Official URL: https://doi.org/10.1017/9781316335765.002

Moschetta, Jean-Marc and Namuduri, Kamesh Introduction to UAV Systems. (2017) In: UAV Networks and Communications. Cambridge University Press, Cambridge, 1-25. ISBN 9781316335765

1 Introduction to UAV Systems

Jean-Marc Moschetta and Kamesh Namuduri

This chapter provides the background and context for unmanned aerial vehicles (UAVs) and UAV networks with a focus on their civilian applications. It discusses, for example, the types of UAVs, fuel, payload capacity, speed, and endurance. It will also discuss the state-of-the-art in engineering and technology aspects of UAVs and UAV networks and the advantages of UAV networks, including enhanced situational awareness and reduced latency in communications among the UAVs. It presents the applications of UAV networks, research opportunities, and challenges involved in designing, developing, and deploying UAV networks, and the roadmap for research in UAV networks.

Over recent decades, many different terms have been used to refer to UAVs, the most recent of which being remotely piloted aerial system (RPAS), which insists that the system is somehow always operated by somebody on the ground who is responsible for it. The term is very much like the old name for UAVs of the 1980s, that is remotely piloted vehicle (RPV). The RPAS puts emphasis on the fact that the aerial system includes not only the flying vehicle but also, for example, a ground control station, data link, and antenna. It also provides room for the case where several aircraft belonging to the same system may be remotely operated as a whole by a single human operator. In that case, it is not possible for the operator to actually control each flying vehicle as if he or she was an RC pilot.

Yet, in aeronautics, piloting an aircraft basically means flying an aircraft. It has a very precise meaning which is related to the capability to control the attitude of the vehicle with respect to its center of gravity. While most UAVs are remotely operated, they almost all have an on-board autopilot in charge of flying the aircraft. Therefore, it is not a remotely piloted vehicle but only a remotely *operated* vehicle where navigation commands are sent to the aircraft. Furthermore, navigation orders such as waypoints, routes, and decision algorithms may even be included in the on-board computer in order to complete the mission without human action along the way. In this way, human judgment is devoted to actions at higher levels, such as decision making or strategy definition. The term “remotely operated aircraft system” (ROAS) would therefore make more sense to the current scientific community.

Nevertheless, in the present book, the classical terms UAV or UAS have been chosen to refer either to the aerial vehicle itself (UAV), or to the whole system (UAS), which classically includes a set of UAVs (or possibly one), a control station, data links, a support equipment, and human operators.

1.1 Introduction to UAV Types and Missions

Many authors have already proposed various classifications for the different kinds of UAS. One may classify UAS by vehicle types, sizes, mass, mission range, altitude, endurance, etc. Each kind of classification is a way to point out a particular feature, but is doomed to hide another important aspect of UAS. Most lectures given on UAS start with a classification of UAVs based on some sort of conventional typology including: high altitude long endurance (HALE), medium altitude long endurance (MALE), tactical UAVs, vertical take-off and landing (VTOL) UAVs, and mini- and micro-UAVs. The main drawback of such descriptions is that they are basically based on existing systems, mixing mission capabilities (VTOL, long endurance), size (mini or micro), and other features such as altitude (high or medium altitude). Such a classification does not provide a comprehensive outlook of the various choices as applied to missions and vehicle configurations. Furthermore, it makes it very difficult to anticipate future UAS since it is rooted on the existing UAS market segmentation.

A more appropriate way to classify the different kinds of possible UAS would be a double-entry matrix to combine typical mission profiles and the major vehicle configurations.

Mission profiles may include:

1. Recognition missions (outdoor/indoor) requiring VTOL capabilities,
2. Surveillance missions (close range/long range) requiring long endurance capabilities,
3. Other specific missions such as delivering goods, monitoring special facilities ranging from wind turbines to nuclear plants, some tactical missions in the military domain requiring covertness (low acoustic and radar signature), and robust transmission.

In terms of mission profiles, it should be pointed out that most end-users have difficulty in actually defining their mission requirements without resorting to the prior definition of a configuration at the same time. Yet, it is very important in the UAS design process to properly distinguish between mission requirements and the payload/vehicle definition. For instance, in order to survey a remote area in the ocean, one may specify the size of the area, the distance between the launch zone and the area of interest, the maximum time allowed to get the required piece of information, additional practical constraints related to logistics, regulations, operating costs, etc. If the remote area is far from the launch zone, one has to select a long-range vehicle. If the remote area is not that far but permanent surveillance is required, the system may consist of either a single long-endurance vehicle or a fleet of smaller vehicles, each vehicle having a limited endurance but providing almost unlimited surveillance capability by taking turns between vehicles. The latter option may represent a much better trade-off between cost and mission performance than the former option. Indeed, a small vehicle, which is easier to deploy than a larger one, may also be equipped with a cheaper payload since it is devoted to a much smaller surveillance area.

Vehicle configurations are typically split into three main categories: fixed-wing, flapping-wing, and rotary-wing configurations. One should add a fourth category which combines any of the first three categories. The fourth category would mainly include convertible vehicles, either tilt-rotor, tilt-wing, or tilt-body platforms. It would also include most of the existing ornithopters, which usually combine flapping wings and a fixed-wing control surface, which plays the role of a tail or elevator. Other vehicle configurations, such as airships and paragliders, may be considered as a separate category, although they represent a smaller portion of current and future UAS.

1.1.1 Fixed-wing UAVs

Fixed-wing UAVs may typically range from micro-sized UAVs, also called micro air vehicles (MAVs), up to UAVs almost larger than any existing conventional aircraft. An example of a small fixed-wing MAV is given by the Wasp from AeroVironment, a 41-cm span electrically powered flying wing of 275 grams. Even smaller fixed-wing MAVs may be designed, such as the 10-cm span flexible-wing MAV developed by Professor Peter Ifju from the University of Florida in 2005 (see Figure 1.1) [26].

As opposed to extremely small-scale fixed-wing UAVs, the Boeing “SolarEagle” (Figure 1.2) is supposed to be a “satellite-drone” which can fly virtually 24/7 thanks to its solar cells covering the upper part of its wings and the very stringent constraints on the airframe fabrication to make it as light as possible. The 130m span fixed-wing

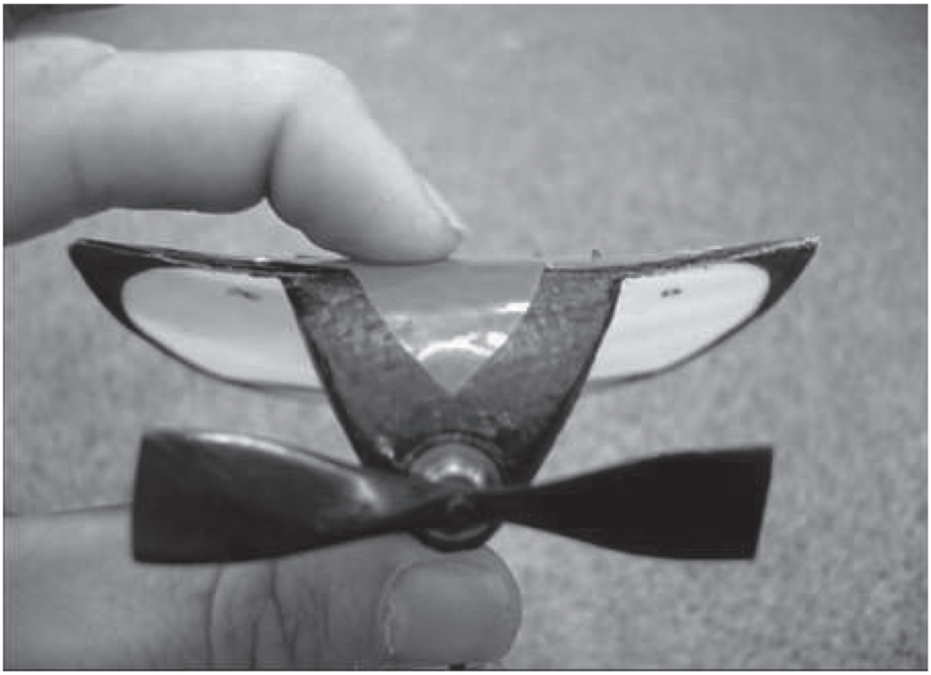

Figure 1.1 A 10cm-span fixed-wing MAV (Courtesy of Michall Sytsma)

