Chapter 21

Technology and Fabrication of Ultralight Micro-Aerial Vehicles

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Abstract Recent advances in micro-air vehicles have produced impressive results for platforms weighing below 50 g. The lightest platforms to take flight with a minimum of functionality are below 0.5 g, but researchers dream of flying at insect size. However, many difficulties occur when scaling down existing technologies. Aerodynamic laws equate to decreased efficiency at smaller sizes and hence more power per weight is required. Current energy storage technologies do not have the required capacity and powertrains are no longer efficient enough. Construction is difficult due to small size and low weight requirements. This chapter surveys the status of current technology and its prospects in miniaturization and shows several examples to illustrate the state of the art and the difficulties in reaching ever-smaller platform sizes.

21.1 Introduction

Natural evolution found many solutions for short and sustained flight, with weights ranging from milligrams for little insects to kilograms for large birds. Human technical evolution has developed standard solutions in the 5 g to the hundreds of tons range. The overlap is very narrow and the dream of some researchers to get closer in size to insects and small birds is indeed the topic of this book.

The last decade has seen an explosion in the field of micro-aerial vehicles (MAV) with the design of ever-smaller platforms capable of flying longer and more robustly than ever before [11, 21]. The main driver in the outdoor MAV field was the Defense Advanced Research Projects Agency (DARPA), which defined the maximum dimension of an MAV at 15.24 cm (or 6 in.) and funded many successful projects. The 56 g Black Widow (Fig. 21.1a) designed by Matt Keennon and the team at Aerovironment [11] was an impressive success in 2000, optimizing the aerodynamic performance of the platform for the size constraints. Flying outdoors, however, implies high speeds and empty space, and thus recent emphasis has been on larger platforms with bigger payloads to get better autonomy, more powerful cameras, and better sensors.

In confined environments, the toy and radio-controlled (RC) hobbyist market contributed the largest advances in MAV technology. The advent of new energy sources, such as lithium-polymer (Li-Po) batteries and increasingly miniaturized actuators, fueled mainly by the RC market, has only recently yielded ultralight MAVs capable of useful mission indoors. Tele-operated flight in confined, room-sized spaces, which implies low speed and sharp turns, was first demonstrated in 2002 by David Liu's design of a 10 g triplane[1] (Fig. 21.1b). The lightest indoor flyer as of 2008, the Shark, was built by Martin Newell[2] (Fig. 21.1c) weighing in at a mere 0.5 g. The Shark cannot carry any payload, however, since saving weight with tricky construction was required just to have it stay airborne and remain controllable.

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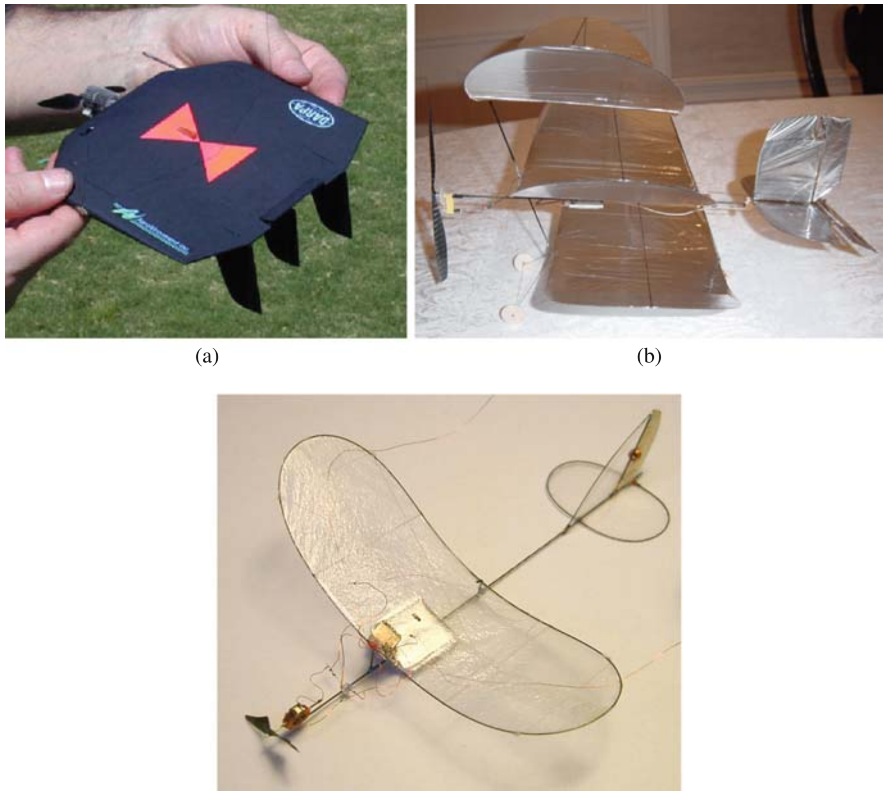
[1] see: http://www.didel.com/DavidLiu.html.

[2] see: http://mnewell.rchomepage.com.

D. Floreano et al. (eds.), *Flying Insects and Robots*,
DOI 10.1007/978-3-540-89393-6_21,



(a) (b) (c)

Fig. 21.1 Aerovironment's Black Widow (56 g) (**a**), David Liu's triplane (10 g) (**b**), and Martin Newell's Shark (0.495 g) (**c**). Figures reprinted with permission from M. Keennon, D. Liu, and M. Newell, respectively

The ability to fly indoors has many applications. Search and rescue in damaged buildings can best be done from the air, due to the large amount of debris blocking ground-based robots and the better viewpoint. Swarms of small aerial vehicles can be used to establish communication and sensor networks inside enclosed spaces. Designing platforms that can fly indoors also presents a unique set of challenges. Constrained environments require slow flight speed to avoid obstacles including people that may be present. Slow flight implies light weight, and building ultralight-weight actuators, sensors, electronics, and energy sources is indeed a great challenge.

MAVs have progressively become smaller and smaller, but how small can MAVs really get? The main object of this chapter is to show the possibilities and limitations of building ultralight flying devices. Different possible platform types will be discussed, along with their prospects of miniaturization. Power and energy requirements will then be looked at, followed by actuators required for flight control. Some aspects have great promise, such as the constant miniaturization of electronics and sensors, whereas other aspects such as energy storage are creating bottlenecks with no immediate solutions. This chapter outlines what is possible today, what may come tomorrow, and what must still be invented before we can expect to efficiently fly in confined environments.

The chapter begins with a description of the different types of flying platforms that fly at small scales and the aerodynamics that govern them. Energy sources are then discussed along with the power plants that convert this energy to thrust which keeps the platforms airborne. Finally the actuators that control flight are discussed and the sensors that are required to fly autonomously.

21.2 Platforms

Practically, there are only a few ways to get off the ground and to remain airborne in the ultralight aircraft range. Chemical rockets are extremely difficult to control, cannot be used indoors, and are not practical at small scales. Jumping and gliding is a possibility (as shown in Chap. 19), but is generally a slow and restricted mode of locomotion, not suitable for many applications. Airships [32, 51, 50] have a very poor lift-to-volume ratio (around $300\,\mathrm{g/m^3}$ for a helium-filled balloon, accounting for the weight of the envelope) and a large inertia which makes them bulky and difficult to fly.

There remain three main solutions for sustained flight:

- fixed wings with forward motion (gliders or powered airplanes)
- vertical rotating propellers (helicopters) or ducted fans
- flapping wings

In all these cases, the speed and orientation of a surface, be it a wing or a propeller, generate a reaction from the surrounding air, creating lift. The challenge is to get enough lift with the available power and to reach a useful maneuverability and payload.

