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

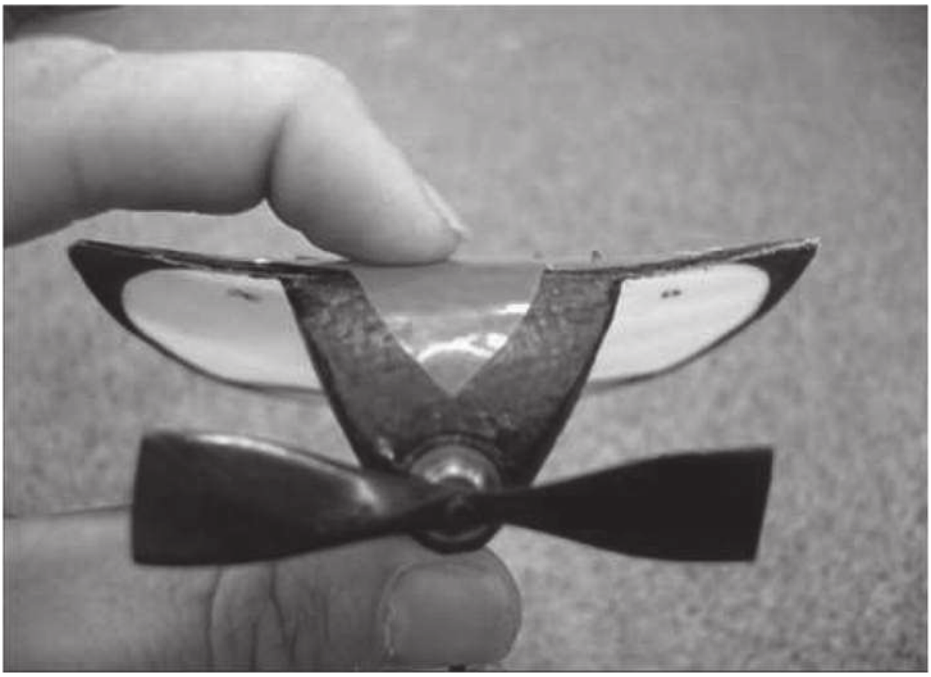

Figure 1.1 A 10cm-span fixed-wing MAV (Courtesy of Michall Sytsma)

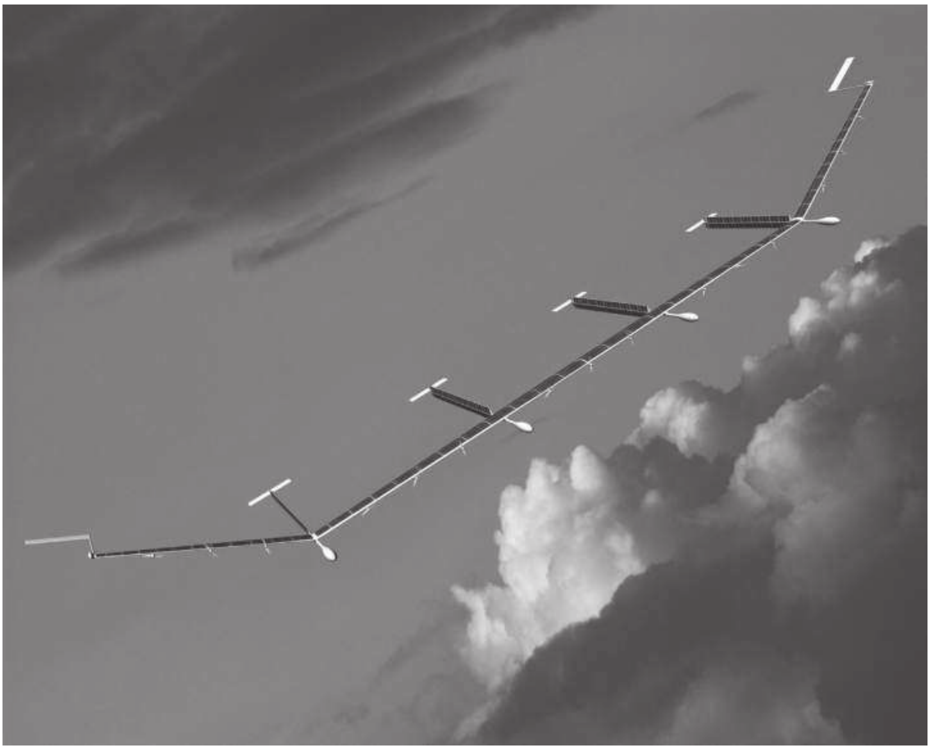

Figure 1.2 Boeing SolarEagle concept in flight (photo credit: Boeing)