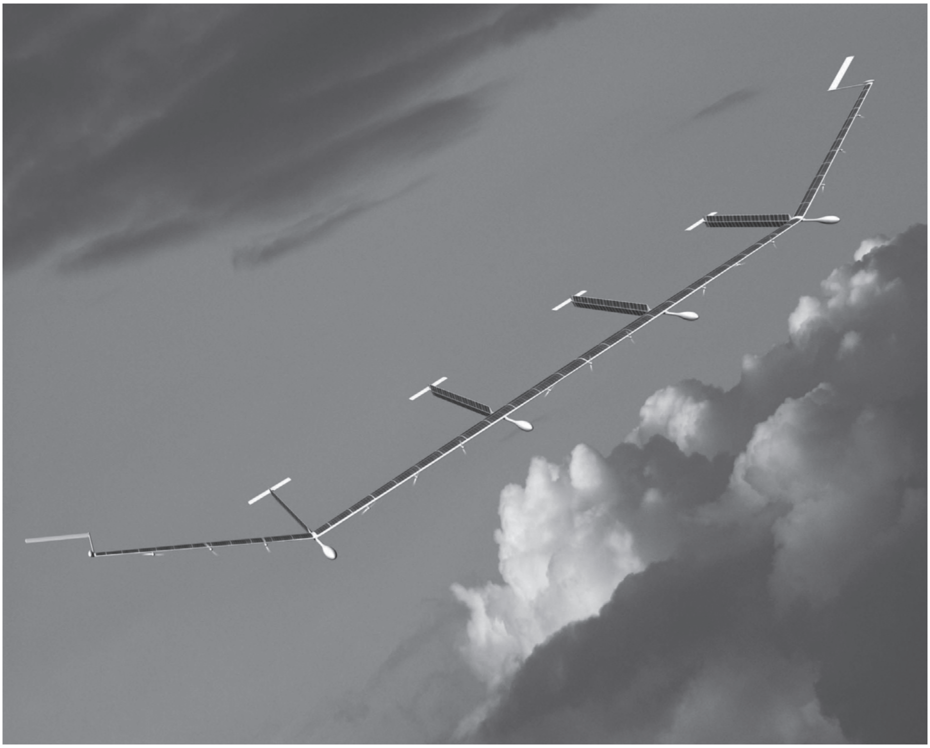

Figure 1.2 Boeing SolarEagle concept in flight (photo credit: Boeing)

solar-powered UAV has to struggle against the famous square-cube law, which states that mass increases quicker than wing surface. As a consequence, solar-cell UAVs may be more appropriate at smaller sizes since a greater portion of the power needed to supply the motor may be obtained from the sun as compared to larger aircraft.

As an example, a 50cm-span fixed-wing covered with thin flexible solar cells, called Solar-Storm, has been designed and fabricated in order to extend the endurance of an existing version entirely powered with standard batteries. On sunny days, the Solar-Storm (see Figure 1.3) [7] was able to extract up to 45% of the total power needed to fly. From a practical point of view, it should be noted that such small solar-powered vehicles do not require a battery charger which needs to be plugged into some electrical source. While one mini-UAV is airborne, an identical model may recharge itself on the ground.

Although fixed-wing UAVs intrinsically suffer from difficulty to hover, they remain very good candidates for long-range or long-endurance surveillance missions as compared to rotary-wing UAVs. Even hand-launched medium-sized fixed-wing UAVs (less than 10kg) may stay airborne for up to 8 hours a day, which is usually more than enough for a typical surveillance mission. Although airplane design has become a well-known engineering technique for conventional airplanes, it is still poorly documented for mini- or micro-UAVs because of the low Reynolds effects degrading the aerodynamic and propulsive performance. It should be pointed out that careful design and fabrication techniques should be specifically applied and adapted to the field of mini-UAVs in

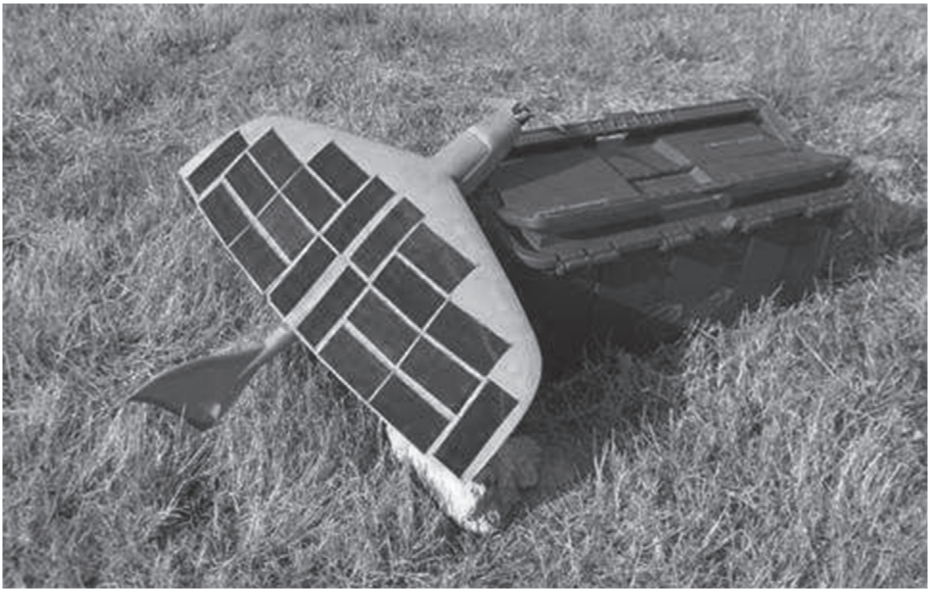

Figure 1.3 A 50cm-span fixed-wing solar-powered UAV (Solar-Storm from Murat Bronz)

order to achieve good performances. Furthermore, long-endurance requirements rely on high values of the ratio $C_L^{3/2}/C_D$, where C_L denotes the lift coefficient and C_D denotes the drag coefficient. As a consequence, long-endurance fixed-wing UAVs correspond to fairly high values of C_L and may lead to cruise conditions close to wing stall. Designing a long-endurance fixed-wing UAV should therefore include the requirement of minimum load factor, take-off, and landing performances. Specific wind tunnel tests and optimization process should then be conducted as illustrated in Figure 1.4, which shows the fixed-wing mini-UAV DT18 developed by Delair-Tech in the ISAE-SUPAERO low-speed wind tunnel [133].

Beyond some recent progress in the miniaturization of fuel cells, one interesting way to dramatically enhance mini-UAVs endurance is to extract energy from the atmosphere. Energy harvesting may be realized using thermals, such as in the case of gliders, or wind gradients. The best example of such a mechanism in nature is given by the albatross flight, which benefits from wind gradients created by the atmospheric boundary layer above the sea surface. That phenomenon, also known as dynamic soaring, is now better understood and can be mathematically simulated. Some authors have suggested that the principles of dynamic soaring could be exploited to create an unmanned aerial vehicle that could be used for surveillance, monitoring, and search and rescue missions over the ocean (see Figure 1.5) [1].

1.1.2 Flapping-wing UAVs

From the very beginning of aviation, some authors have argued that engineers should get inspiration from existing flying animals, either birds or insects. The idea underlying such a view being that animals have been gradually optimized over the centuries.

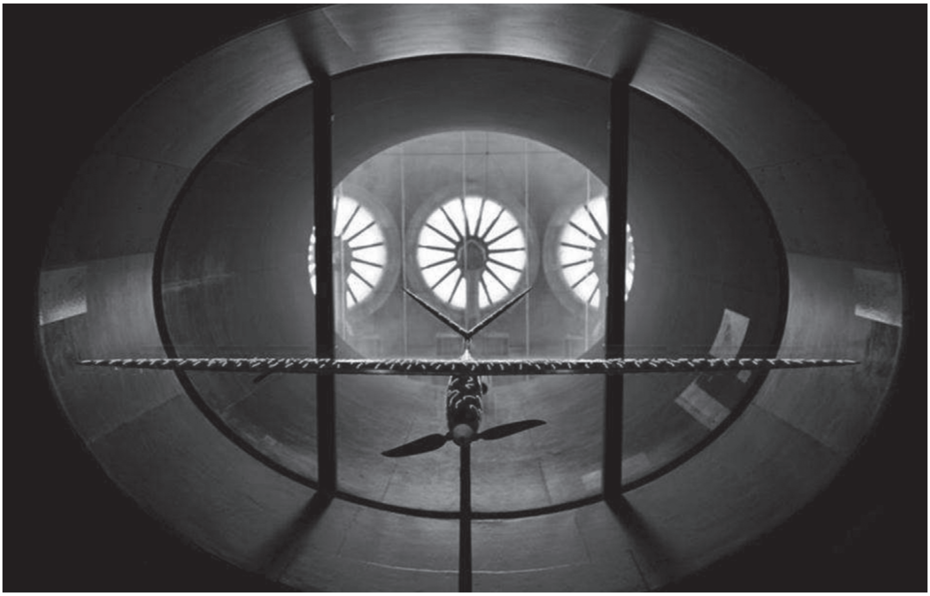

Figure 1.4 A 1.8m-span fixed-wing long-endurance UAV (DT18 from Delair-Tech)

Figure 1.5 Long-endurance mini-UAV concept inspired from the albatross flight (Courtesy Philip Richardson, 2012)

Figure 1.6 AeroVironment with left-hand image courtesy of Lavvy Keller, Litiz Ba/Getty Images. Right-hand image courtesy of Coral von Zumwalt

Fascinating examples of small and large flying animals include various species ranging from the fairyfly, the smallest known flying insect at only 0.15mm long (0.0059in.), up to the famous pteranodon, a flying dinosaur with up to 7m wing span although its actual weight is still a matter of debate [450]. A special mention should be made about the hummingbird, which represents a source of inspiration for a nano air vehicle recently developed by AeroVironment (Figure 1.6) [254].

