44. Aerial Robotics

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A wide array of potential applications exist for robots that have the level of mobility offered by flight. The military applications of aerial robotics have been recognized ever since the beginnings of powered flight, and they have already been realized to sometimes spectacular effect in surveillance, targeting, and even strike missions. The range of civilian applications is even greater and includes remote sensing, disaster response, image acquisition, surveillance, transportation, and delivery of goods.

This chapter first presents a brief history of aerial robotics. It then continues by describing the range of possible and actual applications of aerial robotics. The list of current challenges to aerial robotics is then described. Building from basic notions of flight, propulsion, and available sensor technology, the chapter then moves on to describe some of the current research efforts aimed at addressing the various challenges faced by aerial robots.

The challenges faced by aerial robots span several and distinct fields, including state regulations, man–machine interface design issues, navigation, safety/reliability, collision prevention, and take-off/landing techniques. The size of aerial robots can considerably influence their flight dynamics, and small aerial robots can end up looking considerably different from their larger counterparts. Similar to their manned counterparts, aerial robots may enjoy diverse propulsion systems and operate over large speed ranges.

Aerial robots must be equipped with reliable position and actuation equipment so as to be capable of controlled flight, and this constitutes a nontrivial requirement prior to doing research or development in this field. However, many universities, research centers, and industries have now met this requirement and are actively working on the challenges presented above. The largest obstacle to the commercial development of aerial robots is, however, the necessity to comply with and support a regulatory environment which is only beginning to address these rapidly developing systems.

44.1 Background

The term *aerial robotics* is often attributed to *Robert Michelson* [44.1], as a way to capture a new class of highly intelligent, small flying machines. However, it is clear that the range of systems and activities covered under the label *aerial robotics* could extend much further, and that its roots can be found far back in the beginning of the 20th century, together with the birth of aviation. Behind the word *aerial robotics* we can find several meanings: it could mean *robotic flying machines*, that is, a mission-independent, platform-oriented concept; however, it could also mean *robotics that use flying machines*, that is, a platform-independent, mission-oriented concept. Finally, it could mean a combination of the above, that is a description of the robotic platform, together with its robotic mission. In aerospace jargon, robotic flying machines are commonly referred to as *unmanned aerial vehicles* (UAVs), while the entire infrastructures, systems and, human components required to operate such machines for a given operational goal are often called *unmanned aerials systems* (UASs). Finally, it is worth noting that many current manned aerial systems definitely carry relevant features of some robotic systems, and so much of this discussion is relevant to manned aircraft.

44.2 History of Aerial Robotics

The history of aerial robotics is very closely tied to the history of flight itself. Indeed, the rate of fatalities associated with early manned flight tests probably convinced engineers that there was a need to operate flying machines without the presence of humans on board even before potential applications of unmanned aircraft surfaced. In 1903, heavier-than-air flight was unambiguously shown to be feasible, following the achievements of the Wright brothers. The first successful powered flight was unmanned, presumably to reduce the risk to the pilot and to allow a smaller and less expensive vehicle (reasoning that is still put forth today) by Samuel P. Langley's *Number 5* in 1896 [44.2].

Finding a truly defining moment for aerial robotics is a challenge, with encyclopedias dating the concept back to Leonardo da Vinci, while *Newcome* [44.3], in his history of unmanned aviation, gives early credit to Nikola Tesla for devising a robotic vehicle remotely controlled by electromagnetic waves, and with enough onboard logic to recognize and execute remotely transmitted orders. However, the concept imagined and engineered by Tesla did not apply specifically to airborne vehicles.

Using the definition

> *An aerial robot is a system capable of sustained flight with no direct human control and able to perform a specific task,*

leads us almost immediately to the Hewitt–Sperry automatic airplane, developed before and during World War I [44.3]. The airplane's purpose was to act as a flying torpedo, carrying onboard *intelligence* to sustain flight over long periods of time without human intervention. Such intelligence was provided by a complex system involving Sperry's own gyroscopes, mechanically coupled to the airplane's control surfaces so as to stabilize the vehicle. This made the airplane suitable for

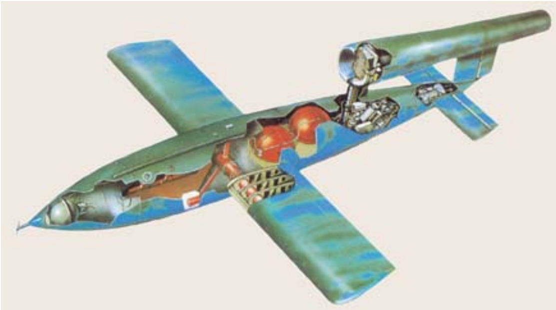

Fig. 44.1 V-1 German cruise missile (1940s)

Fig. 44.2 QH-50 DASH unmanned helicopter on final approach (US Navy)

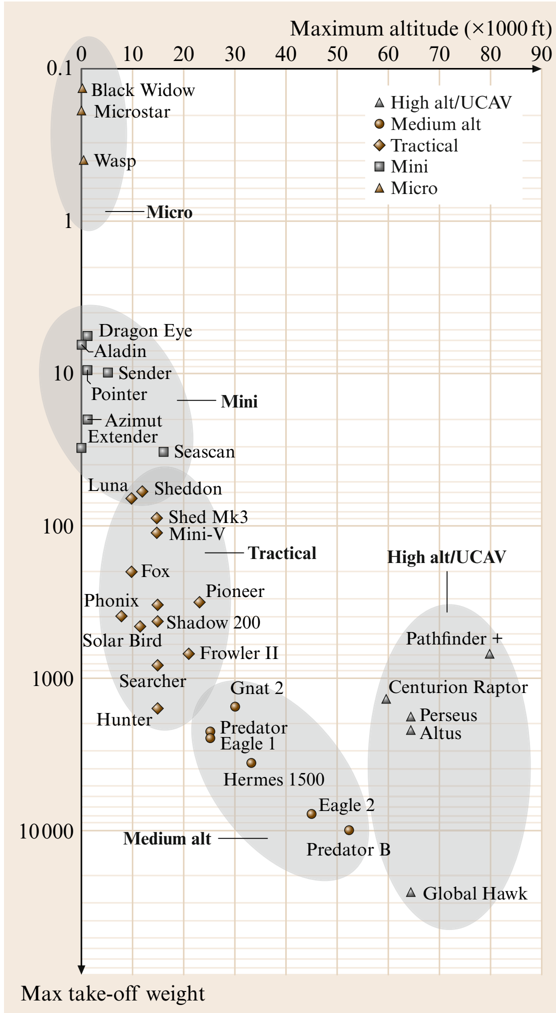

Fig. 44.3 Taxonomy of unmanned aerial vehicles (after *R. Weibel* [44.4, 5])

human remote control and, eventually, prosecution of distant targets. As discussed later, one of the key characteristics of aerial robotics is this particular necessity for the robot to sustain itself in the air with no human intervention, which requires the early adoption and understanding of the critical role played by *onboard intelligence*, much more so than other robotic applications. While a string of inventors in many countries came to develop ever more sophisticated machines, credit goes to the German V-1 cruise missile for making a lasting, and unfortunately deadly, impact on large segments of the population in England. This form of robotic aircraft owed its relative inefficiency (three out of four vehicles reportedly missed their target – predominantly London) to mechanical failures and lack of good navigation capabilities beyond dead-reckoning assisted by gyroscopic devices. Many of the ensuing aerial robotics developments followed the initial idea of defense applications for unmanned systems, that is, ever more accurate flying machines for the purpose of either reconnaissance or weapon delivery. One notable machine was the US Navy's Gyrodyne QH-50 DASH, an unmanned helicopter developed in the 1950s and operated from US destroyers, which was able to perform reconnaissance missions and deliver torpedoes (Fig. 44.2). However, these machines remained relatively *unintelligent*, and their level of autonomy remained limited to the ability to sustain flight using complex inertial and other measurement systems.