21.2.1 Fixed-Wing Platforms

Fixed-wing platforms, or airplanes, are by far the most successful type of flying platform invented by man. The basic concept is simple: a fixed wing combined with forward speed creates lift, keeping the platform in the air [43]. The forward speed usually comes from a spinning propeller, described in detail in Sect. 21.3.2. The main challenges in designing a fixed-wing plane is to balance wing size and shape, power and total weight. This section first describes the aerodynamics that govern the wing size and shape, then covers the effect of weight on the loading of the wing, and finally the power required to keep a platform of a certain weight airborne.

21.2.1.1 Reynolds Number and Polar Plots

The Reynolds number (Re) is a nondimensional parameter that relates the inertial forces (size and speed of the object) to the viscous forces (dynamic viscosity of the fluid) for an object in given flow conditions. Wings with a chord of L (m) at speed V (m/s) at standard atmospheric conditions in the air have a $\mathrm{Re} = 68{,}000 \times V \times L$ [41]. For example, a wing with a chord of 10 cm flying at 2 m/s in standard air pressures has a Re = 13,600.

At the Reynolds (Re) numbers we are concerned with (1,000 – 20,000), the inertial and viscous effects of the air mix up and there is no reliable mathematical model [41]. Figure 21.2a shows typical polar plots (plots of lift vs. drag) for various Reynolds values. At high Reynolds numbers, the lift to drag (l/d) ratio is maximum (with values between 20 and 60) around incidence angles of 5–10°. At low Reynolds numbers, the l/d ratio is very poor (below 3) [9], that is why insects never soar; they rely as much on drag than lift and have very high incidence angles when moving the wings (described in detail in Chap. 14). This dramatic drop in aerodynamic efficiency of wings for flying platforms below 1 g makes it much more difficult to design fixed-wing platforms capable of actually flying without relying on alternate sources of lift, such as the stable leading edge vortices (LEVs) created by flapping or rotating wings (see Chap. 14 for more details on lift generation from LEVs).

21.2.1.2 Wing Profile

Wing profiles and airfoils (the shape of a wing as seen in a cross section) have been studied extensively in wind tunnels down to Re = 10,000 [33, 35]. Airfoils are characterized by their polar plots (such as the one in Fig. 21.2b), which are plots of lift, drag, and torque for varying angles of attack. These plots can be used to find optimal characteristics such as glide ratios for different operating conditions. Ultralight wings, however, tend to be very flexible and deformable due to the materials used for their construction (see Sect. 21.2.1.4) and are thus difficult to build with enough precision to match the experimental measures. Lift creation due to the wing profile is constantly changing as the wing is deformed in flight, and thus is difficult to model and estimate. Such experiments also require low-speed wind tunnels (more easily found in civil engineering departments than in aerodynamics institutes) and very sensitive balances [33].

In addition, micro-turbulence can considerably help the airflow to stay close to the surface [35], and a

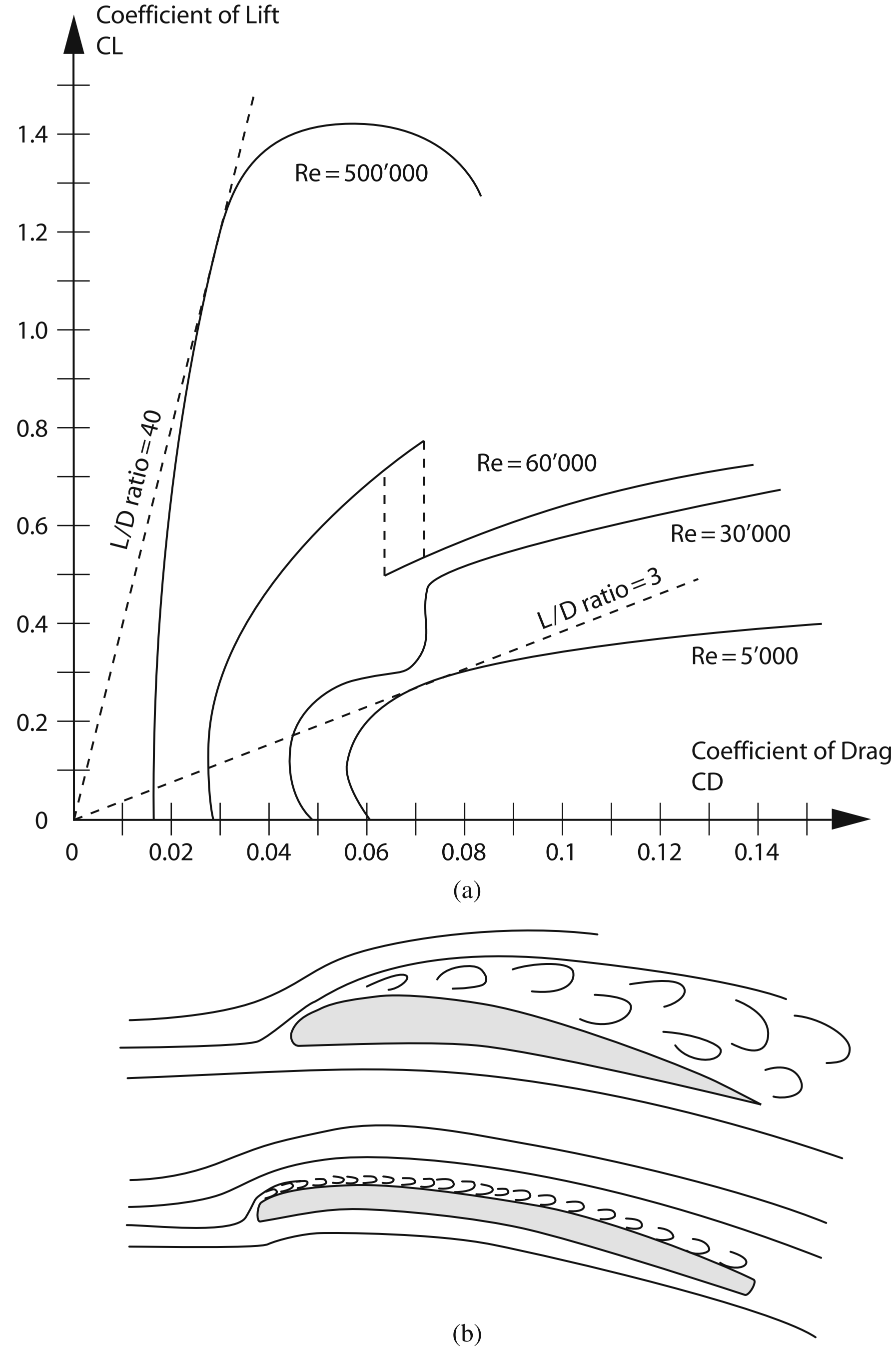


Fig. 21.2 Typical polar plots for an airfoil at high and low Re numbers (**a**). At low Re numbers the l/d ratio decreases significantly. Data collected from several publications and web links. Airflow at low Reynolds number (**b**): the laminar flow separates easily from a perfect surface, while a floppy construction generates turbulence that prevents flow separation

floppy construction with irregularities in the surface can be more efficient than a perfect shape (Fig. 21.2b). Induced micro-turbulence prevents the laminar flow from suddenly detaching close to the leading edge, explaining the hysteresis and irregular curves of the polar plot of Fig. 21.2a. Birds use leading edge barbules, winglets, and alula, sharks have dermal denticles, but engineers have difficulty in reproducing these without adding additional weight that negates their aerodynamic advantages.

