The Economist TQ

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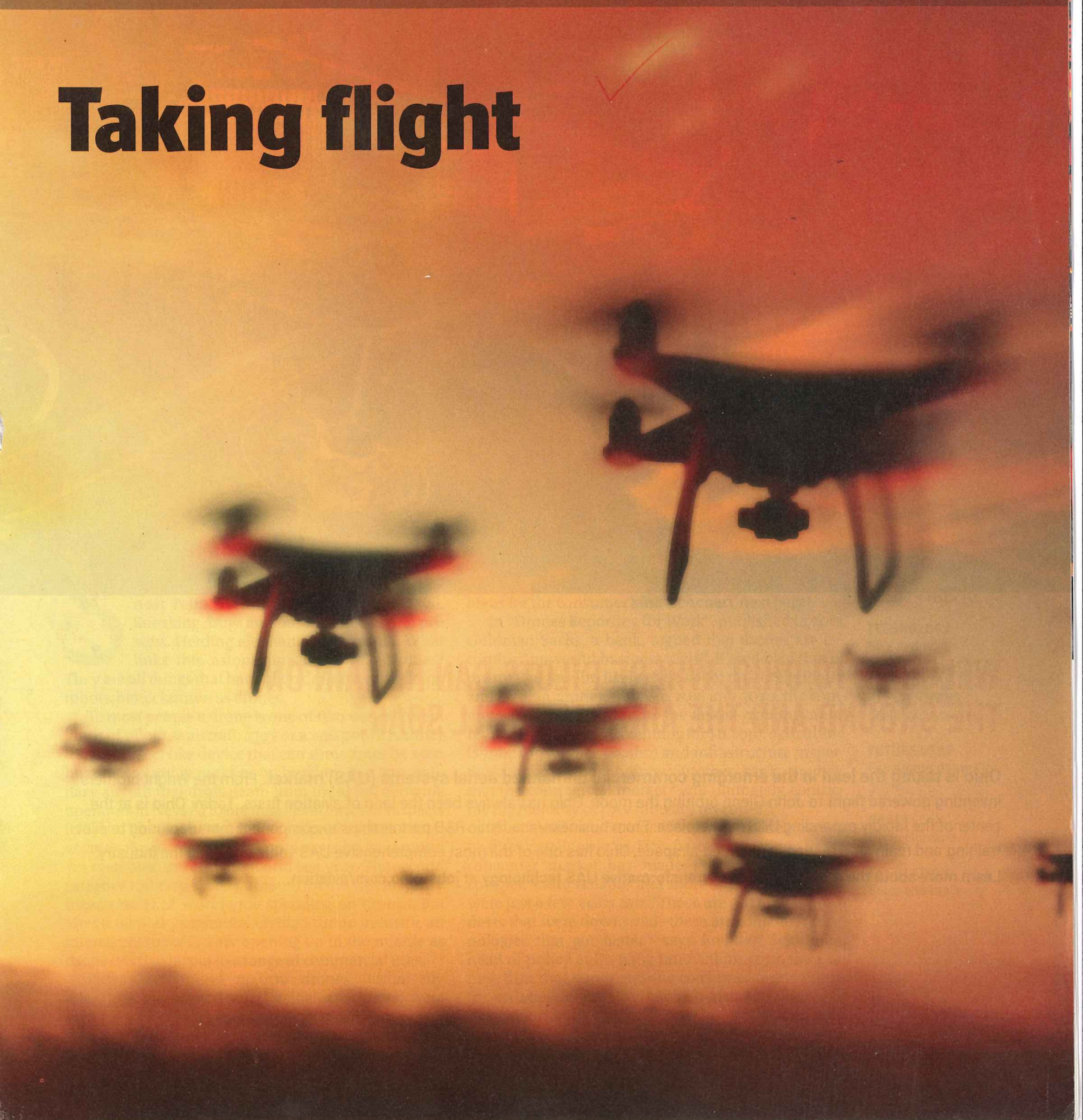
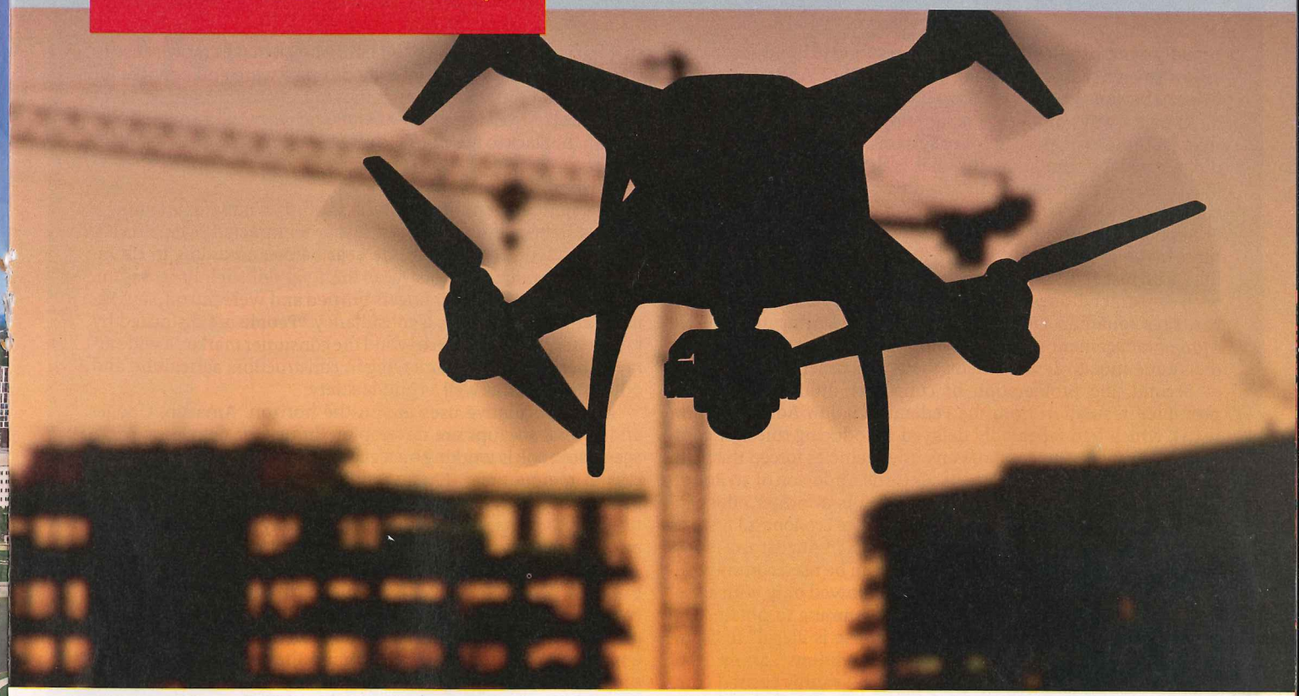
CIVILIAN DRONES