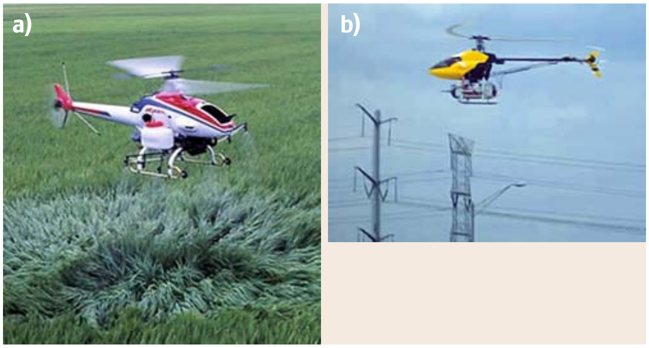

Fig. 44.4a,b Autonomous helicopters: **(a)** Yamaha's R-MAX **(b)** Nascent Technologies Corp's XS

From a robotics perspective, probably the next significant technological enabler is the advent of lightweight processors and sensor systems, together with global navigation satellite systems, which allowed aerial robots to perform increasingly complex tasks. Japan, motivated by a policy of food self-sufficiency combined with a massive shortage of agricultural workforce, took a lead in aerial robotics by developing highly reliable helicopters in the 1980s, such as the Yamaha R-50 and subsequent Yamaha R-Max (Fig. 44.4), with similar systems developed by other companies such as Yanmar. These robotic helicopters are used primarily for crop dusting applications, especially over wet rice fields. These vehicles also turned out to be very popular among universities and other institutions for their unmatched ability to fly reliably and take off and land from limited areas, allowing researchers to focus their attention on developing higher levels of autonomy beyond basic vehicle navigation and control. Military applications of unmanned robotics followed the track of the German V1, with the advent of modern cruise missile technology.

From the mid 1980s on, the development of aerial robots has followed an exponential pace, with one notable trend for operational aerial robots to systematically find military applications as their most significant market.

A snapshot of available aerial vehicle platforms and systems appeared recently in [44.6], and regular updates on available platforms can be found in the aerospace literature. The chart in Fig. 44.3 illustrates the number of machines currently under development or in operation, which exceeds 200 vehicle types. From this chart, one concludes, however, that the vast majority of current, operational aerial robots are fixed-wing aircraft, and that they tend to be present at all altitudes.

We must also remark that onboard robotic intelligence has made its way not only into unmanned aircraft but also manned aircraft. Many commercial airliners now have the ability to fly automatically from right after take-off (a decision left to the pilot) to right *after* landing, by engaging the autopilot and letting the aircraft fly a predetermined profile. In addition, these vehicles are now able to make systems-management decisions based on sensor inputs, sometimes escaping the human pilot's ability to understand them.

44.3 Applications of Aerial Robotics

Listing all possible applications of aerial robotics is very challenging. However, there are fewer actual implementations, because of the necessity for the corresponding operations to comply with stringent air safety regulations. In the following, a brief description of possible and current applications is provided.

44.3.1 Possible Applications of Aerial Robots

The list of possible applications of aerial robots is long. According to [44.6,7], such applications fall within nine categories:

- *Remote sensing* such as pipeline spotting, powerline monitoring, volcanic sampling, mapping, meteorology, geology, and agriculture [44.8, 9], as well as unexploded mine detection [44.10].
- *Disaster response* such as chemical sensing, flood monitoring, and wildfire management.
- *Surveillance* such as law enforcement, traffic monitoring, coastal and maritime patrol, and border patrols [44.11].
- *Search and rescue* in low-density or hard-to-reach areas.
- *Transportation* including small and large cargo transport, and possibly passenger transport.
- *Communications* as permanent or ad hoc communication relays for voice and data transmission, as well as broadcast units for television or radio.
- *Payload delivery* e.g., firefighting or crop dusting.
- *Image acquisition* for cinematography and real-time entertainment.

Military applications of aerial robots follow the same descriptive lines, with a particular emphasis on remote sensing of humans and critical infrastructure, surveillance of human activity, and payload delivery (bombs, missiles, and ad hoc ground infrastructures devoted to communication and surveillance).

44.3.2 Current Applications

Current applications of aerial robots are somewhat fewer and they are at present driven by the military context.

Aerial Observations

The most important application of aerial robots is aerial observations, which can then be used for terrain mapping, environmental surveys, crop monitoring, target identification etc. There is a divide, however, between the state of the art for military applications and civilian applications, detailed below.

Military Operations. Military and government use of aerial robots has sharply increased in recent years in war zones. As a result, dozens of vehicles are now delivered every month, and end up flying in "hot" areas around the globe, most notably in Southwest Asia. The machines being flown range from man-portable machines flying at low altitudes, such as the Pointer or Raven aircraft, to mid-sized machines such as the Aerosonde, Seascan, or Shadow unmanned vehicles, to larger-sized vehicles such as the Predator or Global Hawk. Their wings span from a meter or so for the smaller vehicles to 35 m for Global Hawk (the same as a Boeing 737). Besides their use in military areas or war zones, these machines now find applications in border surveillance, with a particular interest in oceanic borders, where vehicles operate in desert or quasi-desert areas.

Civilian and Private Applications. Current civilian applications of aerial robots for surveillance and observation remain sporadic and ad hoc: unlike many other robotic devices, civilian aerial robots do not operate in *closed* environments but in civilian airspace, which is subject to strong safety regulations that do not yet systematically accommodate aerial robots. Consequently, the current trends in civilian aerial robotics are as follows.

Small-scale, intermittent civilian aerial robotic applications tend to happen in relatively isolated environments (e.g., for film making or environmental surveys), and often follow the safety and operations rules most familiar to their operators, derived from model aircraft operations. Most often, the operated machines do in fact bear much resemblance to radio-controlled model airplanes. Other intermittent applications involve the use of unmanned vehicles for specific reconnaissance tasks, such as the detection of fish banks from trawlers [44.12]. Such a task constituted one of the original purposes for the development of machines such as the Seascan unmanned aerial vehicle.

Long-term scientific applications such as atmospheric sampling experiments [44.13] appear to benefit considerably from aerial robots. One report [44.13] reads

> *From March 6 to March 31 2006, we probed the polluted atmosphere over the North Indian Ocean with lightweight unmanned aerial vehicles (or UAVs) fully equipped with instruments. This UAV campaign launched from the Maldives laid a solid foundation for the use of UAVs to study how human beings are polluting the atmosphere and their impact on climate, including global warming.*

Because such activities naturally require much planning ahead, special permits can be obtained from aviation authorities within time limits that do not significantly affect the overall experimental project. Other scientific missions led with success include [44.14], where the authors were able to survey Mount St. Helens (then active) by taking advantage of the temporary interdiction to fly in the vicinity of the volcano.

With the progressive introduction of aerial robots in the regulatory framework of many countries, we believe that intermittent applications of aerial robotics in populated areas will eventually become commonplace. However, this requires that flight authorizations be delivered within a fraction of the time duration of the event: for example, firefighting operations are often triggered within a few seconds of the fire alert. Permits for aerial robotic support should therefore be delivered about as quickly if they are ever to be embraced by firefighters.