Understanding the aerodynamics of flapping wings is still, to a large extent, an open question due to the intrinsic flow field complexity and the unsteadiness involved. Over the past 40 years, it has been the focus of many research groups, involving various experimental and numerical techniques [382].

It has not yet been clearly established whether flapping flight is actually more efficient than rotary-wing systems, although it has been shown that existing birds and insects do not display a very efficient way to hover [294] as compared to conventional rotors, even at very low Reynolds numbers. Furthermore, recent studies have revealed that flapping flight might be much less efficient for some insects than previously thought [308]. The reason for such poor aerodynamic performance could be related to the fact that the begin and end positions of the flapping motion have very limited aerodynamic efficiency because the relative air speed becomes very low at those points. In contrast, a rotary wing can provide almost constant lift along its revolution.

Another limitation of flapping wings is their intrinsic technological complexity. In flight, flapping wings have to simultaneously provide lift and thrust, and also contribute to the control in pitch, roll, and yaw, which makes an autopilot extremely difficult to design. Finally, the fact that rotary wings have not emerged from the biological evolution of natural systems should not prevent engineers from considering rotary-wing UAVs as valuable candidates for VTOL missions. Indeed, neither wheels nor propellers or rotors, although highly efficient, have been produced by the natural process of evolution. Some authors point out that there are a few exceptions to this lack of imagination from nature, such as maple seeds or the bacteria flagellum. However, the maple seed is only a passive rotary-wing glider, which benefits from its increased lift-to-drag ratio to reach remote places when dropped by the parent tree. Yet, the SAMARAI monowing nano air vehicle [463] is inspired by the maple seed flight and powered by a micro jet located at the wing tip with a total mass of only 10 grams.

In the long run, flapping-wing UAVs might become very useful in specific recognition missions requiring covertness because of their ability to mimic birds or insects and to easily disappear from the human sight. Flapping-wing UAVs may also benefit from new materials such as electroactive polymers associated with different kinds of MEMS [176]. Furthermore, the development of recent microfabrication technologies has enabled complex articulated mechanisms at small scales that open the way towards insect-like resonant thorax [452].

1.1.3 Rotary-wing UAVs

Beside the limitation of fixed-wing UAVs and the complexity of flapping-wing UAVs, rotary-wing UAVs have attracted a good deal of attention from the scientific community. According to recent figures, among the 3000 to 4000 UAVs flying in France and currently registered by the French authorities, about 80% are rotorcraft, that is multi-rotors. A first reason for this attention is related to the fact that rotary-wing configurations provide the capability of hovering, which is essential to guarantee clear identification. Hovering is also a way to easily take off and land without a complex procedure, such as a prepared airfield or a specific landing device. Furthermore, multi-rotors are easy to fabricate and fairly straightforward to fly indoors. As quad-rotors were almost the only multi-rotors available 10 years ago, more recent multi-rotor aircraft now include hexa-rotors, octo-rotors, and various combinations of coaxial multi-rotors. Increasing the number of rotors is generally considered to be a good way to enhance security since if a motor fails, the other motors can immediately compensate. Usually, the different rotors are equally distributed in the azimuthal direction. Yet, some designers have chosen to adopt different configurations in order to allow for a better field of view ahead of the vehicle. Such an example is given by the ASTEC Falcon 8, which has been very popular over the past two years (Figure 1.7).

While helicopters consist of combining a main rotor and an anti-torque rotor, they also rely on a cyclic-pitch swash-plate to allow for flight control. Therefore, designing a helicopter requires a lot more experience and expertise than designing multi-rotors. When reducing the rotor diameter, Reynolds effects start degrading the propulsion efficiency. For a given overall maximum dimension, it is more efficient to use a single rotor rather than many rotors of a smaller diameter, which would cover the same disk area. However, in order to cancel the resulting torque, one can either resort to an anti-torque rotor as in conventional helicopters or add a counter-rotating rotor underneath. Such a coaxial rotor allows for altitude hold and control around the vertical axis. A recent example of a portable coaxial UAV has been given by the Sprite, a 1.2kg coaxial drone equipped with a two-axis gimballed camera (Figure 1.8). The rotorcraft can fly up to 10–12 minutes and can easily be backpacked after folding the blades.

Figure 1.7 An eight-rotor mini-UAV developed by Ascending Technologies (photo credit: Lakeside Labs GmbH)

It should be mentioned that coaxial rotors suffer from a loss in propulsion efficiency due to the fact that the lower rotor is blown by the propeller slipstream produced by the upper rotor instead of being blown by a uniform freestream flow. As a consequence, the overall efficiency loss is generally considered to be around 30% with respect to a pair of isolated counter-rotating rotors. Nevertheless, the interaction penalty is compensated by the benefit of using a larger disk area.

Because of apparent rotating parts, rotorcraft may have difficulty coping with obstacles. Consequently, rotorcraft UAVs are often equipped with a crashproof outer structure, which protects the rotors. Such protections involve a significant weight penalty and may not perform very efficiently if they are not capable of absorbing energy during crashes. EPP foam associated with carbon rods or rubber bands may be used to offer various forms of bumpers or “mechanical fuses.” As an example of such a “mechanical fuse,” propellers may be mounted on the motor shaft using a simple rubber O-ring, which will help avoid the propeller and the shaft being damaged in case of a collision between the rotor blades and an obstacle. In terms of general UAV design, it is advisable to think in terms of lightness and flexibility rather than in terms of stiffness and weight. A soft and light aircraft will recover from a crash much better than a stiff and heavy vehicle.

One good design option that improves the robustness of rotorcraft consists of adding a duct around the rotor. Ducted rotors are more efficient than unducted rotors because they almost completely cancel out the blade tip losses. As a consequence, propulsion efficiency at a given disk area is increased. Furthermore, long ducts may contribute

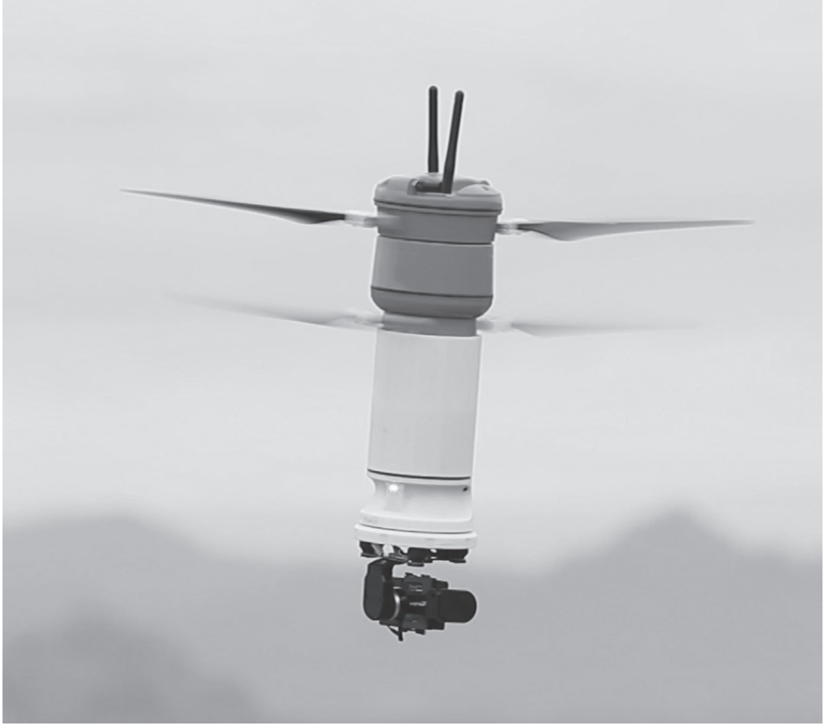

Figure 1.8 A 1.2kg coaxial rotor mini-UAV developed by Ascent AeroSystems (courtesy of Ascent AeroSystems)

an extra lift, mainly due to the design of a diverging nozzle. By combining a proper inlet and nozzle design with optimized rotor blades with almost no blade tip losses, one can obtain a shroud with additional lift and propulsion efficiency, which completely compensates for the weight penalty. The Br2C is an example of a vehicle that takes advantage of a protecting outer structure with full weight compensation due to the extra lift and propulsion efficiency provided by the shroud effect (Figure 1.9). As opposed to the Sprite coaxial UAV, the Br2C is controlled by a pair of flaps located within the rotor slipstream. A disadvantage of long-ducted rotorcraft is the difficulty to withstand strong cross winds due to the bluff body effect.

1.1.4 Convertible UAVs

The success of multi-rotors is somewhat plagued by their difficulty to perform adequately in windy outdoor conditions. High-speed forward flight is limited by various aerodynamic side effects, such as a poor rotor efficiency when the incoming freestream is dramatically tilted with respect to the rotation axis. While fixed-wing UAVs fail to properly achieve hover flight, rotorcraft are limited to low-speed forward flights and are usually much less efficient in fast-speed flight phases. Therefore, some UAV designs aim at combining the advantages of fixed-wing and those of rotary-wing configurations.