Taking flight





Taking flight

Most drones today are either cheap toys or expensive weapons. But interesting commercial uses are starting to emerge in the middle, says Tom Standage

STARTING a riot at a football match. Revealing an unknown monument in the desert near Petra. Performing at the Super Bowl. Sneaking drugs and mobile phones into prisons. Herding elephants in Tanzania. What links this astonishing range of activities? They are all things that have been done by small flying robots, better known as drones.

To most people a drone is one of two very different kinds of pilotless aircraft: a toy or a weapon. It is either a small, insect-like device that can sometimes be seen buzzing around in parks or on beaches, or a large military aircraft that deals death from the skies, allowing operators in Nevada to fire missiles at terrorist suspects in Syria. The first category, recreational drones aimed at consumers, are the more numerous by far; around 2m were sold around the world last year. The second category, military drones, account for the vast majority (nearly 90%) of worldwide spending on drones. But after a pivotal year for the civilian drone industry, an interesting space is now opening up in the middle as drones start to be put to a range of commercial uses.

Last year around 110,000 drones (technically known as unmanned aerial vehicles, or UAVs) were sold for commercial use, according to Gartner, a consultancy. That figure is expected to rise to 174,000 this year and the number of consumer drones to 2.8m. Although unit sales of commercial drones are much smaller, total revenues from them are nearly twice as big as for the consumer kind (see chart, next page).

In "Drones Reporting for Work", published in 2016, Goldman Sachs, a bank, argued that drones are becoming "powerful business tools". It predicted that of the total of $100bn likely to be spent on both military and civilian drones between 2016 and 2020, the commercial segment would be the fastest-growing, notably in construction (accounting for $11.2bn), agriculture ($5.9bn), insurance ($1.4bn) and infrastructure inspection ($1.1bn). Oppenheimer, another bank, predicts that the commercial market "will ultimately contribute the majority of UAV industry revenues".

