REVIEW

Science, technology and the future of small autonomous drones

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We are witnessing the advent of a new era of robots — drones — that can autonomously fly in natural and man-made environments. These robots, often associated with defence applications, could have a major impact on civilian tasks, including transportation, communication, agriculture, disaster mitigation and environment preservation. Autonomous flight in confined spaces presents great scientific and technical challenges owing to the energetic cost of staying airborne and to the perceptual intelligence required to negotiate complex environments. We identify scientific and technological advances that are expected to translate, within appropriate regulatory frameworks, into pervasive use of autonomous drones for civilian applications.

Drones, a popular nickname for unmanned aerial vehicles and micro aerial vehicles, often conjure up images of unmanned aeroplanes that fly thousands of miles for espionage and to deploy munitions. However, over the past few years, an increasing number of public and private research laboratories have been working on small, human-friendly drones that one day may autonomously fly in confined spaces and in close proximity to people. The development of these small drones, which is the main focus of this Review, has been supported by the miniaturization and cost reduction of electronic components (microprocessors, sensors, batteries and wireless communication units), largely driven by the portable electronic device industry. These improvements have enabled the prototyping and commercialization of small (typically less than 1 kg) drones at smartphone prices.

Small drones will have important socio-economic impacts (Fig. 1). Images from drones that are capable of flying a few metres above the ground will fill a gap between expensive, weather-dependent and low-resolution images provided by satellites and car-based images limited to human-level perspectives and the availability of accessible roads. Specialized flying cameras and cloud-based data analytics will allow farmers to continuously monitor the quality of crop growth. Such platforms will enable construction companies to measure work progress in real time. Drones will let mining companies obtain precise volumetric data of excavations. Energy and infrastructure companies will be able to exhaustively survey pipelines, roads and cables. Humanitarian organizations could immediately assess and adapt aid efforts in continuously changing refugee camps. Transportation drones that are capable of safely taking off and landing in the proximity of buildings and humans will allow developing countries — without a suitable road network — to rapidly deliver goods and to finally unleash the full potential of their e-commerce telecommunication infrastructure. Transportation drones will also help developed countries to improve the quality of service in congested or remote areas, and will enable rescue organizations to quickly deliver medical supplies in the field and on demand. Inspection drones that are capable of flying in confined spaces will help fire-fighting and emergency units to assess dangers faster and more safely, logistic companies to detect cracks in the inner and outer shells of ships, road maintenance companies to measure signs of wear and tear in bridges and tunnels, security companies to improve building safety by monitoring areas outside the range of surveillance cameras, and disaster mitigation agencies to inspect partially collapsed buildings where ground clutter is an obstacle for terrestrial robots. Coordinated teams of autonomous drones will enable missions that last longer than the flight time of a single drone by allowing some drones to temporarily leave the team for battery replacement. Drone teams will permit rescue organizations to quickly deploy dedicated communication networks for ground operators. Telecommunication companies can also leverage drone networks to temporarily supplement or replace points of service.

Realizing this vision will require new mechatronic solutions and new levels of control autonomy (Box 1) to safely complete missions in confined spaces and near the ground, where absolute positioning signals and remote control are not available or sufficiently precise. None of today's commercial drones has sufficient control autonomy to complete any of the missions described without skilled human supervision, which makes those operations slow, dangerous and not scalable. We identify the most promising scientific and technological advances that could lead to a new generation of small autonomous drones and offer a tentative road map of capability deployment within suitable regulatory frameworks.

Design and manufacturing challenges

Flight is energetically expensive, particularly when the size of the device is reduced. This is often due to practical issues that arise when scaling a vehicle down, such as reduced power density of electromagnetic motors, decreased transmission efficiency owing to increased dominance of friction from gears and bearings, and greater viscous losses because of reduced Reynolds numbers. Certain flight modes are also challenging — for example, hovering — either owing to energetics or control; these also become increasingly difficult as size is reduced. Scaling issues create problems at the most basic level of autonomy: they limit the ability to simply sustain flight for an adequate amount of time to perform higher-level mission functions. To overcome these challenges, developers of drones must consider system-level design choices that balance trade-offs that arise when selecting the constituent components to power the vehicle. The most common morphologies for flying robots include more conventional fixed-wing and rotary-wing aircraft (rotorcraft) designs as well as bio-inspired designs based on flapping wings. Each of these platform types has pros and cons. For example, fixed-wing aircraft (Fig. 2a) are capable of fast and efficient flight, but typically cannot hover. Rotorcraft (Fig. 2b) can hover and are highly manoeuvrable, but are generally less efficient in forward flight than fixed-wing vehicles. Neither fixed-wing

[1]Laboratory of Intelligent Systems, Ecole Polytechnique Fédérale de Lausanne, Station 11, Lausanne, CH 1015, Switzerland. [2]Microrobotics Lab, Harvard University, 149 Maxwell Dworkin Building, Cambridge, Massachusetts 02138, USA.