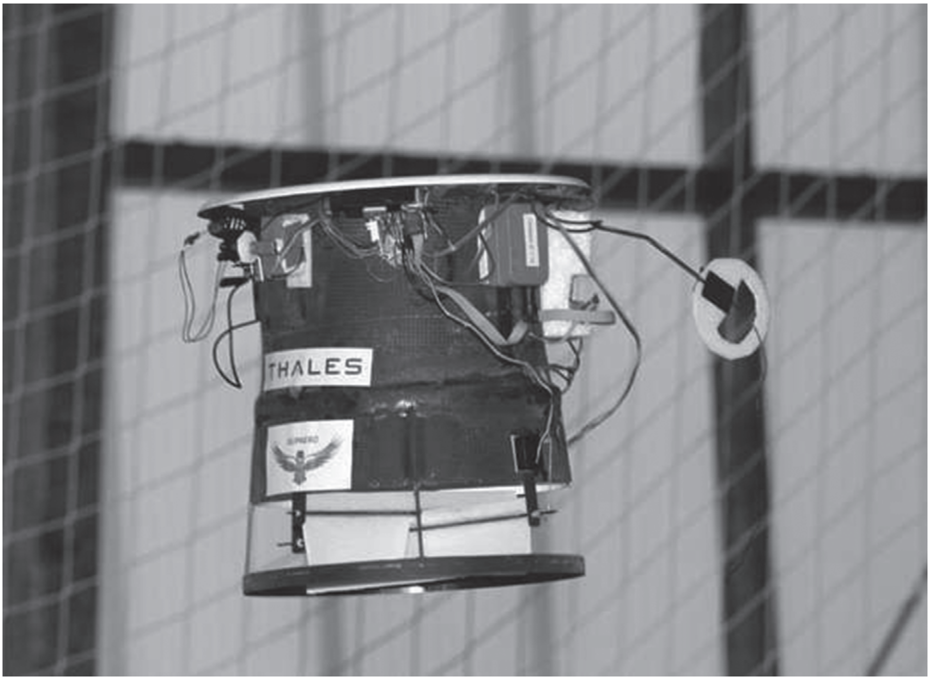

Figure 1.9 A 500-gram ducted coaxial rotor micro-UAV developed by ISAE-SUPAERO (copyright Aéroland. Reproduced with permission from Sylviane & Christian Veyssiere)

These design combinations are called convertible UAVs. Combining the advantages of fixed-wing and rotary-wing configurations may be done following two different design strategies. One is to start from an airplane configuration and to modify it so as to achieve vertical flight. The other strategy consists of starting from a rotorcraft configuration and modifying it in order to achieve horizontal flight. As an example of the first strategy, one can mention the 20kg *Flexrotor* UAV developed by the Aerovel Corporation, USA. It basically consists of a regular 3-meter span airplane with an oversized propeller and two small anti-torque rotors located at either wing tip (Figure 1.10).

The *Flexrotor* belongs to the family of tilt-body UAVs or tail sitter UAVs, which means that they may take off and land vertically and perform cruise flight horizontally. When flying in airplane mode, the folding blades in the wing tip rotors allow limitation of the drag penalty. The aircraft is powered by a large propeller, which also plays the role of a main rotor when flying in helicopter mode. Therefore, the pitch may be varied so as to adjust itself with the flight phase: low pitch in hover and high pitch in cruise flight.

An example of the second strategy is given by the convertible biplane concept, which consists of combining a standard multi-rotor configuration with a set of lifting surfaces added underneath [215]. Again, the key point is that when flying horizontally, the whole body is tilted at an angle of 90 degrees. In airplane mode, the vehicle behaves as a biplane flying wing with a good aerodynamic efficiency. While the flying wing may not

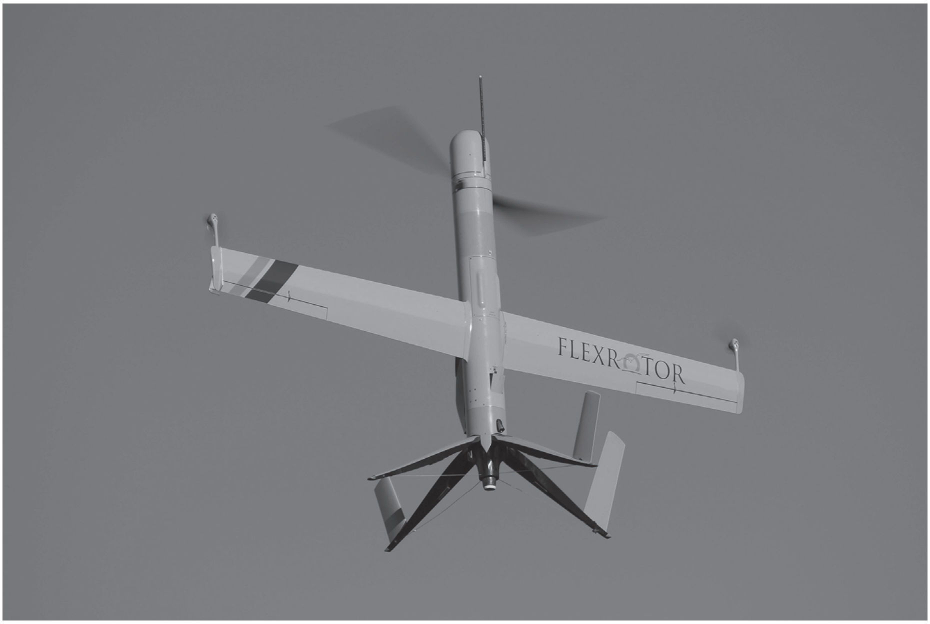

Figure 1.10 A 20-kg convertible UAV developed by Aerovel Corporation (copyright Aerovel. Reproduced with permission)

be statically stable because of the absence of a horizontal tail, the motors placed along the wings may be used to maintain control in pitch. Recently, a commercial version of such a biplane tilt-body UAV concept has been proposed by the French UAV company Parrot with the *Swing*, which makes use of an X-wing rather than a regular biplane wing (Figure 1.11).

Other examples of convertible configurations include tilt-rotor and tilt-wing UAVs. Tilt-rotor UAVs consist of mounting the rotors on a rotating axis, which allows the main body to remain horizontal while transitioning from cruise to hover. On tilt-wing UAVs, a portion of the wing located in the propeller slipstream is physically connected to the rotor so that both the rotor and that part of the wing rotate during transition flight. In both cases, such convertible aircraft require an additional tilting mechanism, which means additional weight and complexity. Also, with movable parts, including motors, the location of the overall center of gravity will vary during transition, which adds some complexity when developing the autopilot. An example of a tilt-wing UAV is given by the *AVIGLE* developed by RWTH Aachen University [328]. The *AVIGLE* UAV looks like a regular airplane except that its wing can be tilted vertically while the fuselage stays horizontal. It should be noticed that an additional vertical rotor has to be added near the tail in order to maintain control in pitch during transition (Figure 1.12).

A good example of an efficient tilt-rotor UAV is given by the *Skate* developed by Aurora Flight Sciences. The *Skate* is a rectangular flying wing powered by a pair of electric motors mounted on independent tilting mechanisms which allow for control in roll and pitch. Yaw control is supplied by differential throttle. No other moving parts,

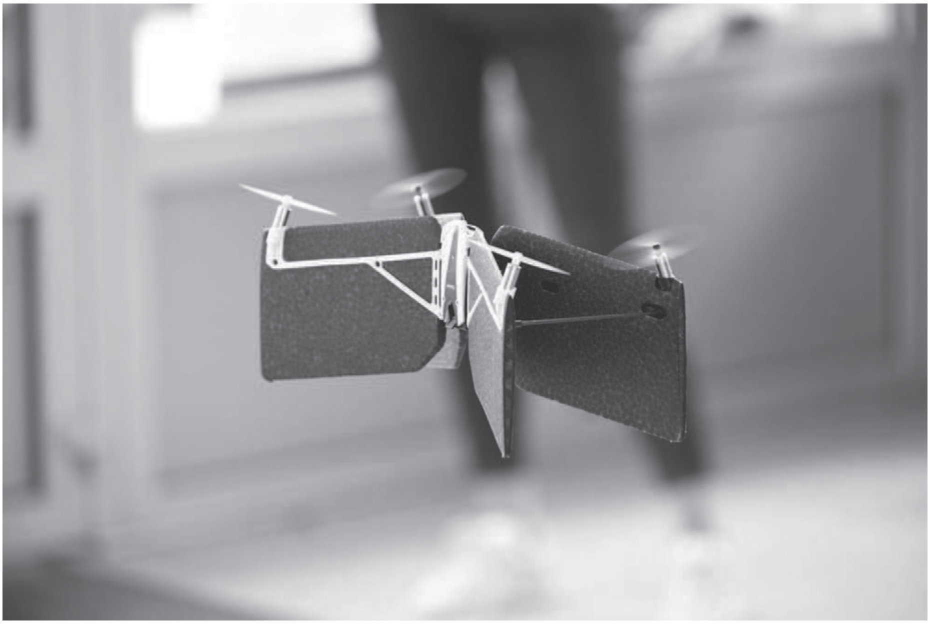

Figure 1.11 A tilt-body 4-rotor mini-UAV developed by Parrot (photo credit: ISAE-SUPAERO)