Payload Delivery

Under the heading *payload delivery*, we find the numerous applications of aerial robots aimed at delivering solid, liquid or gaseous products in areas that are hard to reach for humans. So far, the most successful civilian application has been chemical crop spraying using small unmanned helicopters. Leveraging the high costs and prices associated with crop culture in Japan, several thousand helicopters have been purchased by farmers, resulting in a profitable operation both for themselves and for the helicopter manufacturers, among them Yamaha and Yanmar. However, this application remains unique and involved the involvement of Japan's government for it to be successful.

Besides this particular application, military applications form the bulk of unmanned aerial robotics for the purpose of payload delivery, beginning in its crudest form with missiles, and evolving towards cruise missiles, able to navigate for thousands of miles and reach their targets with high precision. One of the most talked-about recent military application of aerial robots for payload delivery involves the Predator aircraft equipped with Hellfire missiles.

General Characteristics of Current Applications: Level of Autonomy

Most, although not all, aerial robots currently under operation are automatically controlled as far as their dynamics are concerned. However, higher levels of autonomy, such as path planning, object detection, and recognition and mission management involve human operators, who always remain in contact with the flying machine. Thus not much distinguishes current aerial robots from traditional manned aircraft, except that the pilot sits on the ground rather than in the air.

As such, most of today's operational aerial robots may be justifiably called remotely piloted vehicles (RPVs).

44.4 Current Challenges

In the following, we introduce six major challenges for aerial robotics. This list is not meant to be exhaustive, but it reflects the current focus of researchers. How these challenges are addressed will be discussed later.

44.4.1 Regulations and Certification

A big challenge to the success of aerial robots is doubtlessly their acceptance by certification authorities. Indeed, the operation of aerial robots is currently significantly limited by regulatory constraints. This is due to the complex set of regulations put in place by national agencies (e.g., the Federal Aviation Administration in the US, the National Air Traffic Services in the UK, or the Direction Générale de l'Aviation Civile in France), whose aim is to maintain very high levels of safety for air traffic. The downside of the excellent safety record reached by regulatory agencies is their (justified) risk adversity, and therefore a slow acceptance of disruptive technologies such as aerial robots. This is compounded by the current rapid pace of change and related lack of standards among aerial robotic systems and how they are used. However, with the help of other organizations, such as the Radio Technical Commission for Aeronautics (RTCA), regulatory agencies have moved forward towards establishing rules for the routine operation of aerial robots. Such rules include the ability for aerial robots to *see and avoid* or *sense and avoid* other traffic at least as well as a human pilot.

In the recent past, many aerial robotics research activities and corresponding flight tests have occurred at very low altitude. In the absence of clearly defined rules by regulatory bodies until recently (2000), many researchers have operated under the rules of local radio-controlled aircraft associations (e.g., the Academy of Model Aeronautics). However, there is a rapidly growing trend for radio-controlled vehicles to incorporate more onboard electronics, including radio transmitters and sometimes guidance systems. In this environment, one can expect regulatory bodies such as the FAA to continue to evolve their policies.

The ensuing challenge is for the research community is to develop the requirements and subsequent technology that meets the constraints set by the regulatory agencies, or to propose and justify alternate constraints. In particular, the maturation of aerial robots leading to their everyday use in populated areas will require the development of more reliable components, defined maintenance procedures, formal training programs, and the automation of emergency procedures (such as the forced landing process). The core technology for UAS already exists to demonstrate safety concepts. However, developing highly dependable systems – and making such dependability guarantees acceptable to the regulatory authorities – is a current and urgent challenge.

44.4.2 Human–Machine Interfaces

The pilot interfaces used for manned aircraft have evolved continuously since the first manned aircraft. The standards that exist today directly benefit safety and operator costs by minimizing operational errors and training time when transitioning between aircraft types. Despite ongoing development efforts [44.15], this can-not be said of aerial robotic systems, which run cover a much wider range of autonomy, mission capability, and operator skill. Add to this the desire to have single operators control multiple aircraft, and it clear this area presents an ongoing challenge for researchers.

44.4.3 Navigation

Figuring out absolute and relative position is a central issue for aerial robots, as it is for other robotics activities. The existence of a significant manmade infrastructure (the global navigation satellite system – GNSS) makes basic navigation easy but remains the subject of an intense debate; indeed, systems that overly depend on such infrastructure lack resilience and tolerance to positioning services shortage, whether such a shortage originates from the system itself or from the particular robot configuration (in cluttered environments such as cities). This situation will improve with the development of highly reliable multimode navigation systems with built-in integrity monitors, and with three independent satellite navigation constellations (Glonass, Galileo, and GPS) currently deployed or under deployment.

The challenge for researchers is to develop navigation technologies that allow aerial robots to live without manmade external navigation infrastructure, to handle the situations when it is not available.

44.4.4 Agile Flight and Fault Tolerance

Nearly every aircraft in operational use today has been challenged to fly far beyond its flight envelope during flight tests, including famous maneuvers such as that of the Boeing 707 that, during early flight demonstrations to customers, performed a full barrel roll. The purpose of these demonstrations is not only to show the full capabilities of the vehicle, but also to bring a sense of safety to the pilots, that the aircraft is still able to perform well after its goes into some upset condition. What applies to large, manned aircraft also applies to aerial robots, which must be able to keep operating well at unusual attitudes and under partial system failures such as loss of actuation [44.16]. Researchers must develop automation systems that meet this need.

44.4.5 Obstacle Avoidance

The ability for a vehicle to manage its position away from obstacles represents a significant issue and a necessity for low-altitude operations in crowded environments. One of the key features of aerial robots is their possibly high speeds, which challenges many existing sensor management and data processing algorithms, especially their ability to detect hard-to-see obstacles such as suspended cables quickly.

44.4.6 Aerial Robot Landing and Interaction with Other Vehicles

Owing to the finite endurance of aerial robots, landing and docking are particularly important to them. While landing constitutes an important element, docking with other vehicles, such as during aerial refueling, is also very important. All operations involving close coordination and physical interaction between vehicles or between a vehicle and the ground require further research.

44.4.7 Multivehicle Coordination

Several tasks require aerial robots to operate as a group, rather than as individual systems. This happens, for example, in order to create phased array antennas, or to perform object geolocation, or to improve the quality of a surveillance service (e.g., fire monitoring). Other tasks requiring multivehicle coordination include the requirement for collision avoidance. More recently, multivehicle coordination has been seen as a valuable way to design aerial robotic systems that remain functional despite individual vehicle failures.

44.5 Basic Aerial Robot Flight Concepts

44.5.1 Aerial Robot Flight and the Importance of Scales

Like all flying machines, the performance of aerial robots depends extensively on: (1) their size and (2) the characteristics of their lifting mechanisms (wings, rotors). A detailed description of vehicle flight mechanics is outside of the scope of this chapter; we can, nevertheless, recall a few fundamental and useful notions critical to successful flight. The reference [44.17] is an excellent and entertaining introduction to the subject, while [44.18, 19] offer a more academic perspective on

Fig. 44.5 Flying wing (Northrop's YB47) and its shrunk version flying together

the matter. One important quantity is the *mass* of a flying machine. Roughly speaking, the mass of a flying machine is proportional to its volume, and therefore grows like the cubic power of its size. Another quantity is the lifting forces that keep a vehicle up in the air; these are proportional to the pressure exercised on the lifting surface (rotor or wing), times the *area* of the lifting surface, that is, roughly the second power of the vehicle size. The pressure itself is proportional to the density of the surrounding atmosphere (it need not be air only, think of Mars), multiplied by the square of the average velocity of the gas molecules relative to the lifting surface.