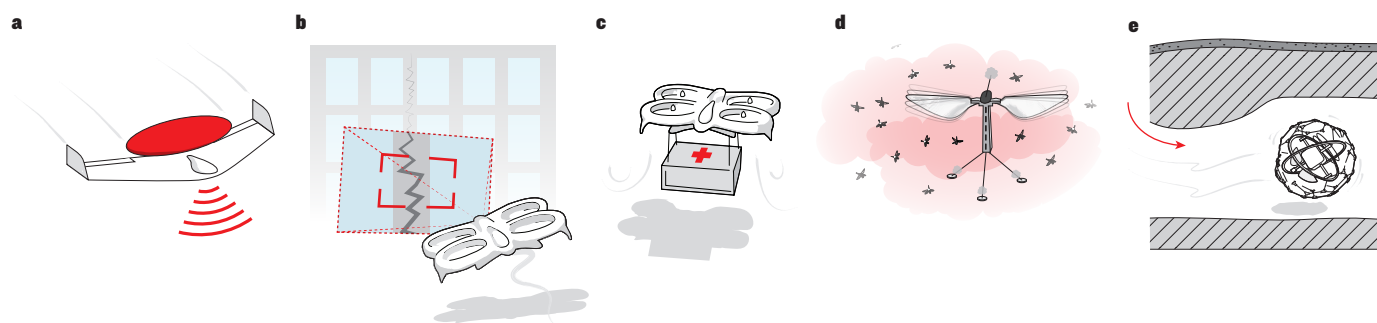**Figure 1 | Autonomous drones in rescue situations. a,** Fixed-wing drones with a long flight time could provide bird's-eye-view images and a communication network for rescuers on the ground. **b,** Rotorcrafts with hovering capabilities could inspect structures for cracks and leaks; and **c,** transport medical supplies from nearby hospitals. **d,** Swarms of dispensable drones with flapping wings could enter buildings to search for chemical hazards. **e,** Multi-modal caged robots could fly and roll into complex structures to safely search for signs of life.

craft nor rotorcraft scale down well — both in terms of the aerodynamics that govern flight and in the performance of the components that are necessary to generate propulsion. Bio-inspired flapping-wing flight (Fig. 2c) offers an alternative paradigm that can be scaled down in size, but brings fluid-mechanics-modelling and control challenges.

Propulsion and manoeuvrability considerations

Small-scale aerial vehicles are predominantly fixed-wing propeller-driven aircraft or rotorcraft. The latter can be further broken down into conventional primary and tail rotor configurations, coaxial dual rotors[1], or quadcopter designs, which have recently become popular. For each of these configurations, and for propeller-driven aircraft at larger scales, there have been only small incremental improvements to propeller design over the past several decades, since the advent of standards and tools to generate airfoil shapes by the National Advisory Committee for Aeronautics[2]. Propulsive efficiencies for rotorcraft degrade as the vehicle size is reduced; an indicator of the energetic challenges for flight at small scales. Smaller size typically implies lower Reynolds numbers, which in turn suggests an increased dominance of viscous forces, causing greater drag coefficients and reduced lift coefficients compared with larger aircraft. To put this into perspective, this means that a scaled-down fixed-wing aircraft would be subject to a lower lift-to-drag ratio and thereby require greater relative forward velocity to maintain flight, with the associated drag and power penalty reducing the overall energetic efficiency. The impacts of scaling challenges (Fig. 3) are that smaller drones have less endurance, and that the overall flight times range from tens of seconds to tens of minutes — unfavourable compared with human-scale vehicles.

There are, however, manoeuvrability benefits that arise from decreased vehicle size. For example, the moment of inertia is a strong function of the vehicle's characteristic dimension — a measure of a critical length of the vehicle, such as the chord length of a wing or length of a propeller in a similar manner as used in Reynolds number scaling. Because the moment of inertia of the vehicle scales with the characteristic dimension, L, raised to the fifth power, a decrease in size from a 11 m wingspan, four-seat aircraft such as the Cessna 172 to a 0.05 m rotor-to-rotor separation Blade Pico QX quadcopter implies that the Cessna has about 5×10^{11} the inertia of the quadcopter (with respect to roll). Depending on the scaling law used for torque generated by the quadcopter, this leads to angular acceleration that scales either by L^{-1} or L^{-2}, both cases indicating that the quadcopter will be much more manoeuvrable[3]. This has resulted in remarkable demonstrations of aerobatic manoeuvres in rooms equipped with real-time tracking and control by external computers, including flying through windows at high speeds[4] and manipulating objects in flight[5]. This enhanced agility, often achieved at the expense of open-loop stability, requires increased emphasis on control — a challenge also exacerbated by the size, weight and power constraints of these small vehicles. Implementing these behaviours in autonomous drones (with on-board sensing and computation) is a significant challenge, but one that is beginning to have promising results[6,7] — even for aggressive flight manoeuvres. The

challenges for further scaling down these sensing and control systems are discussed in the final section of this Review.

