.

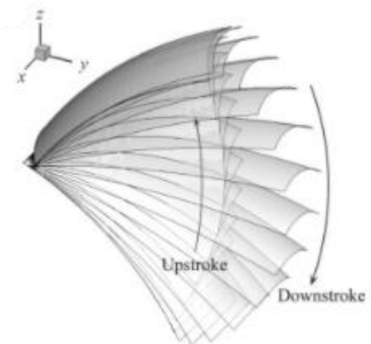

Figure 2 Shape of a bat's right wing throughout the wingbeat [10].

These adjustments made by the bat allow it to produce large amounts of lift and thrust on the downstroke, while minimising any counterproductive forces generated by the upstroke [10] (shown in Fig. 3.).

This may make the upstroke seem less important, but that is far from the case. The upstroke is incredibly important for manoeuvring –in fact the most common method for a bat to initiate a manoeuvre relies on the upstroke and is to vary the magnitude of the forces generated during it. Mechanically, this is an incredibly effective system. It’s much easier to produce extra forces than to use the alternative – vary the timing of wing strokes. If the wingbeats are able to remain in synchrony, far fewer adjustments are required on the part of the bat. Furthermore, the use of the upstroke, which doesn’t generate as much lift and thrust as the downstroke, means the bat uses each and every second of the wingbeat to the best of its ability and makes the entire flight mechanism as efficient as possible [17] – so much so that a bat’s flight mechanism may be more efficient than a bird’s [18]. Efficiency is especially important for flying animals, as flapping flight is one of the most energy draining activities an animal can perform [18].

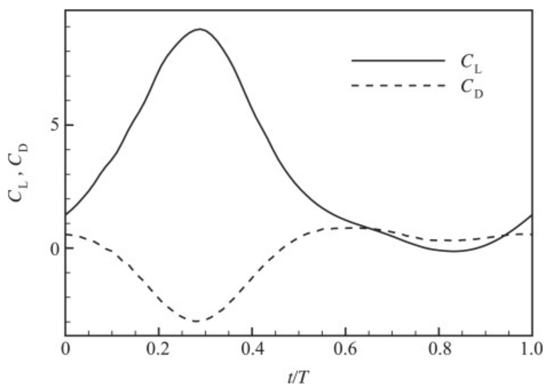

Figure 3 Forces generated throughout the wingbeat, where Lift = C_L and Thrust = $-C_D$. The downstroke is $0<t/T\leq0.5$ and the upstroke is $0.5<t/T\leq1.0$ [10].

As well as giving bats an evolutional advantage, this efficiency and manoeuvrability has also drawn scientists to bat flight technique and begun efforts to mimic it.

Bat Bot B2

‘Bat Bot B2’ (Bat Bot, B2) is a ‘fully self-contained, autonomous flying robot that weighs 93 grams’ [19] constructed by researchers at both the California Institute of Technology and the University of Illinois in 2017, inspired directly by the flight of bats (Fig. 4.). B2 has two wings either side of its centre which are then split to have a front and hind mechanism and covered in a silicon membrane. It has been able to mimic bat flight, specifically that of the Egyptian fruit bat (*Rousettus aegyptiacus*) [8], incredibly faithfully [19], as shown in Table 1. The creators of B2 achieved this by replicating the 3 most important motions required for bat flight – the flapping of the wings, the twisting of the forelimb and the movement of the legs [8].

	B2	Bat[1]
flight speed, m s^{-1}	4.0	4.4
aspect ratio, -	3.57	5.0
flapping frequency, Hz	10	≈ 10
flapping amplitude, °	± 27.5	≈ 35
mean wing span, m	0.469	0.6
mean wing area, m	0.0694	0.072
mean wing chord, m	0.14	0.12
wing load, kg m^{-1}	1.328	2.22
total mass, kg	0.093	0.16
body width, m	0.02	0.035
humerus (arm) length, m	0.035	0.038
radius (forearm) length, m	0.045	0.068
digits (fingers) length, m	0.14	0.12
femur (leg) length, m	0.1	0.055

[1] *Rousettus aegyptiacus [25].*

Table 1 Morphological and kinematic details of B2 [8].

The scientists involved reverse engineered bat flight, striking a delicate balance between reflecting bat flight in their design and directly copying it. To do this, they referenced 'functional groups' of bat joints from prior research. These groups allowed them to place each movement of a bat's wing during flight into categories, and later select more specific parts to mimic, while minimising the amount of joints Bat Bot has, and, in the process, its weight [8][19]. As a result, B2 has only 9 joints in each wing, as opposed to the total 40 a real bat has [20].

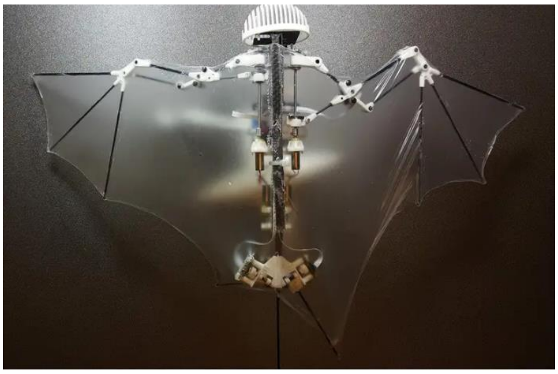

Figure 4 Bat Bot B2 [20].

This has not, however, limited Bat Bot's capability. It has, instead made B2 much more efficient. To keep Bat Bot's mass low, it only has a few actuators (components which create movement), but because of the way in which the limbs are constructed, each actuator can create a range of motion. Take the forelimb for example. Each has only one actuator, but can still produce three distinct, effective movements at the shoulder, elbow and wrist respectively [8].