For illustrative purposes, consider the flying wing shown in Fig. 44.5 and a notional scaled-down version of it flying together. To make matters simpler, we assume that the scaled-down wing is about half the size of the full-sized wing. We now examine the impact of scales on the way these wings must fly.

Consider for example the lift created by the full-scale flying wing depicted in Fig. 44.5: it is proportional to $S\rho V^2\alpha$, where S is its total surface, ρ is the air density, V is the wing speed relative to the surrounding air, and α is the angle of attack (roughly speaking the angle between the wing chord and the flow of air).

To get an idea of the importance of scales, and following arguments developed in much greater detail in [44.17], we now examine the requirements for the scaled-down wing to fly at the same speed as the large wing, assuming all its components are shrunk by a factor two in size as shown in the picture, and examine the consequences of having to meet such requirements.

First, the mass of the wing roughly gets divided by a factor 8 (2^3). However, its lifting surface has shrunk by a factor of 4 only (2^2). So, if we were to fly this smaller wing at the same speed, same altitude, and same angle of attack as its big sister, the total generated lift must be $S/2\rho V^2$, that is, twice as much as necessary to balance out the effect of gravity.

Several solutions to this issue are possible: to reduce the the actual wing dimensions at constant mass, slow it down, or reduce its angle of attack.

Shrink the Wing

To obtain the proper lift (while keeping the speed and angle of attack constant), we must shrink the wing area by another factor of two, or the wing dimensions by a factor $\sqrt{2}$. Thus we already see one important conclusion, which is that, at equal speed and angle of attack, *the relative size of the wings with respect to the overall vehicle must shrink as the overall vehicle size goes down*. Borrowing again from [44.17], this explains much of why a Boeing 747 looks, with its large deployed wings and relatively narrow fuselage, like a condor while a B737 feels more like a puffin, and the smaller Embraer 145 is like a dart, as shown in Fig. 44.6. All

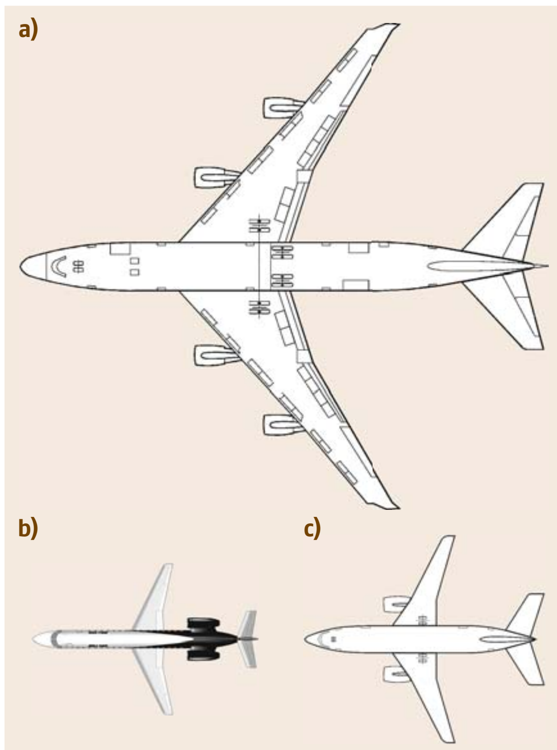

Fig. 44.6a–c Relative fuselage and wing sizes for various aircraft: **(a)** Boeing 747: **(b)** Embraer 145: **(c)** Boeing 737

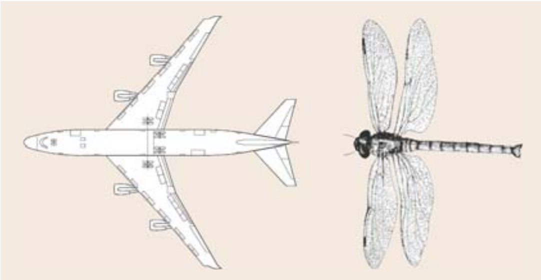

Fig. 44.7 Boeing 747 and dragonfly

these aircraft can fly about the same speeds and altitude ranges.

Reduce the Speed

If this option is chosen, then speed must be divided by a factor $\sqrt{2}$ for our scaled model to balance lift and weight. The consequences of reducing speed are many: the time required for mission completion of course increases. On the other hand, the drag generated by the flying machine (and which must be paid for by the propulsion system) goes down.

Pushed to their limits, the consequences of slowing down the vehicle as it shrinks can be quite dramatic: consider a dragonfly (one of the role models for micro-aerial robots) trying to land next to a Boeing 747 at the same airport. The figure below shows that the two share (very roughly) the same proportions.

For the sake of simplicity, assume that the dragonfly is the 1/1000 scaled-down version of the Boeing 747. In order for both to fly level, and according to our rule, the dragonfly must fly a factor $\sqrt{1000} = 32$ slower than the B747. Assume the B747 flies at 500 km/h; that makes the dragonfly fly at about 17 km/h. Imagine now that the weather is gusty, with winds topping 30 km/h. The 747 (and its passengers) will see little variation in airspeed (from 470 to 530 km/h), and the variation in produced lift will be 33%, enough to shake the aircraft a bit, but not unusually bad. As for the dragonfly, the same gusts will create airspeed variations of *well over* 100%, and the produced lift will vary from zero to five or six times the nominal lift. A rough ride naturally follows, and indeed, the flight of smaller vehicles often looks much less smooth than that of large ones.

Reduce the Angle of Attack

The latter option, reducing the angle of attack, rests upon the fact that, roughly, the lift created by a wing (or a rotor), is a linear function of the angle of attack. This makes it possible to fly about the same speed with a scaled-down model of a flying machine. However, this option comes with significant drawbacks, especially for fixed-wing aircraft. In particular, the *sensitivity* of the lift created by the wing to external perturbations (e.g., air turbulence and wind gusts) would again be higher, creating another recipe for *bumpy rides*.

The previous considerations about the forces acting on aerial vehicles also apply to moments: consider the flying wings shown in Fig. 44.5, and assume that their density (mass per unit volume) is constant throughout. Their angular inertia about any axis are proportional to the *fifth* power of their size. On the other hand, the forces that apply to the wings are proportional to their area; thus when *moments* are computed, forces are multiplied by distances, and the resulting moments become proportional to *volume*, that is, the third power of vehicle size. Consider then the angular momentum equation

$$J\ddot{\theta} = M , \tag{44.1}$$

where J is the moment of inertia of the vehicle and M is the applied torque. The term to the left of (44.1) decreases *much faster* with vehicle size than that to the right of the equation. As a consequence, we might immediately conclude that the scaled-down flying wing is inherently *much more maneuverable* than the larger one, in the sense that it can change orientation much faster.

This opens up a wealth of possibilities for robotics: venturing into the world of small flying robots, enabled by improvements of battery power and computation densities opens new possibilities in terms of defining the way these vehicles fly and interact with their environment.

44.5.2 Propulsion Systems

Several propulsion systems exist for aerial robots, including: jet, internal combustion, rocket, and electric. Older but recurrent options also include pulse engines such as those used on the German V1.

Owing to established aircraft and helicopter propulsion technologies, internal combustion engines and jet engines form the bulk of the propulsion means for medium to large-sized operational vehicles (50 kg or more), allowing many of them to fly reliably over periods of several hours to several tens of hours. When considering operational robots, the kind of fuel used matters: preference is given to fuels ala)

b)

Fig. 44.8 **(a)** Helios high-altitude long-endurance aircraft, **(b)** Mars aircraft [44.20] (Source: NASA)

ready used in other devices, and preference goes to heavy fuels, which are less prone to sudden and dangerous combustion or explosion, for example after a crash.