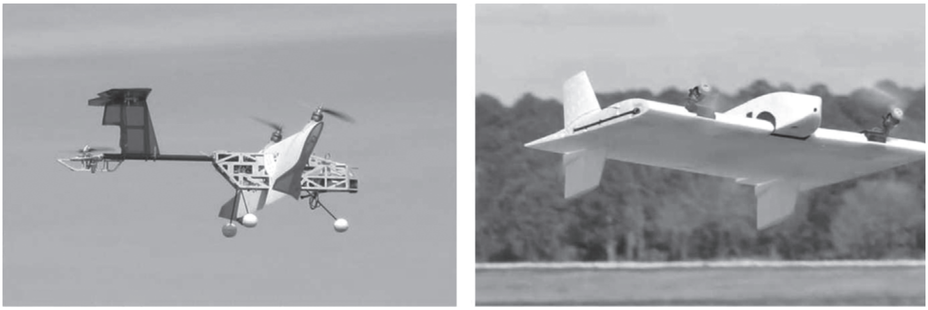

Figure 1.12 Left: a tilt-wing UAV developed by RWTH Aachen University (reproduced with permission from the Institute of Flight System Dynamics); right: a tilt-rotor UAV developed by Aurora Flight Sciences (reproduced with permission from UAVGlobal.com)

such as flaps or elevators, are therefore needed to control the vehicle. In cruise flight as well as in hover, the rotors are almost aligned with the wing chord since the vehicle is tilted vertically in hover. Only the transition flight requires the rotor axis to tilt with respect to the wing. Some tilt-rotor configurations, however, require the fuselage to remain horizontal as in the case of the Osprey V-22. The main advantage of such a tilt-rotor configuration is that the arrangement of the embedded system, antennas, and payload does not need to be modified to take into account a change in attitude when hovering. Yet, tilting the rotors usually implies a download force due to the propeller slipstream impinging on a portion of the wing.

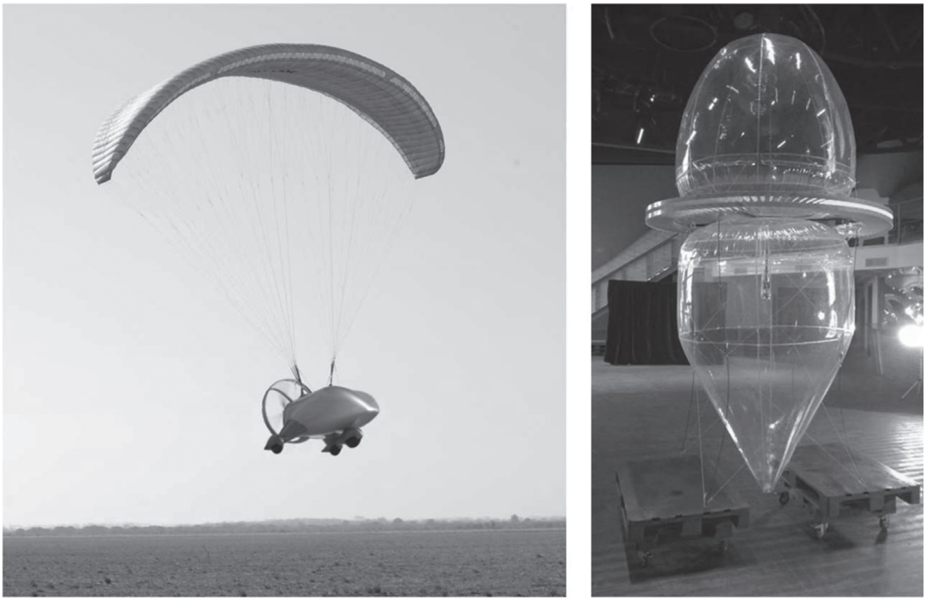

Figure 1.13 Left: a paraglider UAV developed by Flying Robots, Switzerland (photo credit: Flying Robots, Switzerland); right: a lighter-than-air UAV developed by Ride Engineering (photo credit: Ride Engineering, Russia)

As a final note, one should mention two additional configurations which play a limited role in the field of UAV designs. The first configuration is the paraglider. A paraglider consists of a fuselage usually equipped with a propeller in pusher position and a parachute which plays the role of a flying wing. An example of such a UAV is given by the *Swan* developed by Flying Robots, Switzerland (Figure 1.13). The main advantage of a paraglider UAV is its capability to fly very slowly and to be packed in a very compact way. Because they can be deployed and dropped from an airplane, paragliders are good candidates for search and rescue missions that cover large areas. The second configuration is the airship. An example of such a solution is given by the *Sphere-P2* project developed by Ride Engineering. While lighter-than-air UAVs are attractive because of their capability to stay airborne for a very long time, they suffer from two major drawbacks: (1) their sensitivity to winds, (2) the limited payload which can be lifted for a given airship volume. Some airships are tethered so as to be kept within a certain range for permanent surveillance of an area. In the *Sphere-P2* project, a coaxial rotor has been designed to provide altitude hold, while the horizontal control is obtained from a movable center of gravity.

1.1.5 Hybrid UAVs

Special attention should be paid nowadays to a new category of UAVs, which has recently emerged for very practical reasons. When flying in the vicinity of the ground, either in a forest or in an urban environment, a UAV which has to carry out a recognition mission cannot avoid hitting unpredictable obstacles of any kind: trees, electric wires, antennas, chimneys, roofs, etc. Also, some recognition missions may include building intrusion and the vehicle might be required to enter very narrow corridors or tunnels. In such mission profiles, the obstacles cannot be avoided. Using a conventional ground vehicle may still be very limited because jumping over obstacles is always difficult and risky. Also, in many cases, landing the UAV in the middle of the mission may be desirable. For instance, a police operation may suddenly require a totally silent UAV, which implies switching off the motors. Then, the UAV has to land or to cling to a surface but still be able to take off and continue the flight without human intervention. Hybrid UAVs are vehicles which aim at combining the capabilities of aerial and ground vehicles.

The main idea of hybrid UAVs is that obstacles are no longer considered as problems but as *opportunities* to add some new features. In terms of design, adding an outer crash-proof structure, such as a set of carbon rods, represents a weight penalty but may also bring a new capability on-board, such as rolling on the ground or hanging from the ceiling. A first example of such a hybrid vehicle is given by the *MAVion* “Roll & Fly,” which is a rectangular flying wing powered by two counter-rotating propellers in tractor position equipped with a pair of free wheels located on either side of the wing (Figure 1.14). Far from obstacles, the vehicle can fly vertically, thanks to its two elevators located along the wing trailing edge, that is in the propeller slipstream. The MAVion can also fly horizontally as a conventional bimotor flying wing. In both situations, control in pitch and roll is provided by the elevators, which remain efficient over the whole flight domain. Control in yaw is provided by differential throttle. When hitting a flat surface, such as floor, ceiling, or walls, the wheels not only protect the propellers but also allow them to roll at a constant distance from the wall. Differential throttle can help the vehicle to “drive” when rolling on the ground.

Following the same idea of combining ground and aerial vehicles, two additional interesting concepts should be mentioned here. They are both based on the idea that the

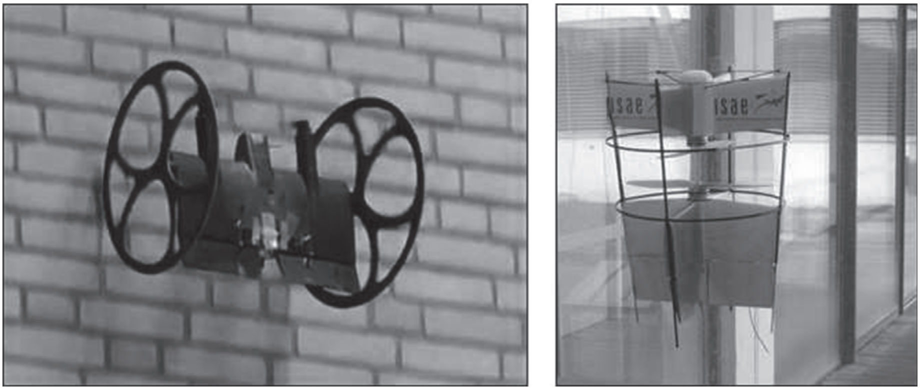

Figure 1.14 Left: the *MAVion* “Roll & Fly” rolling along a vertical wall (photo credit: ISAE-SUPAERO, France); right: the micro-UAV *Vision-Air* “Stick & Fly” clinging to a window, motors switched off (photo credit: ISAE-SUPAERO, France)