As discussed earlier, the membrane of a bat's wing is integral to their flight mechanism. To best mimic this variable membrane, an entirely new material had to be made, as traditional alternatives, such as nylon, weren't stretchable enough. The resulting product was a 56µm, silicon-based membrane, which was then attached to the skeleton of the robot. Using such a material, while it may not have all the benefits of a bat's natural 'muscularized membrane' [10], still makes Bat Bot more efficient– the membranes 'fill up' with air and deform with the upward movement of the wing, then expel the air and return to their initial shape with the downward motion, amplifying any power already in the wingbeat [21].

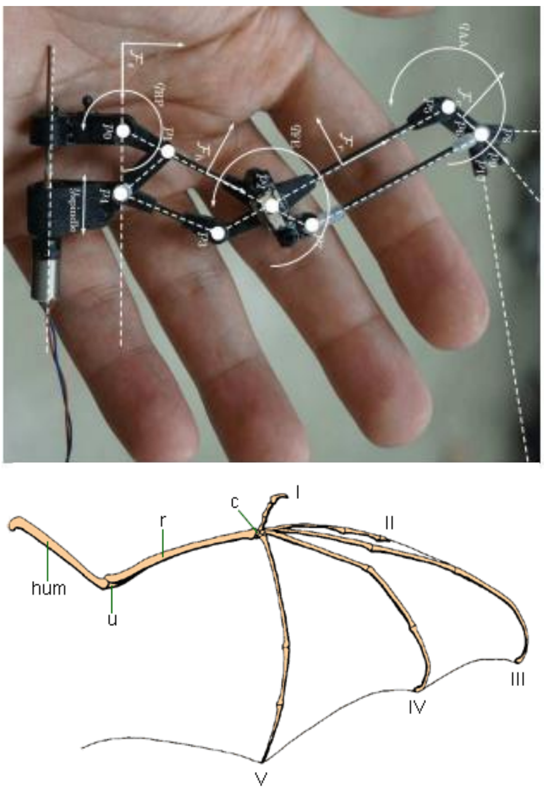

Figure 5 A comparison of Bat Bot's forelimb mechanism [8], and a generalisation of a bat wing [22].

It's undeniable that B2 has huge amounts of potential – it has a flapping frequency of 10Hz, can reach speeds of 4ms^{-1} [8] and can perform straight flight, banking turns as well as dives [19]. And while Bat Bot may not be a perfect replica of its namesake, the source of inspiration remains incredibly clear in its intricate design (Fig. 5.).

Real-world Applications

The field of MAVs is a relatively modern one – the first few were initially developed as recently as the 90s [23] – and the field of FWMAVs is even younger. This unfortunately means that while we have many theoretical applications of Bat Bot B2 and other similar vehicles, the technology, by and large, is simply not ready for practical implementation.

However, there are a few examples of MAVs in use currently which we can use to imagine the potential robots like B2 have. One such example is the Honeywell T-Hawk MAV, a 17lb (around 8kg), backpack portable drone which uses a ducted fan to produce lift. Its development began in 2003, with its first deployment by the US Army in 2007. Most notably, the T-Hawk was used in April 2011, when four conducted video surveillance and radioactivity readings after the level 7 Fukushima Daiichi nuclear incident [24] [25]. Another is the Black Hornet Nano, a 16g rotorcraft developed between 2008 and 2012 by Flir Systems. It's so small the whole system can fit in a pocket, and has mainly been used for surveillance by the British Army in Afghanistan [26]. Both of these examples demonstrate some clear possible uses of Bat Bot in the future – surveillance and monitoring of areas humans can't reach, from earthquake sites to flaming buildings and everything in between.

The developers of B2 also have some other ideas for their creation. Professor Soon-Jo Chung has envisioned potential in the construction industry, saying "With multiple drones you can create a 3D model of your building in almost real time, that can be used in comparison with your CAD design to make sure you are building the structure properly" [4]. Further in the future he also imagines grander applications, with plans to scale the design up to a more human size, to produce flying cars or emergency vehicles with the ability to skip the rush hour traffic [4].

A slightly more unexpected use of Bat Bot is in the research of the very creature that led to its creation – bats. Its creators are so confident in the fidelity of their replication that they believe B2 can reveal in further detail the mechanics of bat flight [19]. Other possibilities include as part of a drone delivery service, or in aiding conservation efforts [27].

Bat Bot also brings a range of specific advantages to these roles. Firstly, it's much safer than many more traditional drones. This is both simply because it's smaller, but less obviously due to B2's lower kinetic energy. With its mass of 93g and velocity of $4ms^{-1}$, it only has around 0.74J of kinetic energy in flight, far too little to do much damage [28]. Its soft, silicon membrane wings are also generally less dangerous than those of its more common rotorcraft cousins, as well as less likely to get tangled in obstacles such as branches or power lines [21][29]. Furthermore, B2 is silent and incredibly manoeuvrable, as explained above, which could help further with stealth during surveillance or similar uses [4]. It's also less affected by strong winds [20], an issue which plagues many MAVs [30]. Finally, on a smaller scale, like that of Bat Bot, FWMAVs require less power than their fixed wing counterparts [31], making them more efficient, and giving Bat Bot yet another favourable quality.

Conclusion

It's imperative that as we enter this new age of micro-aviation, we continue the human tradition of taking inspiration from nature. And no where's better than from our chiropteran cousins, as Bat Bot B2 has proven.

Human flight has existed for only a few hundred years, to varying degrees of success [32]. Bats, however, have been flying for millions of years [6], leading to the evolution of an incredible flight system. This intricate mechanism has given them an edge over their fellow organisms, and is offering the same to us. We must take it.

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