Electric propulsion systems, once unthinkable, have become a reality for several small-sized aerial robots, thanks to the development of affordable brushless electric engines and lightweight batteries. Initially developed for computer and communication applications, these batteries have been very quickly adopted by small-sized (a few kg) aerial robots such as Aerovironment's Pointer and Raven aircraft, which are able to fly over periods exceeding one hour. The National Aeronautics and Space Administration's (NASA) Pathfinder unmanned aircraft combines lightweight electric engines with wing-mounted solar panels to yield the aircraft shown in Fig. 44.8.

A notable departure from these propulsion systems is the Mars airplane's propulsion system [44.20]: with an inert, low-density atmosphere on Mars, such a vehicle relies on a rocket engine for propulsion.

44.5.3 Flight Vehicle Types and Flight Regimes

Several vehicle types form the bulk of aerial robots, including fixed-wing machines, helicopters, flapping wing systems, and combinations thereof. The boundaries between these vehicle types are, however, mostly inherited from historical developments and intellectual stove-piping, rather than any fundamental guidelines dictated by the laws of mechanics and thermodynamics. For that reason, it is easier and more logical to introduce different *flight regimes* than flight vehicles, although to every regime there naturally corresponds one particular vehicle.

There are essentially two flight regimes. In the first regime, called *hover*, the speed of the vehicle relative to the surrounding air is small, such that few or no forces act on the vehicle except those resulting from the propulsion system itself. In the second regime, which we may call *cruising flight*, there is a significant relative speed between the vehicle and its surrounding environment, and significant aerodynamic forces act on the vehicle; these aerodynamic forces then largely dominate those generated by the power system.

Hover

Hover is the condition when the vehicle body does not move significantly with respect to the air mass surrounding it. Under these conditions, only propulsion systems are available to keep the vehicle up in the air (for heavier-than-air systems). Helicopters epitomize these situations, and they are especially designed to sustain such hover conditions over long periods of time. Helicopters come in all sizes and shapes. Robotic helicopters are best represented by Yamaha's R-50, and now RMAX models (see, for example, Fig. 44.4), and both have been a staple of airborne robotics research for years at several academic institutions because of their reliability and available payload, which allows them to carry many instruments of interest to robotics research (including navigation sensors such as video cameras, laser range finders, and radars). With the evolution of the economic and political context, one is bound to see other such machines abound in the future. Indeed, the ability to hover is extremely useful for delivery/pickup of materials, rescue missions, and, in general, any operations that require close proximity to rugged terrain.

Helicopters are not the only vehicles capable of hover, see for example the hover-capable fixed-wing aircraft in Fig. 44.9. Hovering aircraft, such as tailsitters, have been tested successfully since the 1950s at the very least, and it is a classic trick for experienced remote control pilots to hover airplanes. Transitions from hover to forward flight and back have been automated [44.21]. As radio-control (R/C) equipment shrinks in size and mass, new generations of hovering vehicles will become available. Some of these vehicles include micro air and flapping wing vehicles.

Hovering flight typically not very fuel inefficient: the fuel consumption of a hovering vehicle can exceed that of a fixed-wing vehicle by an order of magnitude of more. This kind of consideration has led manufacturers to seek some of the mixed configurations shown in Fig. 44.9.

Fig. 44.9a–c Non-helicopter, hover-capable vehicles: **(a)** Joint Strike Fighter, **(b)** 1950s tailsitter aircraft and **(c)** Aurora Flight Sciences' Golden Eye 100

Cruising Flight

During cruising flight the aerial robot mostly uses its available surfaces and its speed relative to the surrounding atmosphere to generate lift and maintain altitude. Unlike hovering flight, cruising flight usually results in the aerial robot constantly meeting *fresh air*, which makes the range of adverse events to flight quite narrower. This, of course, is not true in the case when aerial robots fly in formation, in which case turbulence created by one robot may affect its neighbor(s), sometime adversely, and sometimes positively [44.22].

Robotic airplanes such as those shown in Fig. 44.8 epitomize fuel-efficient cruising flight, with large and highly optimized wings. Both aircraft are part of current NASA programs. While optimized for flight, the wings of the Mars aircraft must also be optimized for tight packaging and deployment constraints at the end of its long trip from Earth to Mars.

While many fixed-wing systems are optimized for cruising flight, any system in forward flight operates according to the same principles; for example, a helicopter in forward flight operates like an airplane whose wing is a flat disc spanning the area covered by its rotor. Constant-velocity cruising flight that generates lift from the available aerodynamic surfaces is more fuel efficient than hovering.

Stalled and High-Angle-of-Attack Flight

This flight condition can be seen as a *transitional* flight condition, where the characteristics of both forward flight and hover are present. Typically, an aircraft stalls when its tries to maintain altitude at low speeds: flying level at lower speeds forces the aircraft's angle-of-attack to increase for the wings to produce more lift. However, past a critical angle of attack, the trend reverses and the lift produced by the wing *decreases* as the angle of attack keeps increasing. This reduced aerodynamic lift must then be compensated by increased throttle, resulting in a situation where the aircraft propeller not only acts as a means to move the aircraft forward, but also directly participates in maintaining aircraft altitude.

This flight condition, whether experienced on a helicopter or airplane, often results in important changes of the effect of control mechanisms, for example, a stalled Piper Tomahawk trainer aircraft at low throttle setting will experience ineffective ailerons, while its rudder efficiency will shift from yaw axis to roll axis control [44.23].

44.5.4 Lighter-Than-Air Systems

One way to deflect some of the concerns associated with high fuel consumption of heavier-than-air aircraft is to rely on lighter-than-air vehicles. While these vehicles are often associated with spectacular accidents and slow motion, they also offer an unmatched capability to fly for long periods of time (more than 48 h) and to do so silently [44.24, 25]. Establishing control over lighter-than-air vehicles can be, however, somewhat challenging. In particular these vehicles are quite sensitive to winds and often tend to *go where the wind takes them*. Smaller platforms used for research must therefore evolve in closed environments [44.26]. The use of such vehicles for outdoor research can be quite daunting, because their large size requires considerable infrastructure to store them.

44.6 The Entry Level for Aerial Robotics: Inner-Loop Control

Aerial robots exhibit the complex flight dynamics associated with flight vehicles. As a consequence, precise motion control rapidly becomes a necessity for *any* aerial robotics activity to occur successfully. This means that effort must go into reliable basic flight control before more advanced, intelligent mission management can be attempted. Inner-loop control is achieved by the right sensing equipment, and by adequate control algorithms. Efficient hovering vehicles tend to be unstable, which makes their stabilization more difficult than that of purely cruising vehicles, for which many commercial control packages are now commonly available.

44.6.1 Sensing and Estimation

Airborne robots come with a variety of sensing options, which include

- inertial navigation systems (gyroscopes, accelerometers)
- global navigation satellite systems (GLONASS, GPS, Galileo)
- terrestrial radio navigation systems (VHF omnidirectional range (VOR), distance measuring equipment (DME), instrument landing system (ILS))
- air data probes and altimeters
- radar and passive vision sensors
- magnetic compasses
- distance measuring (altitude radars, ultrasonic sensors, and laser range finders)

The choice of sensors is critical to obtaining a properly flying robot. Usually, the same suite of sensors may not apply to all phases of flight. We will concentrate our discussion on the first four sensor types.