21.2.1.3 Wing Loading

Wing loading, the ratio between wing area and total weight of the airplane, influences the flying speed and the power required to maintain horizontal flight, together with the l/d ratio which expresses the aerodynamic performance. Lift is proportional to the square of the speed and to the wing area [41]. Hence, doubling the speed allows to reduce the wing area by a factor of 4 and the wing size by a factor of 2. The power requirement to maintain horizontal flight, however, will double, since as a glider it will fall twice as fast. For a detailed analysis of scaling factors for planes and propellers, see [25]. Typically, lower speed means less power, and hence longer duration flights.

Figure 21.3 presents the wing loading of various small flying platforms as well as some birds. What is interesting to see in the plot of Fig. 21.3 is that MAVs and UAVs follow the same trend as birds. Hobby planes are generally lighter and require less power, partially due to their simplicity and lack of sensors and on-board computation. Ultralight construction is required when the power source must be minimized (such as for human- or solar-powered flight), though this makes them very fragile and sensitive to turbulence (Chap. 20 presents more details on scaling in solar-powered MAVs). The dashed line in Fig. 21.3 represents the limit of what is possible with current construction techniques and we believe that it will move insignificantly as long as completely new materials are not invented for the construction of platforms, and lighter motor and battery technologies are not available.

21.2.1.4 Wing Construction

A large surface area of wing is necessary to sustain flight at the low speeds required for flight in confined environments (for example, the 10 g MC2 robot from Chap. 6 has a wingspan of 4.13 dm^2), and the possibility of collision with obstacles demands robustness in construction. Minimal weight, strength, and crash resistance are thus the important features of a wing. Traditional model and glider constructions with balsa ribs, spars, intrados, and extrados are too complicated and fragile at small scales. Wings cut from a sheet of foam, such as the expanded polypropylene (EPP) type

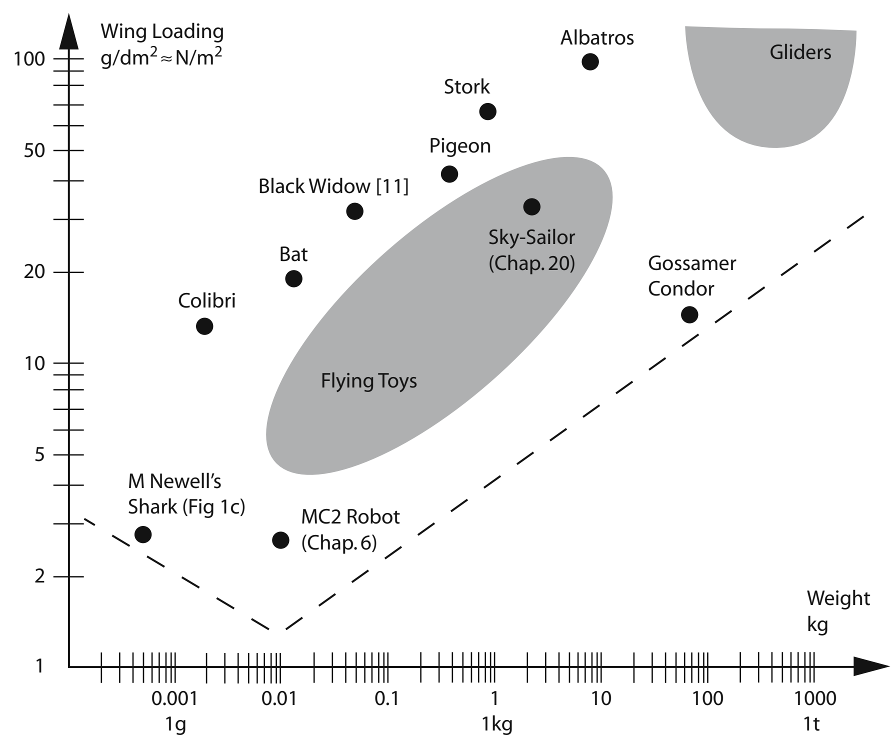


Fig. 21.3 Wing loading of birds and planes of different weights. Data collected from several publications and web links

used for toy planes, are a good solution for outdoor planes but is generally too heavy for indoor flyers with a small wingspan. A 3-mm-thick EPP weighs around 400 g/m^2 (depending on the type of EPP). The best solution currently available is to use carbon rods for the perimeter of the wing and a thin plastic foil (such as Mylar that can weigh only 2 g/m^2) as the wing surface (such as the wing of M. Newell's plane, Fig. 21.1c). Such a construction can result in a 20 cm wing of only 0.1 g, though it is unlikely that any new materials will produce significantly lighter constructions at this scale.

At smaller scales microelectromechanical systems (MEMS) can be used to build small flat surfaces inspired from bat and insect wings [34]. Precision stereolithography may be a solution for 3D pieces used to link hinges, carbon rods, and MEMS. Hand-assembling wings becomes difficult and impractical for wings below 10 cm in size, at which point micro-construction techniques such as stereolithography to produce wing spars become more practical.

21.2.1.5 Power Requirements

The power required to fly depends on aerodynamic and construction constraints. Flight speed must be low for saving power and to permit indoor flight, but high enough to create lift and sustain flight. Fig. 21.4 plots the power–weight ratio on a logarithmic scale for different types of flying platforms, from small insects to large airplanes. From this figure we see that natural evolution has yielded an average aerodynamic power of around 10 W/kg for birds and 15–20 W/kg for insects, with indoor slow flyers in the same range as birds. Ultralight construction can reduce this number when necessary, such as for human-powered or solar-powered flight, though not without consequences to structure robustness and durability. For example, the Gossamer Condor, a human-powered plane, has a very low power-to-weight ratio (5 W/kg) due to its light-weight construction, but is very fragile and would likely be damaged if flown in turbulent atmospheric conditions.

21.2.2 Rotary-Wing Platforms

Rotary-wing platforms remain airborne solely by using the thrust created by one or several propellers, instead of using a fixed airfoil and forward motion. The big advantage is the ability to hover, since no forward motion is required to create lift. The downside is that