Actuation, power and manufacturing

Beyond autonomy considerations, the size and type of the flying robot also engender associated challenges with actuation and manufacturing. For actuation, rotorcraft and propeller-driven fixed-wing drones generally use electromagnetic motors. Some flapping-wing aircraft[8,9] also use electromagnetic motors, but require a linkage mechanism to convert the rotary motion of the motor to the flapping motion of the wings. However, as the scale is reduced, conventional motors become inefficient, require substantial gearing to achieve a desired wing or propeller velocity, and are extremely difficult to manufacture. Therefore, for vehicles below a few grams, alternative methods of actuation are required. Similarly, 'macro size' flying robots (tens to hundreds of grams and larger) may be constructed using conventional methods such as additive and subtractive machining and 'nuts-and-bolts' assembly. However, for 'micro size' flying robots (less than a few grams), manufacturing needs to be rethought and novel methods applied. To give a perspective on the challenges for actuation, we need to consider how the physics of scaling[10] affects the performance of electromagnetic motors. At macroscopic scales, motors used in electric cars can achieve an efficiency of nearly 90% with a power density of several kilowatts per kilogram whereas at millimetre scales, existing motors produce a few tens of watts per kilogram of power at less than 50% efficiency[11]. This reduction in performance and the energetic expense of flight at small scales means that both power source and power distribution are important considerations[12]. For vehicles for which the primary propulsion system is also responsible for generating control torques, this does not apply (for example, quadcopters). However, for fixed-wing aircraft and some flapping-wing vehicles, it is essential that most of the power budget must be allocated to staying aloft with a proportionately smaller power for actuating control surfaces. For example, nearly 90% of the power budget of the RoboBee (Fig. 2c) is dedicated to the primary power actuators that generate lift to stay in the air[13]. As already discussed, for power actuators, the typical choice is electromagnetic motors. There are alternatives, including electroactive materials such as piezoelectric actuators[14] or ultrasonic motors[15], however, these are most appropriate for the smaller end of the size spectrum. Control actuators have more options at most scales, including voice coils, shape memory alloys[16] and electroactive polymers[17].

Given the challenges for small-scale propulsion, an unsteady approach to force production is potentially a viable option for small vehicles. Unlike fixed-wing aircraft and rotorcraft that produce lift and thrust in a quasi-steady way (either directly in the case of rotorcraft or indirectly by the movement of air over the wings of a fixed-wing drone), the aerodynamics of flapping-wing drones is complex and involves the generation and manipulation of vortical structures in the air[18]. As is obvious from its existence in nature, flapping-wing propulsion is an effective form of locomotion, but translating this into

functional designs is not a trivial exercise given the morphological diversity of the flight apparatus of insects, bats and birds. Nonetheless, drone researchers have effectively reproduced natural flight in many different ways. Examples include robotic insects such as RoboBee[19] and the four-winged DelFly[8], and bird-sized drones such as the Nano Hummingbird[9] (Fig. 2c).

As size is reduced, in addition to the challenges for actuator selection and manufacturing, there are also considerations of how to manufacture the entire vehicle. At scales for which electromagnetic actuation and bearing-based rotary joints are feasible, more conventional manufacturing methods are used, such as subtractive machining, additive printing and moulding of composite materials. At small scales — for example, for aircraft of comparable size to insects and small birds — some of these techniques fail, typically owing to limited resolution. Alternative methods have been developed; for example, those based on folding (an inherently scalable technique) have been used to create insect-sized robots, avoiding the challenges that are inherent to macro-scale nuts-and-bolts approaches[20].

BOX 1

Control autonomy

According to the definition by the International Organization for Standardization, robot autonomy is the ability to perform intended tasks based on current state and sensing, without human intervention[98]. This definition encompasses a wide range of situations, which demand different levels of autonomy depending on the type of robot and the intended use. For example, although autonomy in tethered robots does not concern energy management, mobile robots with long-range travel may require the capability to decide when to abort the current mission and locate a recharging station. In the case of the small drones discussed here, we can identify three levels of increasing autonomy (Table 1).