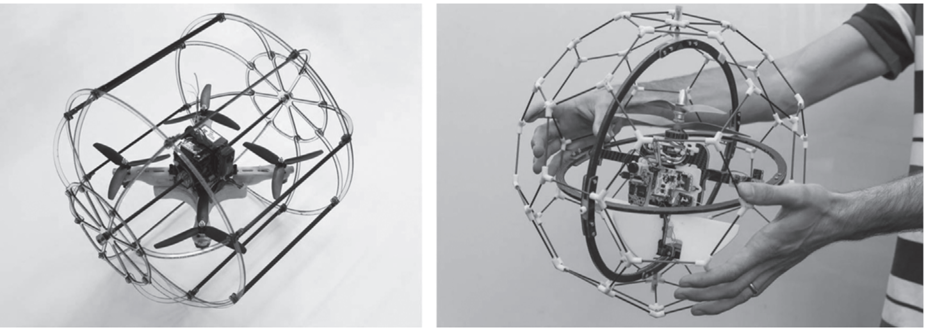

Figure 1.15 Left: the *HyTAQ* quadrotor equipped with a rolling cage (reproduced with permission from Matthew Spenko, Illinois Institute of Technology); right: the mini-UAV *GimBall* with a double-axis rotating sphere (copyright Alain Herzog. Reproduced with permission)

outer crashproof structure may freely rotate around the flying vehicle. The first example is given by the HyTAQ project (Hybrid Terrestrial and Aerial Quadrotor) developed by the Illinois Institute of Technology (Figure 1.15, left). On the HyTAQ, a rolling cage has been added to an original quadrotor in order to make terrestrial locomotion possible. During terrestrial locomotion, the vehicle consumes much less energy compared to the aerial mode and can easily cope with an obstacle by simply flying over it. The second example is given by the GimBall developed by the Ecole Polytechnique Fédérale de Lausanne, Switzerland (Figure 1.15, right). In the GimBall, the aerial vehicle is fitted inside a sphere, which can freely rotate around a vertical axis and around a horizontal axis. As a consequence, the vehicle can cross very complex environments, such as a forest or a network of wires, without being stuck.

As a conclusion to the first section, it appears that cutting-edge technology has thoroughly reshaped the standard classification of UAVs so that they cannot be reduced to fixed-wing, rotary-wing, or flapping-wing UAVs. A general overview of UAV concepts requires inclusion of novel configurations, such as convertible and hybrid UAVs. The use of convertible and hybrid UAVs is believed to be of the utmost importance for the purpose of networking UAVs since they open the way to multi-tasking missions, which require cooperation and dynamic tasks allocation.

1.2 UAV Swarming and Miniaturization

There are many good practical reasons to develop unmanned aerial systems (UAS), one of which is purely economic. If one can achieve a given surveillance or recognition mission for less money, it will have a competitive advantage over conventional systems such as light aircraft. This also happens to be the case within UAS between larger UAVs and smaller ones in which the small size of each individual vehicle is compensated by a large number of such vehicles operating as a team.

Although networking UAVs can virtually be done using vehicles of any size, it only makes sense for mini or micro-sized UAVs. Indeed, only mini-UAVs can be launched in a short time since they require a very limited logistic footprint and few crew members. As a consequence, launching dozens of UAVs with the view of achieving a coordinated flight would simply not be possible if each UAV required more than a minute to be launched. Otherwise the first airborne UAV will have terminated its mission while the last one will not have taken off. Only small UAVs may be eligible for the networking of a large number of vehicles.

Operating a large UAV such as the *GlobalHawk* requires a large number of human operators, and conducting a multi-vehicle surveillance mission is only possible with mini- or micro-UAVs. Therefore, UAV swarming is basically a matter of the number of operators while increasing the number of vehicles. Instead of requiring many operators for controlling multiple UAVs, the idea of UAV networks would be to have a flock of vehicles controlled by a single operator. Having a fleet of UAVs controlled by a single operator not only requires a high level of autonomy for each flying vehicle, it also requires new control and navigation algorithms to efficiently drive the UAV network. These new algorithms will be further detailed in the following chapters. For the moment, it is important to look at the practical issue of launching dozens of flying vehicles in a row and manipulating a flock of UAVs heavily reliant on the capability to miniaturize each vehicle up to a point where crashing one vehicle does not represent a major technical or economical concern, and will still allow the mission to be fully completed. As a consequence, it is important to carefully examine to what extent UAVs may be miniaturized before going any further.

1.3 UAV Miniaturization: Challenges and Opportunities

If UAV networks consistently rely on the capability to miniaturize aerial vehicles, miniaturization itself implies several opportunities as well as new design challenges.

In terms of opportunities, miniaturizing UAVs offers a small visual and electromagnetic footprint. For some applications related to defense and security, smaller vehicles may therefore represent a great advantage in terms of covertness. Smaller vehicles also tend to produce less noise and to become barely noticeable if properly adapted to their environment by the well-known technique of camouflage. Another advantage of miniaturizing UAVs is that they can slot into highly confined environments, such as tunnels, collapsed buildings, ventilation pipes, pipelines, sewer pipes. In such tight spaces, ground vehicles are more likely to become stuck than flying vehicles. Finally, smaller vehicles usually means cheaper vehicles. Losing a 100-dollar flying robot, while hundreds are pursuing the recognition mission, is not a big issue, while losing a Predator-sized UAV is more likely to be of critical importance for the operator. Finally, combining a large number of vehicles flying in cooperation may, in some applications, represent a very efficient way to achieve complex and multi-tasking missions, while a single vehicle would require considerably more effort.

Although very desirable, miniaturizing UAVs faces major design challenges and technical bottlenecks, such as gust sensitivity, energy source, aerodynamic efficiency to name a few.

1.3.1 Gust Sensitivity

Designing mini-UAVs cannot be reduced merely to scaling down conventional aircraft configurations. There are several reasons for this. One is related to the gust sensitivity perceived by the vehicle. In order to illustrate that effect, let us consider a conventional fixed-wing aircraft. In level flight, the lift equation equates the vehicle weight and the lift force as

$$mg = \frac{1}{2}\rho S V^2 C_L \tag{1.1}$$

where the mass m and the wing surface S vary as L^3 and L^2 respectively according to the famous square-cube law, L being the overall vehicle size. Provided that C_L remains almost of the order of unity, the flight speed necessarily varies as

$$V \simeq \sqrt{L} \tag{1.2}$$

which shows that the flight speed needs to decrease when scaling down the vehicle. Now, if we consider the equation of motion along the pitching moment axis, we may write

$$J\ddot{\theta} = \frac{1}{2}\rho S L V^2 C_m \simeq L^4 \tag{1.3}$$

where J represents the moment of inertia that is proportional to L^5. As a consequence, equation (1.3) reduces to

$$\ddot{\theta} \simeq L^{-1} \tag{1.4}$$

which simply means that the roll acceleration will tend to increase when down-sizing the vehicle. As a result, a smaller vehicle will be much more sensitive to wind gusts than a larger one. That effect comes in addition to the fact that by flying more slowly as a consequence of (1.2), the smaller vehicles will also encounter atmospheric perturbations where typical speeds become comparable to the vehicle speed. In other words, flying mini-UAVs goes back to flying a regular airplane through a storm.

1.3.2 Energy Density

Although the energy density of gasoline remains high compared to the best available batteries, thermal combustion engines fail to remain efficient when their size is drastically reduced. The reason for this phenomenon is that the heat produced in the combustion chamber is proportional to L^3 while the heat flux dissipated through its walls only reduces as L^2. Consequently, miniaturizing thermal engines will inevitably lead to poor thermodynamic efficiencies since most of the heat produced within the combustion chamber will rapidly evaporate through the walls. Increasing the rotation speed to compensate for heat losses will not bring a viable solution either because of the limitations on chamber residence time. Furthermore, poor pressure tightness and friction increase are additional problems, which also ruin the attractiveness of thermal combustion engines when reduced in size [381]. Mini-UAV designers are therefore left to the sole choice of electrically powered vehicles, which suffer from limited specific energy with a maximum value of about 200Wh/kg for a high quality lithium-polymer battery. In spite of rapid progress in the field of fuel cells and other new chemical alternatives to LiPo cells, energy density remains a strong limitation for further miniaturizing UAVs at the present stage.

1.3.3 Aerodynamic Efficiency

The Reynolds effect, which drives the importance of viscous effects in the flowfield surrounding a flying vehicle, varies as

$$Re = \frac{VL}{\nu} \simeq L^{3/2} \tag{1.5}$$

showing that the importance of viscosity dramatically increases when the vehicle size is reduced. When the Reynolds number is lower, laminar separation is likely to occur, which results in poor maximum lift capabilities and a high drag level even at low angles of attack. Since the aerodynamic performances of wing airfoils as well as the efficiency of the propeller blades drop miserably when the Reynolds number decreases, it follows that the aerodynamic efficiency of small aircraft represents a crucial design challenge which requires new aerodynamic ways of producing lift with limited drag.