Inertial Navigation Systems

Inertial measurement systems consist of a combination of usually three orthogonally mounted accelerometers and three orthogonally mounted gyroscopes (more may be used for the purpose of achieving redundancy). The accelerometer suite measures, up to sensor error, the accelerations experienced by the vehicle at the location of the inertial sensor minus gravity. Gyroscopes measure vehicle angular velocities. Modern inertial sensors are usually rigidly linked to the vehicle to form strapdown inertial measurements systems. Such systems have become very cheap and very popular. Unlike many nonflying applications, unaided inertial measurement packages are not sufficient for estimating the attitude of an airborne vehicle. Indeed, consider Fig. 44.10, showing two helicopters equipped with inertial measurement systems. One, straight up, is hovering. The second, upside down, races towards the ground with an acceleration of 2g. The accelerations and rotation rates recorded by the onboard inertial measurement unit will be strictly the same in both cases. While attitude can be estimated by integrating angular rates over time, the approach will eventually fail without correcting for accumulated error from another source. It remains that inertial measurement units are extremely useful to measure variations in acceleration and angular velocities, and constitute a staple of inner-loop control systems. Small radio-controlled helicopters now come with built-in gyroscopic yaw dampers that make their manual operation much more manageable. A key progress was made when Analog Devices introduced a low-cost micromechanical gyroscope [44.27]. Since then, this technology appears to have made its way into most commercially available inertial measurement units (IMUs), thereby greatly reducing their cost and weight. Practical inertial navigation systems on aircraft typically receive at least position updates from other sensors (discussed below), called inertial aiding.

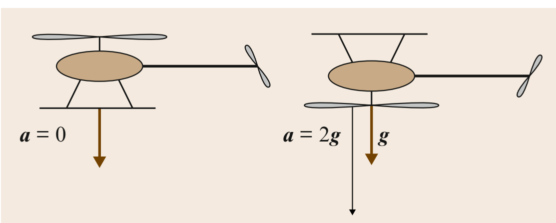

Fig. 44.10 Two inertially equivalent helicopter configurations

Global Navigation Satellite Systems

The Global Positioning System (GPS) and its Russian equivalent GLONASS and future European Galileo space-based systems offer real-time absolute position information, using a constellation of satellites circumnavigating the earth. Ever since the beginning of their operation, global navigation systems (GNS) have been the object of a debate concerning their use in aerial robotics, with many researchers recommending against using such a large manmade navigation infrastructure to achieve *true autonomy*. Their arguments tend to become justified by the occurrence of recent needs in such applications as Mars exploration and low-altitude flight in obstacle-laden environments (such as cities) where satellite-based navigation is often unavailable. Wherever they are available, however, satellite navigation systems are a convenient and cheap means for a vehicle to locate itself. This modest investment has often been the enabler of automatic flight for many researchers and is currently used by virtually all existing industrial systems. Pushed to their limits, satellite navigation systems have been shown to achieve the entire range of desired navigation and sensing functions, which include vehicle position and attitude: GPS-only flight for a small helicopter robot was achieved in 1995 at Stanford University [44.28].

Altimeter and Air Data Probes

Pressure-measuring devices are immensely useful sensors in aerial robotics. With ingenious arrangements of pressure sensors (such as pitot tubes) it is possible to measure (1) the atmospheric pressure at the location of the robot and (2) the so-called *dynamic pressure*, $\rho v^2/2$, along all vehicle axes. These data can themselves be transformed into precious information about the aerial robot's altitude and direction of motion relative to the air it is flying in. Depending on the vehicle used, air data probes may be challenging to build and constitute an interesting field of investigation. Indeed, pressure probes are very sensitive to flow perturbations generated by fuselage, wings, and most importantly rotors and propellers. Air data probes are therefore positioned as far away from the main elements of the vehicle as possible (for example, along a boom extending forward of the vehicle fuselage). Figure 44.11 shows one such air data probe configuration. Mounted together with inertial measurement systems, air data probes allow aircraft to maintain stable flight at a prescribed altitude. With the current state of technology, they remain somewhat insufficient to achieve, alone, stable hovering flight for helicopters.

Passive Vision

Passive vision has become a very popular sensor for inner-loop control. Even unsophisticated light sensors able to differentiate between the intensity of infrared activity from the ground versus that emitted by the sky has made its way into small commercial products, mostly aimed at assisting remote-controlled vehicle flight. As will be discussed later, passive vision devices have also found applications for vehicle–obstacle and vehicle–vehicle proximity management, and for landing applications. Recent research aimed at using vision for inner-loop control applications includes work aiming at tracking relatively invariant features such as the horizon [44.29].

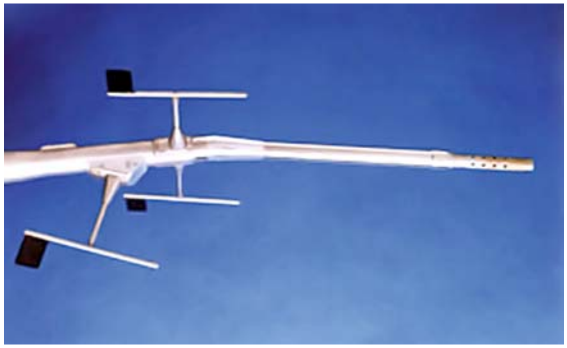

Fig. 44.11 Air data probe (Source: NASA Dryden Flight Research Center). The vanes are used to measure angle of attack and sideslip angle

44.6.2 Estimator Design

The individual inputs collected from each sensor are usually not sufficient to estimate the state of the vehicle. Different sensors may be efficient over different flight regimes. The proper way to leverage individual information provided by each sensor is through an appropriate *filtering* process that can yield rather comprehensive information about the entire system's state. Unlike ground robots, the necessity for good robot state estimates arises early in the robot development process since closed-loop flight would be impossible otherwise. However, the structure of the filters is usually a great deal simpler than their ground-based equivalent, since the difficulty of flight is compensated by a rather simple and uniform environment structure. As a consequence, simple filters such as (extended) Kalman filters are usually enough for a large number of applications and quickly enable flight [44.30].

44.6.3 Inner-Loop Control

Inner-loop control of aerial vehicles naturally builds upon the previously discussed state estimator, and is relatively easy for routine flight operations. By this we mean that the process by which a good vehicle controller is obtained only requires following standard textbook techniques such as proportional, integral, and derivative control or linear quadratic control [44.31–33], appropriately scheduled against essential parameters such as vehicle speed and altitude. As a result, several research groups, and now several companies, have built basic guidance and control packages suitable for aerial robots, both fixed-wing and helicopter.

Among the notable recent advances for the inner-loop control of aerial robots, we find the successful experimental application of adaptive and learning control techniques [44.21, 34, 35], which offer stable controlled helicopter flight from very coarse initial vehicle dynamics knowledge.

44.7 Active Research Areas

This section presents some of the active research in aerial robotics. Such research efforts aim at answering the challenges outlined in Sect. 44.4.

44.7.1 Interfacing with the Human Infrastructure: Meeting the Regulations

While manned flight operations indeed have an excellent safety record, the price paid for this safety is a strong specialization of those regulations to human-operated systems, and a slow evolution of these regulations towards accepting aerial robots of all sizes. Currently none of the existing aerial robots is able to meet these regulations in the absence of a human pilot. This includes the ability to see (or sense) and avoid other aircraft, comply with air-traffic rules, and operate harmoniously with the current ground-based, manned air-traffic control system [44.4, 5, 36]. In the case of the US however, the FAA has acknowledged the economic potential of aerial robots by opening an office specifically devoted to such systems (the Unmanned Aircraft System Group), and by delivering permits to fly over certain areas (especially disaster areas) within a couple of hours of a request. However, the FAA currently emphasizes access for remotely piloted machines (as opposed to fully autonomous machines), where a ground-based pilot must have the means to communicate by voice with the FAA control center in charge of the geographical area where the vehicle is operated.