- Sensory-motor autonomy: translate high-level human commands (such as to reach a given altitude, perform circular trajectory, move to global positioning system (GPS) coordinates or maintain position) into combinations of platform-dependent control signals (such as pitch, roll, yaw angles or speed); follow pre-programmed trajectory using GPS waypoints.
- Reactive autonomy (requires sensory-motor autonomy): maintain current position or trajectory in the presence of external perturbations, such as wind or electro-mechanical failure; avoid obstacles; maintain a safe or predefined distance from ground; coordinate with moving objects, including other drones; take off and land.
- Cognitive autonomy (requires reactive autonomy): perform simultaneous localization and mapping; resolve conflicting information; plan (for battery recharge for example); recognize objects or persons; learn.

Table 1 | Levels of autonomy: requirements, availability and readiness for market

	Exteroceptive sensors	Computational load	Supervision required	Readiness level	Validated on drone type
Sensory-motor autonomy	None or few	Little	Yes	Deployed	All types
Reactive autonomy	Few and sparse	Medium	Little	Partly deployed	Fixed wing, rotorcraft and flapping wing
Cognitive autonomy	Several and high density	High	None	Not yet deployed	Mostly rotorcraft

Multi-modal drones

In many situations, such as search and rescue, parcel delivery in confined spaces and environmental monitoring, it may be advantageous to combine aerial and terrestrial capabilities. Perching mechanisms could allow drones to land on walls[21] and power lines[22] in order to monitor the environment from a high vantage point while saving energy. Agile drones could move on the ground by using legs in conjunction with retractable[23] or flapping wings[24]. In an effort to minimize the total cost of transport[25], which will be increased by the additional locomotion mode, these future drones may benefit from using the same actuation system for flight control and ground locomotion. The different speed and torque requirements of these two locomotion modes could be reconciled by adapting the wing morphology to the specific situation[26], similar to the way vampire bats (*Desmodus rotundus*) use their powerful front limbs when flying or walking[27]. Alternatively, multi-modal locomotion could be obtained by adding large wheels to the sides of hovering drones[28], by embedding the propulsion system in a rolling cage[29], or by completely decoupling the spherical cage from the inner rotors by means of a gimbal system[30] (Fig. 2b); the latter design allows the drone not only to roll on the ground in any direction, but, because the rotors are protected by a cage, also to safely collide with obstacles or humans without attitude perturbations. Conversely, wings could be added to ground-based robots travelling on rough terrain to extend their jumping distances, stabilize the landing phase and reduce the impact with the ground[31]. In this case as well, the total cost of transport could be reduced by sharing the same actuation system between jumping and wing-deployment mechanisms[32]. Alternatively, one could use pivoting wings, which minimize drag at take-off, improve the transition from ballistic jump to gliding and maximize the gliding ratio[33]. In the future, we may also deploy drones in semi-aquatic environments by using design principles inspired by aquatic birds, such as folding wings for plunge diving or hydrophobic surfaces for dry flight, or by flying squid, which use water-jet propulsion for take off[34].

Sensing and control

Conventional unmanned drones that fly at high altitudes regulate their attitude (roll, pitch and yaw) and their position (x, y and z) (Fig. 2d) by continuously monitoring and merging data from an inertial measurement unit (IMU), which contains three-axis accelerometers and gyroscopes, and from a global positioning system (GPS). This technology, which is necessary for sensory-motor autonomy, is now also available in small drones for recreational or professional use. However, GPS information is not sufficiently precise for altitude regulation when flying a few metres above the ground and is not always available or reliable in confined areas, such as cities, forests and buildings. Even if reliable GPS information were available, it would need to be combined with a precise map of the drone's surroundings in order to identify obstacle-free trajectories. However, digital maps, such as those used in car navigation systems, are restricted to traversable roads, do not include three-dimensional information (the height of natural structures, buildings, and bridges, and the presence of cables, poles, and so on) and are not refreshed frequently enough to capture landscape modification. Therefore, small autonomous drones flying at low altitude will need more complex levels of control autonomy and additional sensors to detect distances from the surrounding environment and perform safe and stable trajectories. Vision is a promising sensor modality for small drones because compared with other distance sensors such as sonar, infrared and laser range finders used in terrestrial vehicles, it does not require energy to interrogate the environment, and for comparable mass it can gather richer information and span wider fields of view.