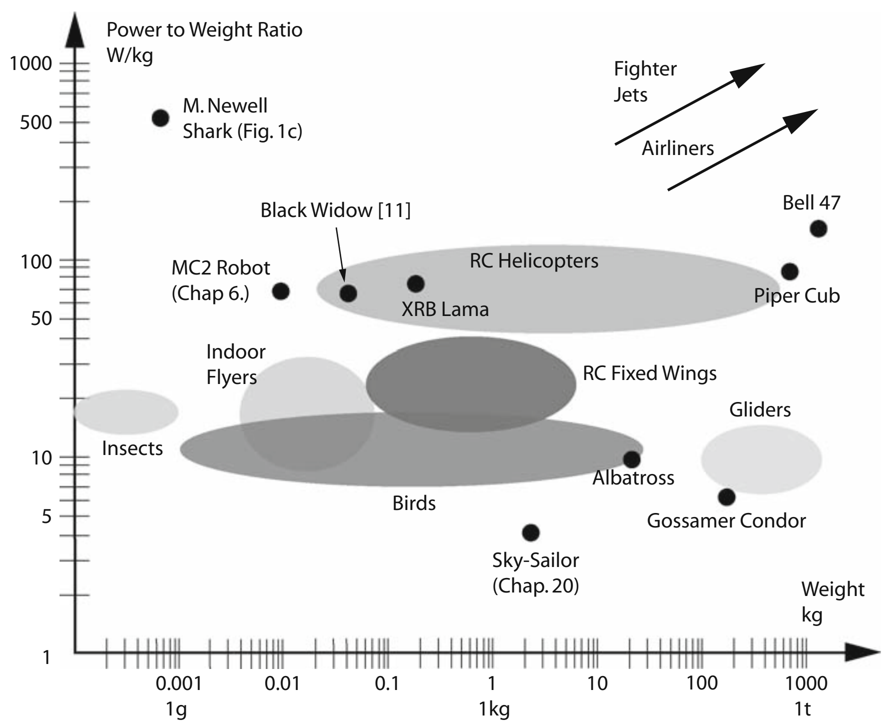
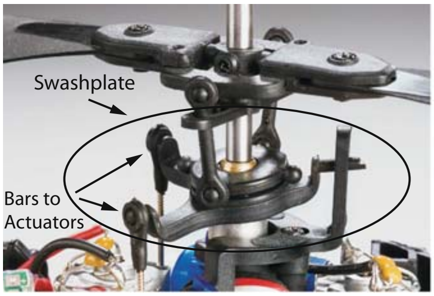


Fig. 21.4 Power to weight of flying objects. The *shaded regions* cover the range of values that each type of platform typically lies in, whereas the *black dots* give specific examples of existing platforms. The *arrows* in the *top-right* corner point toward traditional human-occupied airplanes, which are heavier and have higher power to weight ratios. Data collected from several publications and web links



(a) (b)

Fig. 21.5 Typical swashplate used in RC helicopters (**a**) and P. Muren's 1 g coaxial RC helicopter (**b**). Figure (**b**) reprinted with permission from P. Muren

more power is required to stay in the air (and thus decreased flight time for the same battery capacity), since the high rotation speed of the blades decreases their efficiency as airfoils [36] (see Fig. 21.4). Many types of rotorcraft exist, such as the classic single-rotor [46] (with a tail rotor or deflection vanes), two-rotor designs (coaxial [39] or side by side [27]), quadrotors [12, 17], or even six- or eight-rotor designs.[3] Each construction has its advantages and limitations and is usually chosen based on the application.

The main obstacles to miniaturizing rotary-wing platforms besides the high-power requirements are the complex mechanics. Most rotorcrafts require a swashplate (see Fig. 21.5a) to fully control their attitude in space. A swashplate is a complex mechanism with bearings, control linkages, and rings, all of which have to be precisely manufactured for the device to work. Two actuators are also required to control the cyclic angle of attack of the blades, which have their own miniaturization problems, as described in Sect. 21.4. Fully functioning miniature rotorcraft will thus likely be limited by the ability to miniaturize the swashplate, and thus new configurations must be considered.

It is possible to build rotorcraft without swashplates, however. Petter Muren at Prox Dynamics holds the current record for lightest coaxial rotorcraft at 1 g (Fig. 21.5b). This coaxial flyer only uses two motors without a swashplate, allowing it to fly with thrust and yaw control. The platform does not have any roll or pitch control, however, and thus must have its center of gravity manually displaced to move forward and must turn using yaw control. Active weight shifting can be used instead of a swashplate to steer a rotorcraft in any direction [3], but the additional actuators add weight to the platform.

Another possibility to steer without a swashplate is to use two or more non-coaxial rotors and adjust the speed of individual rotors. A notable example is the quadrotor, which uses four rotors in a cross configuration. Though theorized since the beginning of the 20th century [18], quadrotors are difficult to control and traditionally required complex model-based algorithms to control [4]. It was only recent developments in sensor technology and high-speed electronic stability control that yielded the first practical and stable designs [12]. Quadrotors should be easier to scale down, since they only require four rotating motors and some sensors (which continue to get smaller and more integrated). Their ultimate bottleneck will once again be energy storage, since quadrotors have four motors to power.

21.2.3 Flapping-Wing Platforms

Nature's solution to sustained flight, whether in birds or insects, has been to create lift using flapping wings. In an effort to duplicate nature, humans have been building model flapping-wing platforms or ornithopters for over a century.[4] In the >1 g scale, ornithopters have proven to be a viable solution when hover capability needs to be combined with high-speed flight (Chap. 14 demonstrates the design process of a flapping-wing MAV). The recent release of

[3] Multi-rotor designs by Ascending Technologies: http://www.asctec.de/.

[4] Flapping-wing history: http://www.ornithopter.org.

the Delfly Micro[5] shows the current state of the art in ornithopters, weighing in at a mere 3 g. It is a fully functional platform that is controllable in-flight and has an on-board wireless camera, thus distinguishing it from a mere hobbyist toy.

To reach this low weight, however, the team faced many challenges and had to cut many corners. It is very difficult to imagine that the current strategy of using a motor and a crank to flap the wings can be miniaturized below 1 g, given the complexity of the mechanics and the limitations of motor technology (See Sect. 21.3.2).

New materials, actuators, and construction techniques, however, will yield lighter and lighter insect-like demonstrators, though they start off tethered due to the battery problem. Using a piezo-based actuator with a specially designed transmission has already been demonstrated to create enough thrust to lift the wing/actuator assembly off the ground (as described in Chap. 16), though using off-board power and electronics. Many challenges remain, the first of which is to integrate electronics and the power source onto the platform and be able to lift the entire structure, after which control and sensing can be worked on.

As a final note, it should be noted that the fact that flapping wings are prevalent in nature does not mean that they are the optimal solution to sustained flight. Just as evolution did not invent the wheel which is more efficient on flat ground than legs, flight with a propeller, even at small scales, can be more efficient than with flapping wings [44, 9] (see also the conclusion of Chap. 14).

21.3 Power and Energy Sources

One of the greatest challenges in miniature flying robotics is to stay in the air long enough to perform a useful task. Unlike ground-based locomotion, flying implies a constant fight against gravity, and thus requires a large source of energy to stay afloat (putting aside lighter-than-air platforms such as airships), as well as an efficient power source to transfer this energy into power and thus thrust. This constant thirst for energy can be minimized by landing, attaching to objects [37, 6], or gliding [16] (as seen in Chap. 19) when flight is not necessary, but the problem of sustained flight remains.

Both power and energy must be considered when designing a flying robot. Sustained flight requires power, whereas a long flight time requires energy which is expressed in mW h or J (1 mW h = 3.6 J). As an example from nature, typical bird muscles can provide 200 mW/g of power and store a large amount of energy, approximately 1,000 mW h/g. On top of this a bird can get approximately 10,000 mW h/g from the grease stored in the body, allowing for very long flights [20].

How do these values found in nature compare with current advances in power and energy storage devices? We first discuss energy sources, after which we describe the power plant that transfers the energy into power, and then the propeller that can be used to turn the power into thrust.

21.3.1 Energy Sources

Energy sources can be characterized by their energy density (mW h/g), which is how much total energy they can store, and their power density (mW/g), which is how fast they can sink or source this energy. Figure 21.6 shows the state of the art of electrical energy sources on the market in 2008.

There are many options for energy storage, which depend on the power plant being used. Springs and rubber bands need to be loaded and are difficult to control, and thus are not very practical. Microturbines [10, 28] can be used that run off chemical explosions, but are still too early in the development stage to be used on flying platforms. Current power plants are thus all based on electrical power, which can be supplied by batteries, supercaps (double-layer capacitors or DLPs), or fuel cells.