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

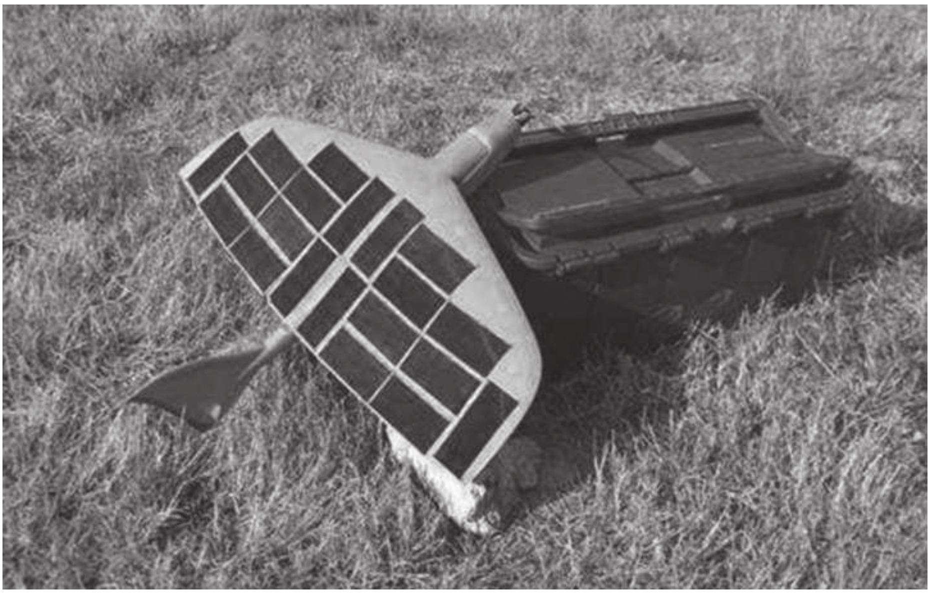

Figure 1.3 A 50cm-span fixed-wing solar-powered UAV (Solar-Storm from Murat Bronz)

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.

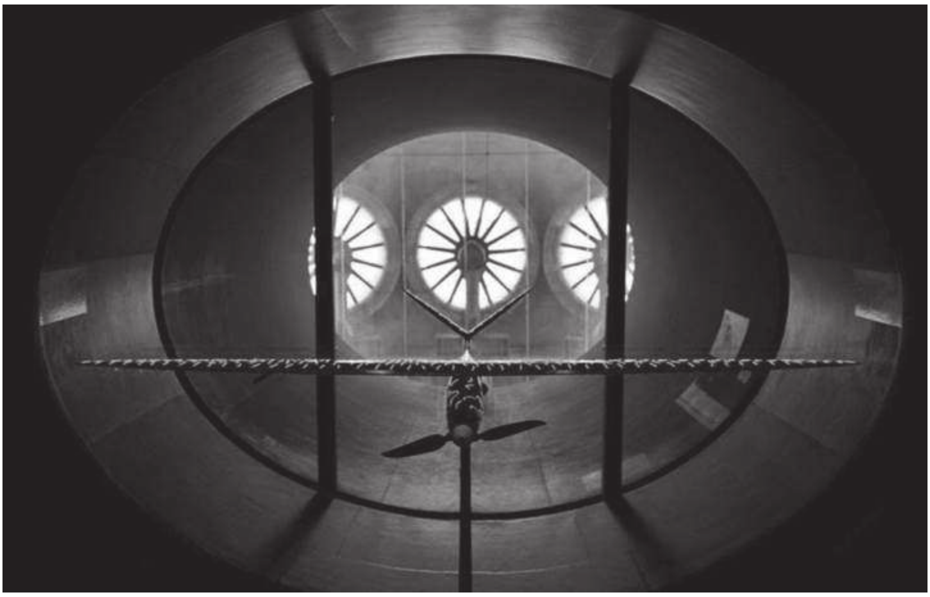

Figure 1.4 A 1.8m-span fixed-wing long-endurance UAV (DT18 from Delair-Tech)

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

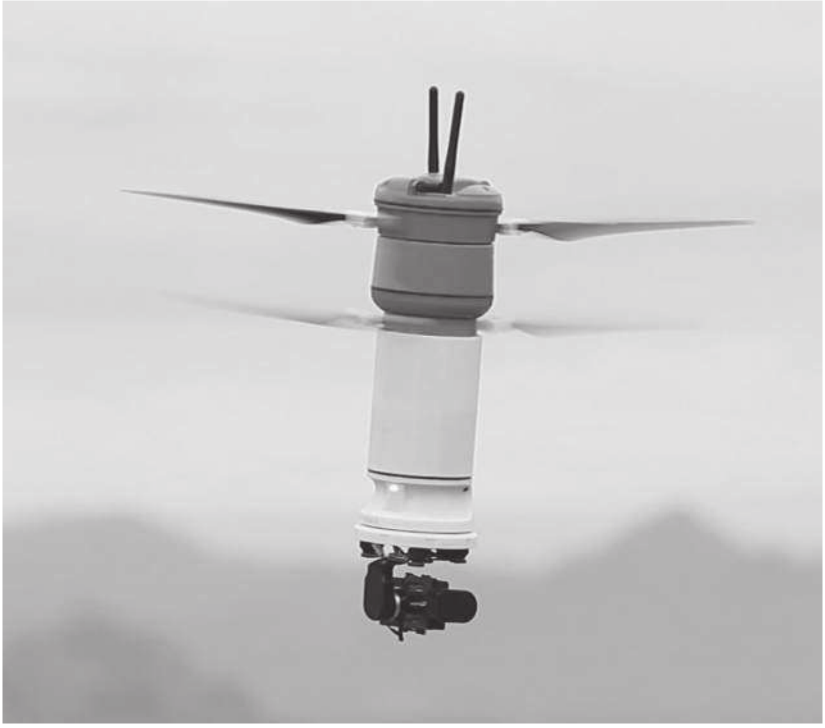

Figure 1.8 A 1.2kg coaxial rotor mini-UAV developed by Ascent AeroSystems (courtesy of Ascent AeroSystems)

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.