Reactive autonomy

Most efforts in small autonomous drones have focused on achieving reactive autonomy (Box 1) by translating decades worth of neuroethological research on vision-based insect flight into simple control algorithms and lightweight sensors[35], with many also serving as validation of biological models. Insect vision relies on compound eyes, which are dense arrays of facets pointing in different directions and spanning large fields of view[36].
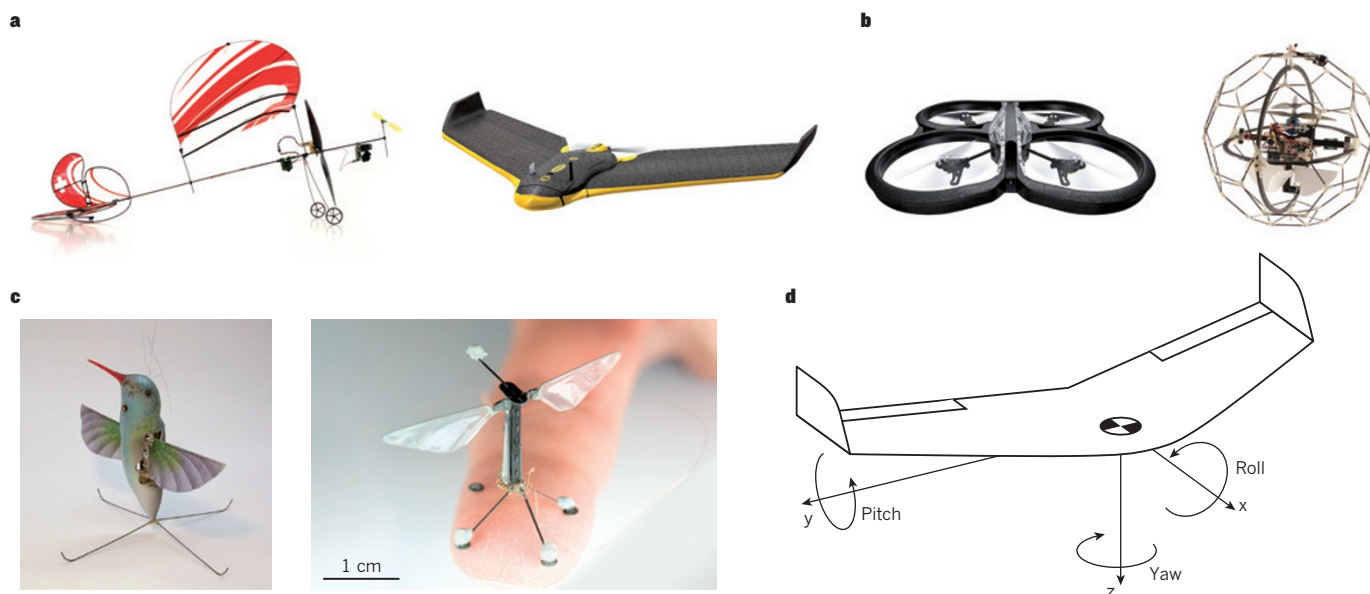
Figure 2 | Drone types with examples. a, Fixed-wing drones. A 10 g robot with rudder and flap on the tail is equipped with insect-inspired cameras to avoid obstacles and regulate altitude (left); the 690 g eBee (right) with elevons on the trailing edge of the wings, is equipped with high-resolution cameras for imaging and ventral optic flow sensor for landing. **b**, Rotorcraft. The 380 g AR.Drone 2.0 (left) is a quadcopter equipped with a high-resolution camera for imaging and a ventral optic flow sensor for maintaining position; the 380 g Gimball robot (right) is composed of a coaxial dual propeller core protected by a decoupled and freely rotating spherical cage. **c**, Flapping-wing drones. The 19 g Nano Hummingbird (left) has a camera for live video streaming; the 80 mg RoboBee (right) can fly tethered to an external power source. **d**, Coordinate system of a generic drone. The drone position is defined in the x, y and z coordinates and the attitude in the yaw, roll and pitch angles. The control algorithms to maintain position and attitude can vary according to drone type, configuration of the actuators and size.

Compound eyes have fixed focus, lower resolution and smaller binocular overlap than human eyes and therefore do not use stereo vision for distance estimation, except for very short ranges[37]. To safely fly in cluttered environments, insects instead rely on image motion, also known as optic flow[38,39], generated by their own displacement relative to the surroundings[40]. It has been experimentally shown that their neural system reacts to optic flow patterns[41,42] to produce a large variety of flight capabilities, such as obstacle avoidance[40,43], speed maintenance[44], odometry estimation[45], wall following and corridor centring[46], altitude regulation[47,48], orientation control[49] and landing[50,51]. Optic flow intensity is proportional to the distance from objects only during translational movements, but not during rotational movements when it is proportional to the rotational velocity of the agent. Furthermore, optic flow intensities also depend on the speed-to-distance ratio, which raises the issue of how insects can estimate ground speed and distance from obstacles at the same time[52].