For flying robots the primordial question is: what will be the flight time? Adding a higher capacity energy source increases flight time, but weight is always at a premium, and above a certain weight a platform cannot produce enough thrust to get off the ground. Using too small of an energy source, however, produces flight times that are not long enough for practical applications. An optimum flight time can generally be found by building a model of the energy source based on the above-mentioned parameters [37, 11, 45].

[5] The Delfly project: http://www.delfly.nl.

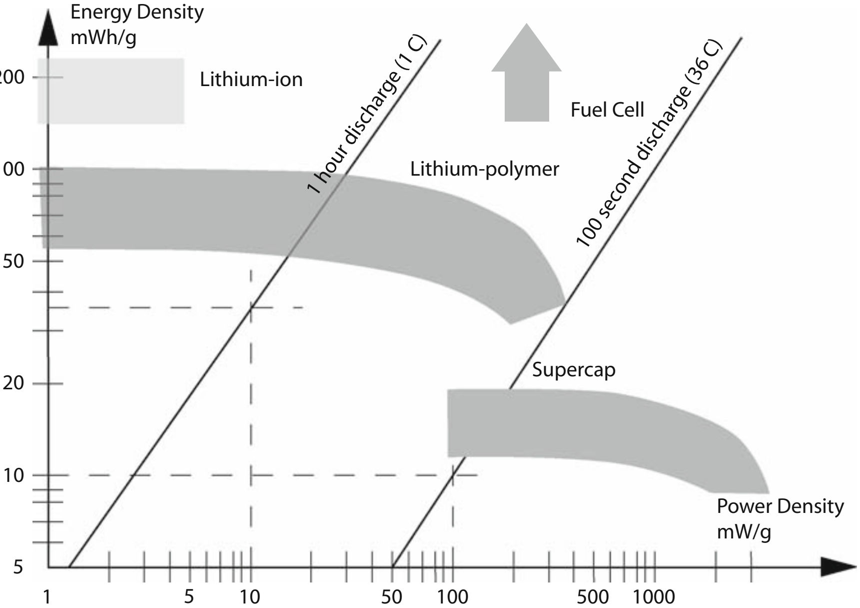


Fig. 21.6 Power and energy densities of various electrical energy storage devices. Internal resistance and saturation limit the power density and higher energy-density technologies cannot discharge very fast. Data obtained from various manufacturer sources

21.3.1.1 Batteries

Rechargeable batteries are the most common source of energy currently used on miniature flying platforms due to their ease of use, general commercial availability, and good energy density. Standard chemistries are either nickel based (nickel–cadmium, NiCad, or nickel-metal-hydride, NiMH) or lithium based (lithium-ion, Li-Ion, or lithium-polymer, Li-Po). Nickel-based batteries are cheaper, but lithium-based batteries are generally preferred due to their higher energy density, which is crucial in flying platforms where lower weight translates into higher flight times.

The two important parameters when determining the size of a battery are the internal ohmic resistance and the total capacity. Internal resistance (due to the electrode chemistries) limits the power density of the battery and can vary between different sizes of a battery due to the total resistance of the electrodes. Capacity is similar to energy density, but provides a more realistic understanding of the amount of energy that can be obtained from a particular cell. Since the voltage of a cell varies during its discharge cycle, capacity is measured in mA h and relates the time it takes to fully discharge a cell using a constant current. Another useful parameter is the discharge rate or C-value. A one C expresses that a fully charged battery will discharge in 1 h (e.g., for a 100 mA h battery the 1 C discharge current is 100 mA). Manufacturers of batteries specify a maximum discharge rate, so a value of 15 C means that the battery can deliver a current of 15× the 1 C current (and the battery will be discharged in 4 min), though such a rate may damage a cell and decrease its life cycle. In addition, a high discharge rate increases the energy lost across the internal resistance of the cell, and thus a battery discharged at 15 C will discharge quicker than the predicted 4 min [13].

Li-Po cells are currently the most popular battery for flying platforms, and significant progress in recent years has increased energy densities into the 180 mW h/g range. The main advantage of Li-Po cells as opposed to traditional Li-ion cells is that they use a gel electrolyte instead of a liquid one and thus do not require a metal case, but use a flexible case instead. This lighter casing provides a large weight savings, which effectively increases a Li-Po cell's capacity per gram, and allows smaller sizes and custom shapes of cells.[6] Li-Po cells are available in capacities as small as 5 mA h, whereas the smallest Li-ion cells are around 1,000 mA h. The discharge rate for Li-Po cells is 20 C above 200 mA h, but only 3 C for the small capacities due to high internal resistance. This is something

[6] Aerovironment's WASP, an outdoor MAV with custom-shaped Li-Po cells built into its wings: http://www.avinc.com/uas_product_details.asp?Prodid=4.

to keep in mind when building ever-smaller platforms with high-power needs.

For larger platforms Li-ion batteries are more competitive, since they are generally cheaper, have better performance (including energy densities above 240 mW h/g), and longer life cycles. Fueled by the consumer electronics industry, recent work using new materials such as nanowires promises capacities 10 times higher [5] than current batteries. Though these claims have yet to produce consistent results, it is clear that both Li-ion and Li-Po batteries are not at the end of their evolution, and the future promises more powerful batteries using both technologies.

21.3.1.2 Supercaps

Supercaps have several advantages over conventional batteries. Unlike batteries, their charge and discharge rate is limited only by the heating of their electrodes. They have a much higher power density and are able to provide large power pulses. They can be charged almost instantaneously, allowing flying robots to return to the air quicker and thus perform longer missions. Supercaps also have a high life cycle (above 300,000 cycles, compared to 100–300 for Li-ion and Li-Po cells [26, 13]).

Their main disadvantage at the moment is their limited energy density, with current commercial supercaps rated at only 6 mW h/g (compared to around 240 mW h/g for Li-ion or 180 mW h/g for Li-Po batteries). Recent work with carbon nanotubes [42, 40] or barium titanate,[7] however, promises supercaps with an energy density of 60 mW h/g or 200 mW h/g, respectively, which makes them competitive with current battery technology. Though high-capacity supercaps are still in prototype form and currently made in large sizes suitable for automobiles, the technology should definitely be followed closely in the next few years.

21.3.1.3 Hydrogen Fuel Cells

Hydrogen fuel cell technology seems to have a bright future, and is driven both by the automotive and the mobile consumer devices industries. Large fuel cells have already been used in public transportation,[8] and smaller ones are being used for portable power generation and in cars. Toshiba is one of a few companies that is exhibiting prototypes of miniature methanol-based fuel cells for use in portable media players,[9] promising 100 mW in a 17 cm^3 package, though production models have not yet been released.

The need for a better power source for ever-smaller portable electronics has fueled research into in-silica fuel cells built using standard microfabrication techniques [48, 30]. This area of research is very promising and may well lead to energy packs for MAVs that are efficient and can be quickly refilled. It is unlikely that they will be miniaturized below the 1 g range, however, since they require a reservoir for hydrogen that has to be small yet still refillable.

21.3.2 Power Plants

Miniature flying robots generally require a main power source to remain in the air, and most of them use rotary motors for this task, either to spin a propeller or to flap wings. Different types of rotary motors exist today, including DC, brushless, or ultrasonic (piezo) motors.