1.3.4 Other Design Challenges

Miniaturizing UAVs is not only a difficulty for physical reasons related to aerodynamics, propulsion, and flight control, it also represents a technical challenge for other practical reasons – one of which is associated with electromagnetic interference. Indeed, when all electronic components are packed within a tight space, the electromagnetic field created by the motor tends to jam signals within the magnetometer or the GPS receiver. Also, the experience of miniaturizing UAVs has revealed that the weight of electric wires represents a significant portion of the overall mass for small UAVs. Integration is therefore needed in order to reduce the weight due to electrical connections between the various components.

1.4 UAV Networks and Their Advantages

A network of UAVs can be viewed as a flying wireless network in which each UAV serves as a node transmitting its own information to other nodes or receiving the information intended for it or relaying information meant for others in the network. The network could be ad hoc without any supporting infrastructure or it could be supported by ground-based and/or satellite-based communication infrastructures. The topology

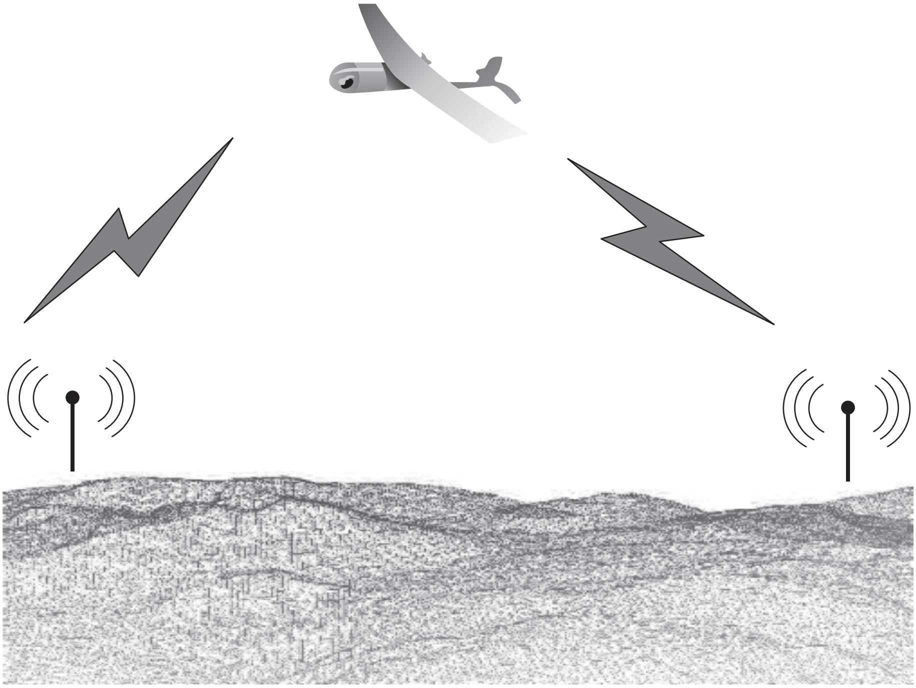

Figure 1.16 A UAV can serve as a relay node between a transmitter–receiver pair, extending the communication range between them

or configuration of the UAV network may take any form, including a mesh, star, or even a straight line, and it primarily depends on the application and use case scenario. First, let us understand why we need a UAV network. A single UAV just by being at a higher altitude offers several benefits, foremost among these being a clear line of sight between the transmitter on the ground (or in the air) and the receiver in the air (or on the ground). Indeed, this is the reason for placing antennas intended for cellular or broadcast communications on a tower, at a typical altitude of 50 to 200ft. A single UAV node could serve as a relay between a transmitter–receiver pair located on the ground extending the range of connectivity between them as shown in Figure 1.16. A UAV enabled communication infrastructure provides a better alternative to ground-based infrastructure, especially when a clear line of sight between a transmitter and receiver is not available due to uneven terrain or cluttered environment.

Figure 1.17 shows how two UAVs can work together relaying information from one radio to another on the ground. Multiple UAVs can serve as a chain of relay nodes, extending the range of communication. Figure 1.18 shows a group of UAVs forming an ad hoc network, as in a mobile ad hoc network or an aerial MANET. An aerial MANET is a multi-hop networking solution for delivering information over long distances. Each node in the aerial MANET acts as a terminal as well as a relay node or router carrying information within the network. In an ad hoc configuration, there is no need for any other infrastructure such as satellites or centralized servers to support the UAV swarm.

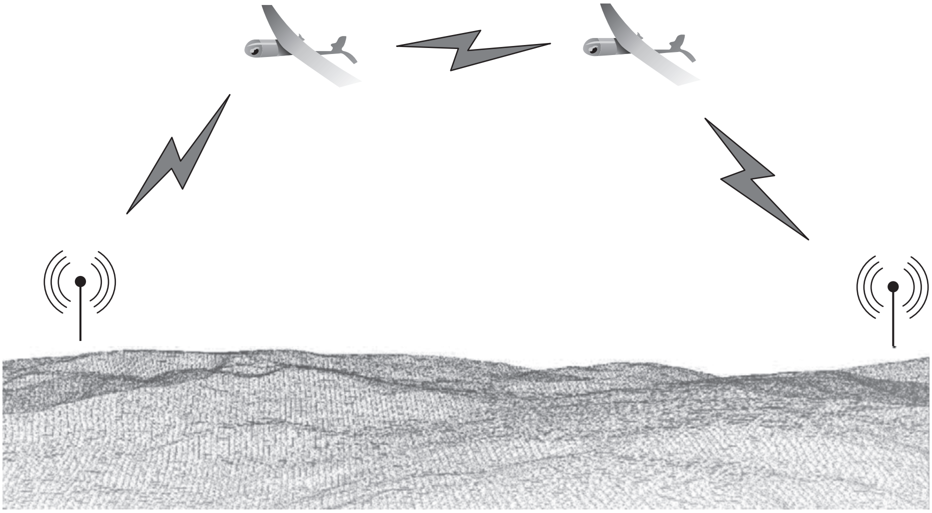

Figure 1.17 Two UAVs working together as a simple relay network extending the range of coverage on the ground

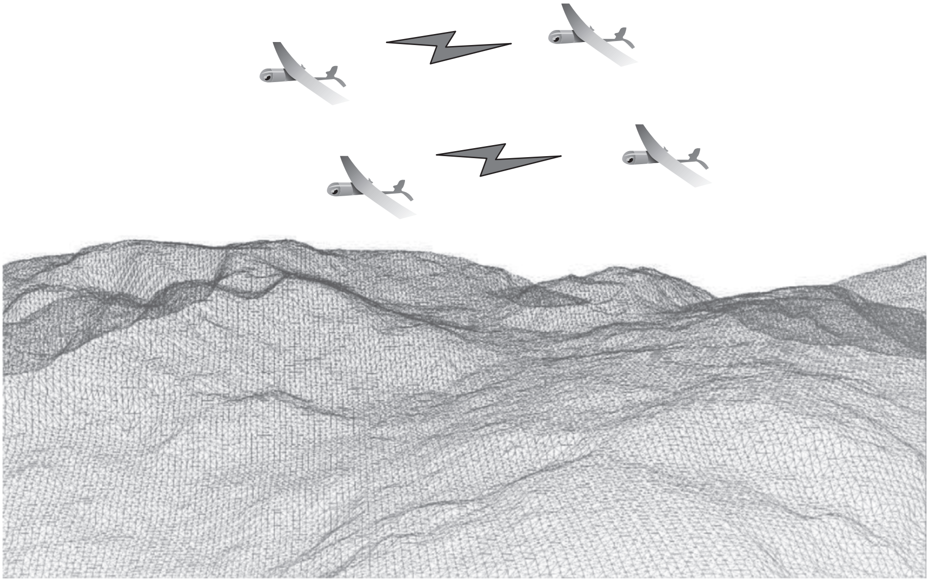

Figure 1.18 Multiple UAVs forming an aerial mobile ad hoc network

However, in real-world applications, ground- and satellite-based services will improve the reliability and robustness of the UAV network. For example, a Global Positioning System (GPS) sensor helps to estimate and exchange geolocation information among the UAVs. A UAV network with ground- and satellite-based communication infrastructure is commonly known as an airborne network.

1.4.1 Unique Features of Airborne Networks

Since aerial nodes move much faster than nodes on the ground, the topology of an aerial network will be very dynamic. Figure 1.19 shows an example of an airborne network. The extremely changing dynamics require specific protocols for routing and secure information exchange. In addition, sense-and-avoid and situational awareness strategies are necessary to make sure that the nodes maintain a minimum safe distance during their flight.

Airborne networks are unique and significantly different from vehicular networks involving only ground vehicles in many perspectives. Classical mobility models and security strategies designed for MANETs and ground vehicular networks are not suitable for airborne networks. Mobility models that take into account the unique characteristics, such as smooth turns, and high-level information assurance, authentication, and integrity verification strategies that can meet the minimum latency requirements, are needed for airborne networks.