Many vision-based insect capabilities have been replicated with small drones. For example, it has been shown that small fixed-wing drones[53] and helicopters[54] can regulate their distance from the ground using ventral optic flow while a GPS was used to maintain constant speed and an IMU was used to regulate roll angle. The addition of lateral optic flow sensors also allowed a fixed-wing drone to detect near-ground obstacles[55]. Optic flow has also been used to perform both collision-free navigation and altitude control of indoor[56] and outdoor[57] fixed-wing drones without a GPS. In these drones, the roll angle was regulated by optic flow in the horizontal direction and the pitch angle was regulated by optic flow in the vertical direction, while the ground speed was measured and maintained by wind-speed sensors. In this case, the rotational optic flow was minimized by flying along straight lines interrupted by short turns or was estimated with on-board gyroscopes and subtracted from the total optic flow, as suggested by biological models[58,59]. Other authors have even proposed bio-inspired control methods that do not require absolute speed measurement with dedicated sensors, thus eliminating a potential source of error. These methods consist of continuously adjusting flight speed and altitude to maintain constant optic flow signals, which has also been suggested by biological models[60]. For example, altitude control and landing was achieved by adding negative feedback from ventral optic flow, either to the control surfaces that regulate pitch angle[53] or to those that regulate thrust[61]. The latter method has also been shown to be effective for altitude control and landing on mobile platforms[62] and, when used in conjunction with lateral optic flow and lateral thrust, also for replicating flight trajectories of honeybees during indoor flight[62]. However, so far this method has been validated only on tethered drones. An error correction method has also been demonstrated on a quadcopter equipped with omnidirectional vision to fly in corridors by continuously making corrections aimed at reducing the difference between measured optic flow and optic flow expected from flight at the desired altitude, attitude, speed, heading and distance from walls[63]. Quadcopter and flapping-wing drones are intrinsically unstable and must compensate for positional drift generated by noise in gyroscope and accelerometer signals to hover in place and maintain attitude. It has been shown that the direction of optic flow can be used to reduce uncertainty in inertial sensor signals[64]. Wide-field optical sensors inspired by the simple eyes of insects, called ocelli[65], have been used for attitude stabilization of flapping-wing drones[66] and quadcopters[67].

The need to detect optic flow over wide fields of view at high temporal frequency in a small package has also driven the development of insect-inspired vision sensors that are smaller, lighter and faster than single-lens conventional cameras. For example, some authors[55–57] have resorted to using the multiple optic flow sensors found in computer optical mice. Whereas others[68,69] have developed neuromorphic chips that not only extract optic flow, but also adapt to the large variety of light intensities that can be experienced when flying in confined spaces. Similarly, specialized micro optic flow sensors have been used for altitude regulation in sub-1 g flying robots[70]. Miniature, curved, artificial compound eyes with a high density of photoreceptors, wide fields of view and computational properties similar to insect eyes have been recently described[71,72], but have not yet been used in drones.

Coordinated flight of multiple drones is another instance of reactive autonomy, but raises it additional challenges in sensing, communication and control[73]. Although very little is known about the sensing and control that underlies coordinated flight in insects, it has been shown that
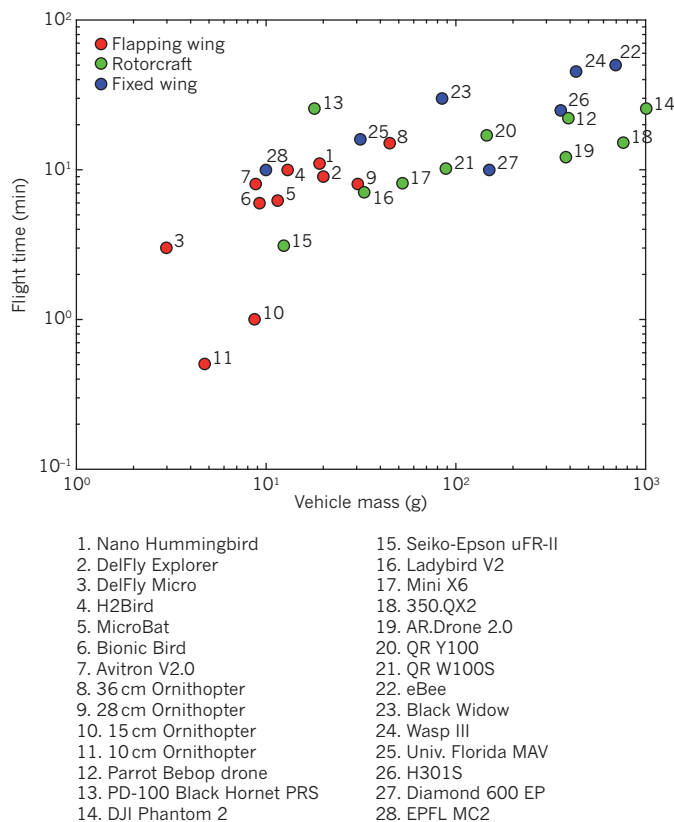
Figure 3 | Flight time against mass of small (less than 1 kg) drones.
Examples include each of the drone types shown in Fig. 2 (fixed wing, rotary and flapping wing). Regardless of the type, there is a clear trend in how flight time scales with mass. Smaller drones have significantly reduced flight times (tens of seconds compared with tens of minutes for larger drones). This is due to actuation limitations and the physics of flight at small scales, as discussed in this Review, and brings about challenges for all levels of autonomy described in Box 1.