21.3.2.1 Brushed DC Motors

Traditional brushed DC motors are the most common type of electric motor in the hobbyist market, can be very efficient (providing up to 300 W/g), and are commercially available in a variety of sizes (Fig. 21.7a). Their main advantage is their ease of use, since they can be driven and regulated simply by using a constant voltage. It should be noted, however, that these mass-produced motors are meant for pagers, not flying robots. To produce significant thrust they must be run continuously at overvoltage, which quickly damages the motors and reduces their useful lifetime. These motors also do not scale down well below around 5 mm of diameter. The latest advances in magnets have improved their performance, but short rotor-stator gaps

[7] See: http://en.wikipedia.org/wiki/EEStor.

[8] See: http://www.ballard.com.

[9] See: http://www3.toshiba.co.jp/ddc/eng/dmfc/index.htm.

(a) (b) (c)

Fig. 21.7 Brushed DC pager motors (**a**), from *left to right*: Seiko 2.8 mm (discontinued) (0.16 g), 4 mm (0.51 g), 6 mm (1.58 g), 7 mm (2.70 g). Small brushless motor (1.4 g) from WES-Technik (**b**), Martin Newell's custom-built brushless motor (45 mg) (**c**). Figure (c) reprinted with permission from M. Newell

and well-filled coils are difficult to manufacture at the millimeter scale.

Brushed motors perform at maximum efficiency around 10,000 rpm, and thus a gearbox is often used to reach the desired propeller speeds of below 1,000 rpm (see Sect. 21.3.3.1). Gearboxes add some weight and sink some of the power produced by the motor, but allow for a bigger, more efficient rotor to be used, and can thus increase the overall efficiency of the powertrain (see Sect. 21.3.3). Finding an optimum between motor size, gear reduction, and propeller size is important when using DC motors, which requires testing and can be limited by the material that is commercially available.

21.3.2.2 Brushless DC Motors

Brushless DC (BLDC) electric motors (Fig. 21.7b) have recently revolutionized the hobbyist market due to their generally increased power to weight ratio compared with their brushed counterparts (up to 40 times higher as shown in Chap. 20). The lack of a mechanical commutator translates to higher efficiency due to the lack of friction between motor and stator. Better cooling and thicker wires allow more current in the coils, while multiple poles reduce the rotation speed which permits BLDC motors to be used without a gearbox, saving additional weight. For flying platforms of more than 10 g BLDC motors have effectively replaced brushed motors in RC applications.

BLDC motors have two main disadvantages, however. First, their commutation is electronic, and thus a fairly complex controller is required, which can often be heavier than the gearbox of a DC motor. The electronic controller also needs to know the position of the rotor, which requires an additional sensor on the motor. Sensorless options exist that measure position based on the counter-electromotive force (the voltage produced by the spinning motor, often called back-EMF) of the motor, but are hard to implement on smaller motors that produce very low back-EMF [1]. Recent BLDC controllers[10] have been made at under 0.3 g, however, and given the trend in miniaturization of electronics, the weight of the control electronics will likely not be a bottleneck in the development of BLDC motors.

BLDC motors' second disadvantage is their initial cost and difficulty in manufacturing. Current motors on the market are mostly hand-wound, and motors below 5 g are difficult to manufacture and suffer in precision and efficiency due to inaccuracies in construction. Current state of the art includes commercially available motors in the 1 g range[11] (up to 20 g thrust, Fig. 21.7b), though Martin Newell's home-made 45 mg motor[12] (Fig. 21.7c) demonstrates what can be achieved with some tricks such as gluing the controller to the motor and not using a casing. New manufacturing techniques should continue decreasing the size of BLDC motors.

21.3.2.3 Other Power Sources

The predominant power source used in large aircraft is not the electric motor but the gasoline combustion engine or turbine. Attempts have been made at miniaturizing this technology in the form of microturbines

[10] Examples can be found at: http://www.microinvent.com.

[11] Examples can be found at: http://www.wes-technik.de/.

[12] See: http://mnewell.rchomepage.com/Planes/Shark/Shark-1.html.

of less than a centimeter, and initial results can already deliver 780 mW/g [28]. Microturbines run at very high speeds, however (above 100 k rpm), and thus require a large reduction gear, adding weight and reducing efficiency. Microturbines are still in the development stage and have many challenges to overcome before they can be used on miniature flying platforms, and thus are not likely to replace electric motors anytime soon.

Piezo-based technology becomes very promising at a scale below 1 g. Piezo-based ultrasonic motors promise rotating motors in the milligram range, with working 1 mm diameter motors already demonstrated [49]. Piezo-based linear actuators coupled to a miniature transmission have also been used to power ultra-light wings [47] (see Chap. 16). Piezo-based actuators require high voltages (in the 100 V range), though modern advances in electronics should be able to provide efficient and low-weight solutions to this voltage transfer in the years to come. For an in-depth review of actuation and power electronics at sub-1 g scales, see [14].

21.3.3 Propellers

With the exception of flapping-wing platforms, rotary motors convert power to lift through the use of a propeller, which is generally made up of two wings attached together in-line. There is no easy formula to select the right propeller for an application, since its shape depends on many factors, including rotation speed, gearbox and motor used, and aerodynamic conditions. As for materials, the weight of plastic propellers becomes significant above diameters of around 50 mm so the best material at the moment is carbon fiber, which can be custom-built to size using impregnated carbon sheets.

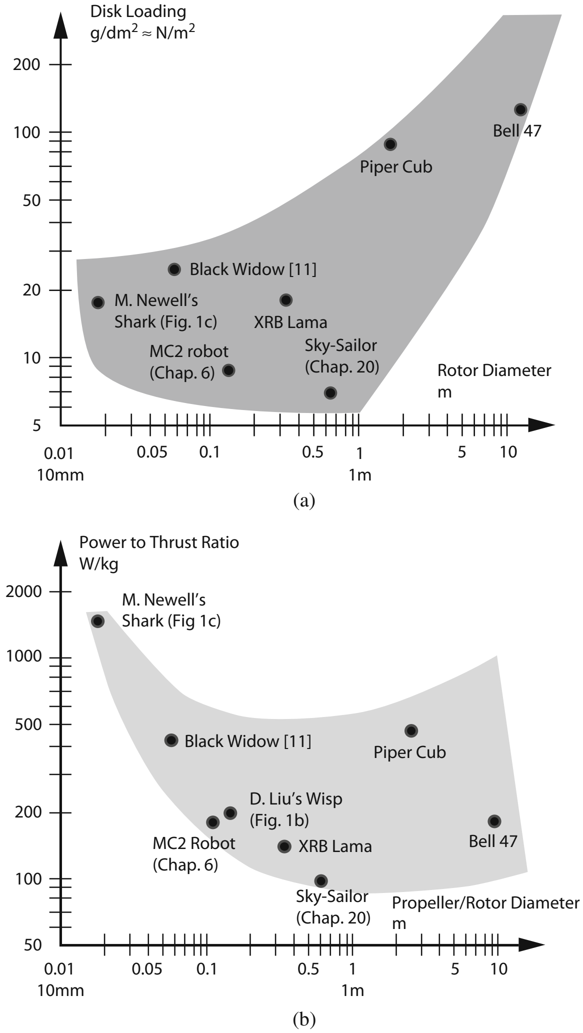


Fig. 21.8 (**a**) Disk loading range for propellers and rotors. Several representative platforms are shown by *black dots*. Solar planes (such as the Sky-Sailor) and indoor slowflyers have low disk loading for slow or efficient flight, whereas outdoor platforms such as the Black Widow fly faster and thus have higher disk loading. (**b**) Power efficiency for different propeller and rotor sizes. Differences in rotation speed explain the wide range in the power to thrust ratio. Data collected from several sources

21.3.3.1 Propeller Sizing

Disk loading is the analogy of wing loading for rotating propellers and is defined as the ratio between the area of the disk formed by the spinning rotor and the generated thrust required to keep the platform airborne. Disk loading is an important parameter when choosing the size of a propeller and is plotted in Fig. 21.8a. As demonstrated by the dispersion shown in the figure, however, rotation speed also needs to be considered, and using or not using a gearbox also influences the required diameter of the propeller. Thus the design of the powertrain must be taken as a whole, where the propeller is matched to the motor and the gearbox to get the required thrust with the minimum power. A good example of a powertrain design using multidisciplinary design optimization (MDO) can be seen in [11].