Efforts to help aerial robots improve their interface with other vehicles include the adaptation of existing systems to prevent mid-air collisions between aerial robots and other traffic, the development of *see-and-avoid procedures*, and means to interact with an aerial robot as one would interact with a human pilot (natural language interfaces). We now detail these efforts.

Collision Avoidance for Remotely Piloted Vehicles

The most immediate efforts aimed at inserting aerial robots in the civilian airspace consists of adapting existing airborne collision avoidance systems (ACAS), originally designed for manned systems, to aerial robots. Such systems are based on cooperative position information sharing between aircraft extracted from radar-based navigation and surveillance systems. The reason for emphasizing such systems over other, newer technologies is that they have already undergone extensive, and expensive, development, validation and testing. As such, several unmanned vehicles, such as the Global Hawk unmanned aircraft, are now fitted with ACAS systems [44.37]. However, such systems are not automated, meaning that the remote human pilot ultimately decides whether to execute the maneuvers recommended by the system. The possibility of completely automating such collision avoidance systems is the object of recent studies [44.38], with the clear intent of fitting them on aerial robots. However, the weight of ACAS system hardware, as well as the power required to operate them, makes such systems suitable only for large vehicles. In the context of rapidly evolving technology (such as the generalization of positioning information using global navigation satellite systems), current ACAS technology may also become rapidly obsolete.

Sense and Avoid

The idea, encouraged by institutional service providers, is to ensure that aerial robots are able to detect the presence of other traffic and avoid it as necessary and at least as well as a human pilot. Several candidate sensing technologies are currently in development, including passive vision systems [44.39–42], in an effort aimed at making aerial robots as able as humans to avoid other traffic when the sky is clear (visual flight rules). While much can be done in the visible spectrum, concerns over vehicle flight in clouds raises the necessity to consider other frequency bands, such as the near infrared, if aerial robots will need to be able to detect other traffic better than a human pilot [44.43].

Human Interfacing

Another active research venue is to facilitate the interfacing of robots with humans (e.g., an aerial robot interacting with a human air-traffic controller). Recent research in human–aerial robot interaction has shown that aerial robots can interact productively with humans, by combining natural language processing interfaces with advanced vehicle path and task planning capabilities [44.44–46]. A natural interface might capture standard, unambiguous phraseology such as North Atlantic Treaty Organization (NATO) phraseology or air-traffic control phraseology. The impact of such technology on aerial robots would be profound since they would then be able to enter airspace with little or no visibility and be able to interact with the predominantly ground-based, human-intensive air-traffic control structure.

44.7.2 High-Agility Flight

One of the important characteristics of aerial robots is the ability to operate at the limit of its structural strength, unimpeded by the presence and physiological limitations of a human pilot. This allows aerial robots, especially small ones, to operate very aggressively. As a result, several research groups have explored the possibility of achieving aggressive flight with either fixed-wing or rotary-wing vehicles. The key factors that have enabled the onset of highly aggressive flight has been the emergence of lightweight computing environments and sensors, notably GPS and inertial systems. Indeed, aggressive flight (where aggressive flight refers to any abrupt change in vehicle attitude) is closely related to available vehicle mass and size, as discussed earlier.

Figure 44.12 shows the evolution of three helicopter configurations over time. While the vehicle platform has evolved little or not at all, the onboard avionics has progressively shrunk. In the mid-1990s, the onboard avionics typically would weigh the same or more than the helicopter mass. By the early 2000s, the onboard avionics would be about half of the vehicle mass, while by the mid-2000s the onboard avionics represent only a small fraction of the helicopter mass. The corresponding levels of achievable agility have evolved correspondingly. By the early 2000s, basic aerobatic maneuvers became feasible [44.47], and by 2007 fully fledged aerobatics had been reported [44.48]. Other efforts involving unusual flight attitudes and fault recovery include those of Chiba University (Japan), who demonstrated autorotation landings for autonomous helicopters [44.49].

Parallel to rotorcraft agile flight, several efforts have also successfully enabled aerial agility for fixed-wing robots [44.21].

44.7.3 Take-Off, Landing, and Interaction with Other Vehicles

One of the richest current areas of investigation for aerial robots involves vehicle operation next to other vehicles or infrastructures. These operations include take-off, landing, docking, and separation.

Take-Off and Landing

Take-off and landing experimentation and research is proving particularly interesting for small-sized aerial robots. Indeed, the dynamics of smaller vehicles enable strong departures from conventional, manned-vehicle take-off and landing operations, for example, most fixed-wing unmanned aerial vehicles under 5 kg are better off simply flying into the ground than attempting to land in a smooth fashion. One of the best illustrations of how vehicle landing procedures may dramatically change for smaller-sized aerial robots is Insitu's and Hood Technology's *Skyhook* concept: small, fixed-wing aerial robots are recovered by allowing them to catch a vertical cable with the tip of one of their wings [44.12]. The cable itself is held by means of a crane, itself mounted on a surface vehicle (e.g., truck or ship). At take-off, similar scaling considerations apply, with many fixed-wing vehicles being launched by hand or by means of a catapult. One of the consequences of the increased tolerance of small ve-

Fig. 44.12a–c Avionics versus vehicle. **(a)** Stanford Helicopter (c. 1995). **(b)** MIT helicopter (c. 2001). **(c)** Stanford Helicopter (c. 2006)

Fig. 44.13 Skyhook system in action (courtesy Insitu, Inc.)

hicles to *crash landings* is also their reduced need for high-resolution navigation information, for example, it has been shown possible to land small-sized vehicles on a designated target with monocular vision only [44.50].

Helicopter robots have, so far, not benefitted from the same kind of developments, and much of their take-off and landing procedures are similar to their larger counterparts. The main reason may be attributed to the presence of a fragile rotor that spins at high speed, and that must avoid contact with other vehicles or the ground. Many of the current robotic helicopter landing procedures simply consist of hovering above the landing area, then commanding a limited descent rate until the vehicle records it has touched the ground. More challenging situations (e.g., sloped terrain or moving platforms), traditionally handled by humans in large platforms, remain difficult for aerial robots. For this reason, the *helicopter landing problem* has attracted the attention of many research teams. On the one hand, there have been many efforts combining advanced sensing environments [44.51–55] with advanced control algorithms to enable affordable landing in structured environments which are not simply horizontal landing pads. On the other hand, identifying suitable landing places in unprepared environments by means of remote sensing and signal processing is also an area of active research [44.56–58].

Fig. 44.14a,b Automatic airborne refueling. **(a)** Typical refueling configuration. **(b)** Camera view of refueling basket (Source: NASA Dryden Flight Research Center)

Operations in the Vicinity of Other Vehicles: Docking and Undocking

Docking operations for unmanned aerial vehicles are necessary to improve their range and autonomy. Indeed, it is conceivable that some optimal aerial robot configuration consist of a parent–child system, whereby a larger machine provides a primary deployment and retrieval mechanism for several smaller vehicles. Such a concept has existed for a long time, with airships acting as carriers for smaller aircraft [44.59]. More recently however, it is in-flight aerial refueling that has motivated recent research on docking aerial robots. Indeed, the possibility for such vehicles to refuel considerably increases their operational range [44.60–62]. The NASA Dryden Flight Research Center has recently reported the completion of the first vision-aided fully automated aerial refueling operation, using computer vision for the purpose of recognizing and tracking the fuel hose

Fig. 44.15 Georgia Tech's unmanned helicopter in a parent–child configuration. The child is a hover-capable ducted fan

that must be captured by the aerial robot, as shown in Fig. 44.14.