1. Nano Hummingbird
2. DelFly Explorer
3. DelFly Micro
4. H2Bird
5. MicroBat
6. Bionic Bird
7. Avitron V2.0
8. 36 cm Ornithopter
9. 28 cm Ornithopter
10. 15 cm Ornithopter
11. 10 cm Ornithopter
12. Parrot Bebop drone
13. PD-100 Black Hornet PRS
14. DJI Phantom 2
15. Seiko-Epson μFR-II
16. Ladybird V2
17. Mini X6
18. 350.QX2
19. AR.Drone 2.0
20. QR Y100
21. QR W100S
22. eBee
23. Black Widow
24. Wasp III
25. Univ. Florida MAV
26. H301S
27. Diamond 600 EP
28. EPFL MC2

cohesion in flocks of starlings is the result of individual birds aligning their trajectories with a small number of their nearest neighbours defined in topological — not metric — space[74]. Evidence from pigeon flocks also suggests that in some conditions, such as homing, a hierarchical organization emerges whereby the trajectories of more experienced birds are tracked and copied by other birds[75]. Computational models of bird flocking build on the combination of three simple behavioural rules, namely repulsion from near individuals, movement towards far neighbours and alignment with average velocities of neighbours[76]. Remarkably, these rules can also account for hierarchical flocking without explicit signalling of experienced agents[77]. However, perceiving the position of other flying drones is still very challenging. Infrared-based bidirectional communication has been used for detecting the range and bearing of neighbouring drones in indoor environments[78], but the relatively short range of a few metres prevents its use in outdoor environments. Consequently, recent demonstrations of outdoor flocking of ten fixed-wing drones[79] and ten hovering drones[80] relied on radio communication of GPS coordinates between neighbouring drones. An alternative approach to perception of neighbours consists of exploiting the direction and intensity of the sound emitted by neighbouring drone engines[81], which may complement or replace visual cues at night or in foggy conditions.

Cognitive autonomy
A different approach is pursued to endow small drones with cognitive autonomy (Box 1). This involves leveraging decades of research in statistical methods for vision-based navigation of terrestrial vehicles, such as visual odometry[82,83] and simultaneous localization and mapping[84]. For example, monocular vision has been successfully used for simultaneous

localization and mapping of quadcopters in indoor[85] and outdoor environments[86]. However, these drones could not avoid obstacles that had not been previously detected and mapped. Stereo vision can provide depth information and has been used in a 4 g flapping-wing vehicle to reactively avoid obstacles[87] and in larger quadcopters to perform simultaneous localization and mapping[88]. Furthermore, both simultaneous localization and mapping and altitude control have been demonstrated in quadcopters with two sets of stereo cameras, one set pointing forwards and one set pointing downwards[89]. Simultaneous localization and mapping algorithms have also been combined with optic flow methods to estimate distances from the surrounding environment and stabilize the drone[90].

The statistical approach to cognitive autonomy builds on high-resolution digital cameras that can provide dense clouds of data points and on computationally expensive algorithms for reducing uncertainties. Consequently, cognitive autonomy requires heavier sensory payloads and more powerful computational units, which may explain why, so far, progress has been slower for small drones. Although various forms of reactive autonomy have been demonstrated in several types of drones with a wide range of mass and flight endurance (Fig. 3), simultaneous localization, mapping, and path planning have so far been demonstrated mostly in hovering platforms with a relatively large total mass and restricted flight endurance.