The thrust of a propeller is theoretically proportional to D^4N^2, where D is the diameter and N is the rotation speed of the propeller [25]. This holds as long as the propeller does not change shape due to stress or the tip reaches sonic speeds. Due to construction precision and lower Reynolds numbers on small propellers, the thrust for a given rotation speed degrades when the diameter gets small.

Figure 21.8b plots the power to thrust ratio of different-sized propellers. Typical values for large propellers are 200 mW/g, though this value increases significantly for propellers below 50 mm due to the low Re number of the propeller and the low efficiency of the motor. Similitude laws show that this ratio decreases linearly with the rotation speed [25], and designers should be aware of this: reducing the diameter by 70% and doubling the rotation speed give the same thrust, but cost twice the power. Large propellers and high gear ratios are usually the most efficient but are more fragile and dangerous, and are only used on solar planes (like the Sky-Sailor described in Chap. 20) and models specifically designed for long-duration flight.

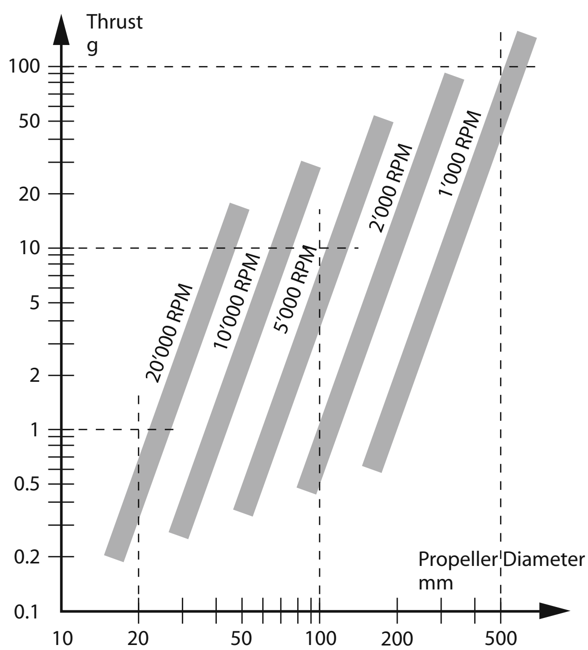


Fig. 21.9 Propeller thrust vs. rotation speed, based on experimental results with various propellers
Source: http://www.didel.com/slow/propellers/

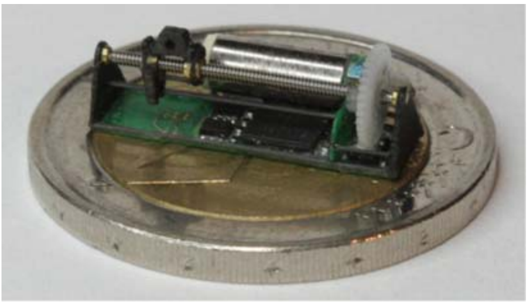
Figure 21.9 is useful to get the approximate values of the diameter for a given thrust once the rotation speed is known from the motor/gearbox combination at max efficiency or max power. As mentioned before, a gearbox and a large propeller are always good for energy saving if they do not bring too much weight.

21.3.3.2 Ducted Fans

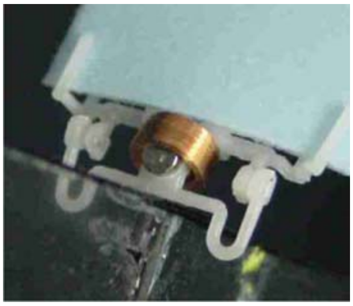
Ducted fans increase the aerodynamic efficiency of traditional propellers by reducing losses from tip vortices and increasing rotation speed (due to the smaller size of duct blades compared to propellers) [31]. At small scales, however, this advantage is more than neutralized by the added weight of the duct and losses due to the use of a small disk diameter, and thus ducted fans are not generally used at small scales. Protection rings around propellers, however, have a different purpose, protecting the propellers from damage as well as protecting the environment from the fast-turning propellers. If built correctly they add minimum weight and drag, while increasing the robustness of the platform which is important when working at small scales with fragile materials.

21.4 Control Actuators

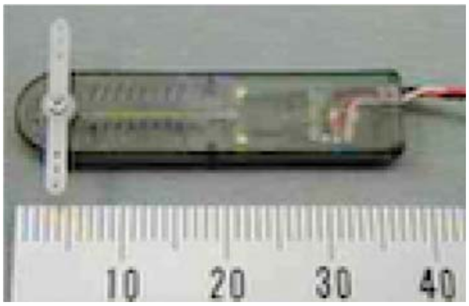
Though thrust is sufficient to be airborne, a flying machine is only useful if it can be controlled, and thus actuators and control surfaces are generally required. The type of control surface depends on the type of platform. As mentioned in Sect. 21.2.2, certain multirotor rotorcrafts can be controlled in attitude simply by varying the speed of their motors, and thus do not require any control surfaces. Other rotary-wing platforms maneuver by changing the pitch of their blades using a swashplate, by deflecting the airflow of the rotor in a desired direction using control surfaces or by shifting the center of gravity [3], all of which require actuators. Fixed-wing and flapping-wing platforms generally use control surfaces, notably an elevator and a rudder (and optionally ailerons). Several common control actuators are presented below.



(a)



(b)



(c)

Fig. 21.10 Servo by Prox Dynamics AS (0.49 g) (**a**), currently the lightest classical servo controllable in position. Didel PolyBIRD (0.25 g) (**b**), controllable only in torque. Toki SmartServo RC-1 (0.8 g) (c), a shape memory alloy-based position-controllable actuator. Figures (**a**) and (**c**) reprinted with permission from N. Zimet and Toki Corp., respectively

21.4.1 RC-Servos

RC-Servo-motors (or servos) are the most widely used control surface actuator in the hobbyist market and are an excellent solution in platforms as low as 10 g. Servos are generally made up of a geared electric motor to provide torque, a feedback potentiometer on the end shaft, and control electronics to set the position. They can be used to accurately set the position of a control surface or the pitch of helicopter rotor blades. The torque to weight ratio of RC-servos is in the range of 30–100 gcm/g, and the current draw, 100 mA for the lightest, occurs when they move.

The last few years have yielded some very light servo designs based on a lead screw and linear potentiometer. The current record for the lowest weight for a servo is 0.49 g. Developed by Prox Dynamics AS[13] for use on miniature rotorcraft, it has a 10 mm range of motion with a resolution of 0.10 mm (Fig. 21.10a). Servos of this size, however, are still hand-built under a microscope and are not available on the market.

[13] See: http://www.proxdynamics.com.

Wobble motors [7] could be an interesting solution for even lighter servos and have been researched for the last 10 years. Theoretically they can go down to 0.3 g, including required electronics, but they have not yet reached production status.