An airborne network is a cyber physical system (CPS) in which there is an intense interaction between its physical and cyber components. While computation, communication, and networking elements form the cyber components of the system, flight paths, maneuver geometries, and multi-mode resources, including ground-based nodes and control stations, form the physical components of the CPS. The fundamental challenge for airborne networks is to bring the synergistic interactivity between its cyber and physical components. This synergy, if successfully explored and exploited, will immensely benefit the next generation of air transportation systems; for example, predicting the trajectories of airborne vehicles within the neighborhood (say, 1000 square mile region), forming a trusted network with friendly nodes, reconfiguring the network as its topology changes, and sharing audio and video streaming data securely over the air among the pilots will significantly improve the situational awareness of an airborne vehicle and enhance the safety capabilities of the air transportation system. However, fundamental design principles, which are needed to explore this synergy between the cyber and physical dimensions, are yet to be developed. There is a great need for generating experimental datasets, which will lead to such design principles.

1.4.2 Mobility Models for UAV Networks

Mobility models provide a framework for connectivity studies, network performance evaluation, and eventually the design of reliable routing protocols. In particular, mobility models capture the random movement pattern of each network agent, based on which rich information related to the varying network structures can be estimated, such as node distribution and the statistics of link and path lifetime. In order to provide accurate predictions to facilitate airborne networking, it is crucial to develop realistic and tractable mobility models for Airborne Networks. Some mobility models have been studied extensively in the literature, such as random direction (RD), and random waypoint (RWP). The RWP model assumes that an agent chooses a random destination (waypoint) and traveling speed; upon arrival, it pauses before traveling to the next

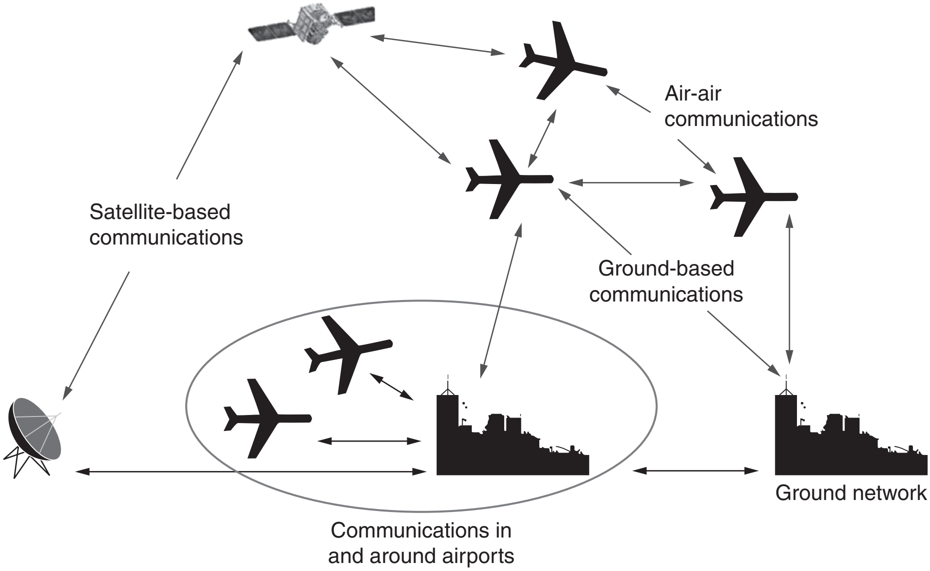

Figure 1.19 A real-world airborne network consisting of unmanned aerial systems as well as the satellite- and ground-based communication infrastructure

destination. The extended version of the RD model assumes that an agent chooses a speed and direction randomly after a randomly selected traveling time. The stochastic properties of these common models, such as their spatial distributions, can be found in the literature. The widely used RWP and RD models are well suited to describe the random activity of mobile users in MANETs. However, they lack the capability to describe features that are unique to airborne vehicles. For example, it is easy for mobile users and vehicles on the ground to slow down, make sharp turns, and travel in the opposite direction (see an enhanced random mobility model that captures such movements). Aerial nodes are not capable of making such sharp turns or instantly reversing the direction of travel. Hence, there is a need to develop realistic models that capture features that are unique to airborne networks.

1.4.3 State of the art in UAV Networks

UAV networking and communications is an emerging field of research. Although there has been immense literature on the applications of small UAVs, the bulk of this research has been in theory and simulations only, with a limited number of real implementations in academic and research institutions. Below, we discuss some of the recent implementations of UAV networks and their outcomes.

AUGNet (University of Colorado, Denver, 2004)

AUGNet is an implementation of ad hoc UAV-ground networks consisting of ad hoc nodes on the ground and ad hoc nodes mounted on small UAVs [71]. This test-bed illustrates two use cases of AUGNet. The first use case is a relay scenario in which a UAV, with a better view of the ground nodes, enhances connectivity of an ad hoc network of ground nodes. In the second use case, ad hoc networking between UAVs increases the operational range and improves communications among the UAVs. Experimental results demonstrate that a UAV supported network generates shorter routes that have better throughput and improved connectivity over nodes at the edge of network coverage. More recent experiments on this test-bed have provided detailed data on network throughput, delay, range, and connectivity under different operating regimes. Such experiments are needed to understand the performance limits of UAV networks.

UAV Networking with Commercial Off-the-shelf Components (Air Force Research Laboratory and Harvard University, 2006)

Air Force Research Laboratory (AFRL) and Harvard University jointly pursued UAV networking with commercial off-the-shelf (COTS) communication equipment [198]. The availability of low-cost and yet highly capable COTS-based communications equipment and UAV platforms allowed the team to conduct two field experiments for UAV-based networks using communication equipment that supports 802.11 (at 2.4GHz and 5GHz) and 900MHz technology, respectively. The experiments were carried out to compare bandwidth and communication range and networking capabilities. The experimental data that were collected through these field experiments were more accurate and realistic than any simulated data available at that time.

Robust Airborne Networking Extension (Boeing and the Naval Research Laboratory, 2009)

The Robust Airborne Networking Extension (RANGE) research project was carried out by Boeing Research and Technology and the Naval Research Laboratory (NRL) with support from the Office of Naval Research (ONR). The team developed, tested, evaluated, and demonstrated protocols and techniques for resilient mobile inter-networking of UAVs and ground stations to extend surveillance range and battle-space connectivity [124]. The field test included an 802.11 ground–UAV network of 11 ground stations, a mobile vehicle, and two fixed-wing UAVs. The field tests demonstrated hybrid air/surface networking scenarios and mobile ad hoc networking (MANET) capabilities.

UAVNET (University of Bern, 2012)

UAVNET is a prototype implementation of a mobile wireless mesh network using UAVs [303]. Each UAV carries a lightweight wireless mesh node, which is directly connected to the flight electronics of the UAV using a serial interface. The flying wireless mesh nodes are interconnected, and communicate with each other over the IEEE 802.11s protocol. Every wireless mesh node works as an Access Point (AP), providing access for regular IEEE 802.11g wireless devices, such as notebooks, smartphones, and tablets. The prototype implementation is capable of autonomously interconnecting two communication peers by setting up an airborne relay, consisting of one or several flying wireless mesh nodes. Experimental results demonstrate that a multi-hop UAV relay network achieves significantly higher throughput compared to terrestrial-based relay network.

Mobility Model for UAV Networks (2014)

Mobility models abstract the movement patterns of mobile nodes in MANETs. They are typically used for estimating the performance of network protocols in different application scenarios. Realistic mobility models are necessary to create a realistic simulation environment. A paparazzi mobility model for UAVs has been suggested in [65]. They developed the paparazzi mobility model, which is a stochastic model that imitates paparazzi UAV behavior based on the state machine in which the five states represent the five possible UAV movements: stay-at, waypoint, eight, scan, and oval. The mobility model is compared with the well-known random waypoint mobility model. In a more recent study, a smooth-turn mobility model has been suggested [438]. This model captures the tendency of airborne vehicles to make straight trajectories and smooth turns with large radii.

SkyScanner (2015)

SkyScanner is a research project targeting the deployment of a fleet of fixed-wing minidrones for studying the atmosphere [6]. This is a collaborative project with five partners, including the Laboratory for Analysis and Architecture of Systems (LAAS) at the Centre National de la Recherche Scientifique (CNRS), the Groupe d'étude de l'Atmosphère Météorologique (GAME) at the Centre National de Recherches Météorologiques (CNRM), the Department of Aerodynamics, Energetics and Propulsion (DAEP) at the Institut Supérieur de l'Aéronautique et de l'Espace (ISAE), Systems Control and Flight Dynamics at ONERA, and the UAV Laboratory at Ecole Nationale de l'Aviation Civile (ENAC). The scope of the SkyScanner project includes atmosphere sciences, aerodynamics of mini-drones, energy harvesting, and distributed fleet control. The project relies on strong cooperation between UAVs that collectively build a 3D map of atmospheric parameters and decide which areas to map further.

1.5 Summary

This chapter discussed UAVs in terms of their types and mission capabilities. It outlined UAV swarming, UAV miniaturization, and the opportunities and design challenges in UAV miniaturization. It outlined the advantages of UAV networks and presented several UAV networking projects that were demonstrated over the past few years. Mobility models for UAV networks were briefly discussed.