Regulatory issues
Unleashing the socio-economic potential of small drones will require not only translating the scientific and technological advances described above into reliable products, but also creating a regulatory framework that will enable public and private entities to operate in full respect of safety, privacy and security concerns. The rapid development of commercial drones and potential benefits prompted the US Federal Aviation Administration (FAA) to define, in 2013, a road map for the gradual integration in the national airspace system of civil unmanned drones that can fly beyond the operator's line of sight by 2028 (ref. 91). In a first "accommodation" stage, which has already started, the FAA allows operation of unmanned aerial vehicles for specific services by issuing airworthiness certificates on request and by defining a set of standards and procedures. In the second "integration" stage, the FAA aims to implement the standards and procedures for operation of civil unmanned aircrafts while retaining on-demand certification for cases that do not fit in the civil unmanned category, and to establish six test sites with diverse geographical and climate conditions to study safety and privacy issues. In the final "evolution" stage, the FAA aims to continuously refine and update regulations, policies and standards on the basis of evolving technological developments and experiences. The FAA has identified sense-and-avoid and communication-and-control as research priorities for full integration of unmanned drones, but for the foreseeable future it will continue to require continuous supervision by a human operator with certified training. In the European Union the legislation is more fragmented because aircraft below 150 kg are separately regulated by individual member states. Some countries, including the Czech Republic, France, Ireland, Italy, Sweden, Switzerland and the United Kingdom, have national regulations for unmanned aircraft; although these regulations differ between countries. For example, the United Kingdom allows operation of drones of less than 20 kg within the line of sight over congested areas on request to the UK Civil Aviation Authority[92]; France allows remotely operated aircraft to operate beyond the line of sight and near cities under specific conditions[93]; and Switzerland allows autonomous operation of drones within the line of sight as long as the operator can regain control[94] if, for example, the drone loses altitude or is about to collide with something. In 2013, the European Commission defined a road map[95] for the integration of remotely operated aircraft in the European aviation system using a staged approach, the aims, timeline and research priorities of which are similar to those defined in the US road map. However, the first stage of the European road map consists of extending European regulations for large unmanned aircraft systems to those below 150 kg by adapting to national regulations, which may result in more liberal regulations than those in the United States. Furthermore,

the European Commission explicitly aims to improve the public perception of drones and to promote widespread use of these technologies for public and commercial use[96].

The future of small drones

Scaling up the use of small drones from a niche market to widespread use in civilian applications depends on two related prerequisites: the capability to autonomously and safely manoeuvre in confined spaces and the removal of the legal requirement of supervised operation within the line of sight. We do not foresee major scientific or technological roadblocks to achieving higher levels of autonomous control in research and commercial drones within the next five years. However, the legal requirement of a certified human operator within the line of sight of every single drone is a roadblock that will almost certainly stay for the next five years in the United States and Europe, and removing it will depend on the reliability and safety of small drones.

Assuming that the legal roadblock will gradually be lifted, we expect that reactive forms of control autonomy (Box 1) will become widely available within the next 5–10 years for small commercial drones for long-range operation. We also anticipate that bio-inspired approaches will dominate because they require relatively simple computation and sensors. For example, some commercial drones (such as the eBee and the AR.Drone 2.0 in Fig. 2) already use ventral optic flow for outdoor landing and for indoor position stabilization. In this context, an interesting scientific challenge will be to understand how different navigation capabilities can be integrated into a coherent control system akin to the nervous system of a flying insect. In parallel, an important engineering challenge will be to define test conditions and performance standards in cooperation with governmental institutions and industrial associations to assess the capabilities and reliability of drone technologies.

We also expect rapid progress in cognitive autonomy, which will continue to be driven by the development of artificial intelligence for smartphones capable of identifying human users, learning their behaviours and creating representations of their environment (http://www.google.com/atap). On the one hand, face recognition and gesture-based interaction without wearable devices will become widely available for hobby and toy drones within the next five years; for example, by equipping small drones with human-motion-sensing devices developed by the gaming industry. On the other hand, mapping and path planning for autonomous flight in partially unknown and changing environments will represent a challenge for small drones for at least the next ten years and will continue to be illegal in the United States and Europe until at least 2028.

Despite these legal roadblocks, we expect an increasing demand for small drones in civilian use because of their intrinsic safety. Kinetic energy — one measure of the potential of a drone to cause physical harm to a human[97] — is linearly proportional to the drone's mass and is quadratic in velocity. Thus smaller drones are likely to cause proportionally less harm as the size is reduced, but more subtly, small drones typically operate at lower speeds, dramatically decreasing the potential for harm. For example, a 500 g drone flying at $5\,m\,s^{-1}$ has 6.5 J of kinetic energy, which is equivalent to the potential energy of a large apple dropped from about 2 m. As the mobile computing industry continues along the path of miniaturization, drone developers will continue to reap the benefits in the form of smaller, lower power sensor packages (for example, the IMUs used in cell phones and video game controllers) and the slow, but steady increase in battery energy density. Another hardware advance that will inevitably affect future drones is the movement away from general-purpose computation in favour of more specialized high-performance and low-power hardware accelerators tuned for the various functions needed by autonomous drones (both reactive and cognitive autonomy). These accelerators are already present in various mobile devices and are suggested to be a solution to computation for the control of insect-scale drones[19]. ∎

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