21.4.2 Electromagnetic Actuators

Electromagnetic actuators are probably the most widely used actuators for platforms in the range of 1–10 g (see Chaps. 6 and 14). Based on a small magnet rotating inside a coil (Fig. 21.10b), they are often called BIRD (built-in rudder device) in the hobby field, are commonly available from many sources, and can weight anywhere from 2 g down to 0.1 g. Not only are they lighter than servos, they are also simple to control, fast, low cost, and easy to install. The torque of the actuator is proportional to the magnet weight (only the best NdFeB magnets are used) and to the magnetic field. The downside of these actuators is that they are controllable only in torque and not position, and thus their position is dependent on the external forces on the control surface, which can vary greatly during a flight. They are best used if a servo of the same weight does not exist. The torque to weight ratio is about 2 gcm/g with a current in the range of 50 mA. Proportional control is done by pulse-width modulation (PWM).

21.4.3 Shape Memory Alloys

Shape memory alloy (SMA) wires of 25 or 35μm have seen some limited use in flying platforms, especially at very small size (below 5 g). The most common material used for SMAs is nickel–titanium (NiTi) with a special thermal treatment that results in two different atomic structures. At high temperature (typically 80° C), NiTi wires take the shape learned during the thermal process, whereas at low temperature they return to their original shape. Frequently named muscle wires, they can shorten by about 4%. Though the force provided is substantial, the response time is relatively poor (0.1+ s). NiTi wires have been used for ultralight rudder actuators down to 0.1 g [15] (see Chap. 19). This custom solution remains delicate, however, since handling of 25μm wires that cannot be soldered is not an easy task. SMA actuators have some promise, with a commercial product weighing 0.8 g[14] (Fig. 21.10c) already available with an announced torque of 15 g/cm for an average current of 30 mA.

21.4.4 Electro-Active Polymers

Electro-active polymers (EAP) [2] are actuators based on polymers that deform when subjected to an electric field. There are two main types of EAPs: ionic EAPs based on the mobility or diffusion of charged ions and electronic EAPs based on electrostatic forces between electrodes that squeeze the polymer.

Ionic EAPs react at low voltages and can provide a good force but are generally slow (0.1–10 s reaction times) and more power consuming, since they require energy to remain at a given position. Their main problem, however, is that they must be wet and degrade quickly if dried, and thus must be sealed inside flexible coatings that add an unacceptable weight for an MAV. Electronic EAPs react more quickly than their ionic counterparts and deliver stronger mechanical forces. They do not have to be wet like ionic EAPs but they require a much higher voltage and provide smaller displacements. Low-voltage EAPs can also be used for sensor applications. Because EAPs are a variable capacitor and variable resistor, force and position sensing can be achieved by measuring the change in capacitance or resistance in the deflected material [2].

It is difficult to predict the future of EAPs. They have been around for 20 years and are still not competitive, although their intrinsic characteristics are attractive. They have seen limited use in robotic prototypes such as walking robots and even flapping-wing mechanisms [29], though they have yet to be seen actually flying.

21.5 Sensors and Processing Power

Sensors and on-board processing are what separate a flying robot from radio-controlled toys. Birds and insects have an incredible number of sensors that they use for general navigation, control of flight, and energy saving. Current MAVs use only a few sensors to avoid the ground and obstacles (as described in Chap. 6) and to reach their target [15] and are only successful in controlled environments with very simple tasks. If MAVs are to come close to flying like their counterparts in nature, the number of sensors must increase, while their size and weight must decrease.

Although the challenges in sensing are great, it is also one of the fields where we can hope for the most improvement over the coming years. In the last decade the size and power consumption of processors have not stopped shrinking, with powerful microcontrollers now available below half a gram. MEMS have miniaturized sensors to the chip scale, with commercially available multi-axis accelerometers and rate gyroscopes now being built into a single package.[15]

21.5.1 Obstacle Avoidance

Autonomous flight in cluttered environments implies obstacle avoidance. Classical robotics uses laser,

[14] See: http://www.toki.co.jp/BioMetal/.

[15] Such as the Analog Devices ADIS16350 3-axis accelerometer and gyroscope, see: http://www.analog.com/.

infrared, or ultrasonic transmitters and receivers to detect distance to obstacles. Standard parts have been developed for mobile robots and can be used on larger MAVs. Lasers are currently quite bulky due to the lenses required to focus a laser beam. Infrared technology uses solid-state transducers and is thus readily miniaturizable, with consumer proximity sensors available down to 20 mg.[16] Ultrasonic sensors have a wider beam and are practical for measuring the distance of an MAV to the ground or the ceiling [38], though they are quite large and require high voltages to actuate the piezo membrane.

All these solutions are active, however, and thus not practical for very small, power-strained applications. Vision is the most powerful passive obstacle detection mechanism. Miniaturization of vision chips, fueled by the mobile phone industry, has yielded cameras similar in size and resolution to bird eyes. The main challenge in larger MAVs is to match the image processing capabilities of bird brains, and to do this with an onboard processor instead of a computer on the ground. Embedded processors are still following Moore's law, thus there is hope that we will one day be able to run advanced image processing algorithms directly onboard MAVs.

As MAVs get smaller, however, the dream for advanced binocular vision may have to be abandoned in favor of low-resolution optic flow-based vision systems, the same as are featured on insects. In conjunction with MEMS rate gyroscopes, optic flow can be useful for obstacle avoidance and flight stabilization [8], and sensors integrating vision with optic flow detection are already quite advanced [24] (see examples of this in Chaps. 3, 5, 6, and 8).

21.6 Conclusion

The last decade has seen great improvements in MAV technology, with outdoor platforms capable of near-autonomous flight and complex missions [11, 19], and indoor autonomous platforms weighing less than 10 g (as in Chaps. 6 and 14). The recent explosion of indoor flying toys, made possible by mass production, miniaturized electronics, and the advent of Li-Po batteries gives the impression that indoor flight is a solved problem. Indeed it is easy to fly in the 10–20 g range, and it is interesting to see the variety of solutions on the market. The next challenge in aerial robotics research for confined spaces is to improve the intelligence and autonomy of the platforms, as the weight of the required sensors and computing is still not negligible. As for the 50–200 g range of outdoor MAVs, the technology already exists to complete useful missions, such as monitoring forest fires [23] or providing medical aid to remote communities [22].

A great challenge remains, however, for platforms below 10 g. Construction is very delicate, with current materials and manufacturing techniques ill-suited for miniature structures. Aerodynamic efficiency decreases drastically at low Reynolds numbers, while current motor technology loses efficiency at small sizes. Battery technology is getting close to its chemical limit and is far from having the energy density required for useful prolonged flight at sizes below 1 g. Though we can hope for 20–100% improvements in current technologies, there remains the challenge of packaging the batteries in a small enough size.

Besides the problem of creating a platform that can sustain flight, there still remains the problem of designing sensors and actuators that are small and accurate enough to control the flight of an insect robot. This chapter does not cover the fact that we are still missing (even for heavier models) agile flying concepts, good obstacle detection sensors, adequate avoidance strategies, and crash recovery mechanisms. The gap between flying robots and nature's flyers is still very wide and promises many challenging research directions for the future such as robust obstacle avoidance (see Chaps. 5 and 6) or integrated actuators for lift, propulsion, and control (see Chap. 12).

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[16] Such as the Fairchild QRE1113, see: http://www.fairchildsemi.com/.

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