Undocking operations are comparatively easier to perform. They remain, however, spectacular since the dynamics of the aerial robot dramatically change as it is dropped from its mother ship. An extreme example of such a situation is illustrated by Georgia Tech's successful dropping of a small ducted fan aerial robot from a larger autonomous helicopter. The small ducted fan then successfully stabilized itself. Pictures of this experiment are shown in Fig. 44.15.

44.7.4 Reactive Flight in Cluttered Environments and Obstacle Avoidance

Flight in cluttered environments includes any phase of the flight where vehicles are in close proximity to obstacles. This flight mode is particularly important for low-altitude applications. Several achievements have been reported in this area in the recent past, using a variety of sensing techniques.

Among the first significant works relying on passive vision techniques, *Beard* and *McLain*'s certainly stands out as one of the most entertaining and spectacular [44.63], using fixed-wing vehicles performing autonomous flight within a canyon using low-cost, optical flow computation techniques.

Other institutions involved with active as well as passive sensing techniques for vehicle navigation in cluttered environments and obstacle avoidance include Carnegie-Mellon University [44.64], where the authors report fast vehicle flight in highly cluttered environments, including obstacles as difficult to deal with as suspended cables. The NASA Ames research center also recently reported successes along similar lines as part of their work on adaptive landing in unprepared environments [44.56–58].

44.7.5 Path Planning and Higher-Level Planning Capabilities

Single-Robot Path Planning

Path planning for aerial robots resembles path planning for any robot, with the following distinctive characteristics: aerial robots are able to fly very fast (or may *have to* fly fast). Thus there is the distinct possibility of significant discrepancies between intended and actual trajectories. The vehicle dynamics must be fully accounted for when designing trajectories. Several path planning concepts have been proposed to handle this problem, including [44.65–67] and many others. Another key issue in aerial robot trajectory planning arises when there is a discrepancy between the complexity of the environment and the maneuvering space needed for the vehicle. When planned for finite time or geographical horizons, it becomes important that a planner constantly keep a feasible loitering solution within the known environment [44.46].

Multirobot Path Planning and Coordination

There has recently been a surge in research activities for multivehicle path planning and coordination. Such research activities have been motivated by problems as diverse as the generation of noncolliding paths, the generation of *swarming* behaviors for applications such as phased-array, robot-borne antenna systems, collaborative target detection and prosecution, and collaborative search for thermal currents.

This rich literature, of which only a few references have been cited, stems from the conjunction of several constraints in the problem under study, including

- highly constrained dynamical systems (with restricted radius of curvatures and minimum speed requirements, for example)
- a variety of information management possibilities (including centralized, decentralized, distributed information)
- catastrophic consequences in case of failures

Initial work aimed at studying aerial-robot coordination from the perspective of mission execution include [44.68–71]. Swarming behaviors, or the ability for a vehicle group to generate a coherent, consensual behavior using only local information, has become the focus of much attention in the research community since the recent paper [44.72].

Collision avoidance has also formed the motivation for much research in multirobot coordination, see for example [44.73–75].

44.7.6 Integrated Aerial Robotic Operations: Aerial Robotics Contests

Research on the ability of aerial robots to perform completely autonomous missions, especially at low altitudes, is clearly well represented in contests such as the International Aerial Robotics Competition, initiated in 1991 by *Michelson* [44.1]. In this contest, universities, possibly supported by industry and government, compete against each other by demonstrating how their vehicles, or vehicle systems, meet the requirements of the competition. A basic tenet of the competition is that the small aerial robotic systems entrants must be capable of complete autonomy (no human interaction) during the mission.

The rules of the competition have evolved from the inception of this effort to reflect advances in the capabilities of the proposed systems. One of the key characteristics of the competition is that it has always emphasized the simultaneous demonstration of several robotic functionalities, including basic mission execution, object reconnaissance and detection, and object manipulation. During the early days of the competition, the task asked for an aerial robot to recognize and pick up an object in a designated area, and carry it to another designated area. As universities were able to meet the initial challenges posed by the competition rules, the rules have evolved to a higher level of sophistication. As of today, the competition rules require complete autonomous operation of the vehicles over longer distances. The vehicles must now find and reach a village from a distance of three kilometers. They must also evolve towards higher reasoning capabilities about the objects and events being encountered. Moreover, emphasis has been placed on multimodal robotics, since the robotic system must be able to enter a building and explore it, a task currently best performed by ground robots.

Recognizing the growing gap between experienced participants and new entrants, several different competition levels have been established. While US participation in the competition is predominant, several non-US participants are also present, including Germany, England, Switzerland, Canada, and India. In 2000, the Technische Universitaet Berlin won the contest. Other contest winners include Carnegie-Mellon University, the Georgia Institute of Technology, MIT/Draper Laboratory, and Stanford University.

Other aerial robotic competitions have since been established. For example, the French governmental organization Delegation Generale pour L'Armement (DGA), together with the Supaero and Ecole Nationale Superieure Des Constructions Aeronautiques (ENSICA) engineering schools have proposed a contest involving very small-sized aerial robots in 2004, with a focus on their flight mechanics at various flight regimes. The government of Queensland, Australia together with the local research organizations Commonwealth Scientific and Industrial Research Organization (CSIRO) and Queensland University of Technology launched a new contest focusing on search-and-rescue missions in 2007.

The distribution of vehicle types involved in these contests is very different from the distribution of operational aerial robots. While operational aerial robotic systems are overwhelmingly of fixed-wing type, the machines used by universities during these contests offer a much more balanced distribution of aircraft and rotorcraft. Several reasons contribute to these differences and they have been outlined earlier. The operation of fixed-wing aircraft at relatively high altitude, for reconnaissance and surveillance missions offers a large and technologically easy market to reach, although it faces significant regulatory constraints. In comparison, the operation of small vehicles in cluttered environments definitely favors hovering-like vehicles. However, these vehicles, like other robots, face significantly more constraints in terms of environment sensing, obstacle avoidance, and task planning and execution complexity. As such, they are closer to the realm of basic research typical of universities.

44.8 Conclusions and Further Reading

Aerial robots represent a very interesting and exciting area of robotics, involving very dynamic platforms whose size ranges from a few centimeters to several tens of meters. It seems highly probably they will continue to see new applications, beginning with those that happen in relatively unpopulated areas and relatively high altitudes. The current applications of aerial robots are focused primarily on military operations. However, an ambitious civilian market led by Japan is currently burgeoning.

Aerial robots currently pose a challenge to all regulatory agencies, which must find modalities and rules to insert them into airspace occupied by other traffic such as manned systems. The resulting technical research challenges include the development of a proper and affordable *sense-and-avoid* technology, and the ability for aerial robots to be conversant with other traffic and the ground control infrastructure.

Lower-altitude aerial robotics, often operating in cluttered environments, offers the opportunity to explore many generic robotics topics, including vision, path planning, mapping, and other algorithms in a progressive manner, while offering potential benefit of still more important applications.

A very dynamic research and development field, aerial robotics can be seen from a historical perspective by reading [44.3]. A snapshot of current UAV technology can be obtained, for example, from [44.76]. The lack of a known comprehensive, book-like presentation of aerial robotics and its applications clearly indicates that the field is still very young, that operational experience is slowly building up, and that many challenges, most notably regulatory and safety challenges, must still be overcome.

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