The rise of commercial drones was made possible by three developments. First, fierce competition in the consumer market has made the machines much cheaper, more reliable and more capable than they were just a few years ago. "These are not military products that were downsized—these are consumer technologies that got better," says Brendan Schulman, head of policy at Da-Jiang Innovations (DJI), the Chinese firm that dominates the consumer-drone industry. DJI's bestselling Mavic, which costs $999, can hold its position in light winds, detect obstacles and land automatically. At a company office in Shenzhen, Shuo Yang, one of the engineers who worked on the Mavic,

ALSO IN THIS TQ

proudly demonstrates that it can even respond to hand gestures to follow its owner around or snap a "drone selfie". And it folds up to fit into a backpack.

In many ways modern consumer drones are more advanced than far more expensive military systems, says Adam Bry of Skydio, a consumer-drone startup that is developing a rival to the Mavic. The best consumer models are now being redeployed for commercial use, often with little or no modification. As previously happened with smartphones, the fastest innovation is taking place in the consumer market and then being adopted by companies. And just as with smartphones, people who enjoyed playing with consumer drones realised it made sense to take them to work too, says Jonathan Downey of Airware, a startup that makes drone-management software. Even military users are beginning to pay attention to developments in the consumer market.

Second, the proliferation of consumer drones in America prompted regulation from the Federal Aviation Administration (FAA), which had repeatedly delayed introducing rules for commercial drones. "The flood of consumer vehicles forced the regulators to allow commercial use," says Chris Anderson of 3D Robotics, another drone startup. (Mr Anderson is a former editor-in-chief of *Wired*, and previously worked at *The Economist*.) A set of rules known as "part 107", issued by the FAA in August 2016, specifies the conditions under which drones can be used commercially; previously commercial use had been allowed only with a special waiver that was costly and time-consuming to obtain. The default thus switched from "commercial use is illegal" to "commercial use is legal under the following conditions". Many other countries follow the FAA's regulatory lead, so this cleared commercial drones for take-off not just in America but worldwide. Still, "the technology is moving so fast that the regulatory and legal frameworks are having a hard time keeping up," says Astro Teller of X, Google's semi-secret research laboratory.

Third, the industry underwent a shake-out as a crowd of jostling startups came to be dominated by DJI. Based in Shenzhen, where the world's technology firms go to develop and manufacture hardware, DJI outperformed both local and foreign rivals and now has about 70% of the consumer-drone market. It is valued at around $8bn and has established itself as a global, premium brand with a reputation for quality and reliability, defying the stereotype of Chinese firms. Its consumer drones generally cost $999 to start with and are subsequently discounted as new models appear. DJI also makes slightly heftier models specifically for commercial use; a fully equipped Inspire 2 costs around $6,000.

Several rival dronemakers, including Autel, GoPro, Parrot and Yuneec, have announced lay-offs in recent months. Lily, a consumer-drone startup that attracted thousands of pre-orders, shut down in January. 3D Robotics laid off 150 workers and stopped making hardware altogether last year after its Solo drone failed to dent DJI's market share. Many drone startups concluded that instead of competing with DJI on hardware, it makes more sense to complement its products by providing software and services for commercial users. "Everyone is moving to a model where we let DJI control most of the on-board stuff and we move all our innovation up the stack to the cloud," says Mr Anderson.

Pause for reflection

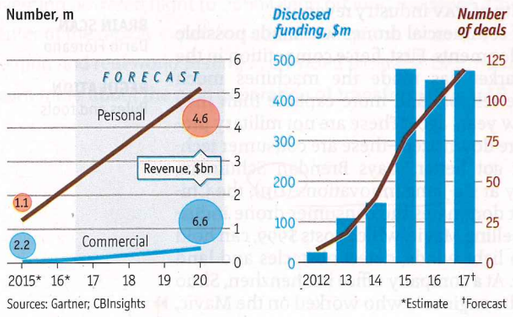
Having jumped, funding for drone startups is now maintaining a roughly stable altitude. In 2015 drone firms attracted $479m in venture capital, up from $149m the year before, according to CB Insights, a research firm; last year the total fell slightly to $452m. Some investors had their fingers burned and were put off, says Peter Harrop of IDTechEx, a consultancy. "People are distracted by toy drones," he notes. But beyond the consumer market, a wide array of potential uses is emerging in construction, agriculture and other industries, as well as public safety.

More speculative uses are on the horizon. Amazon, Google and several startups are developing drones for delivering packages. Facebook is working on a giant drone to provide internet access in remote areas. Energy utilities are looking at generating power using high-altitude tethered drones that act as flying wind turbines. Tiny insect-like drones may one day pollinate plants; big ones might carry not just cargo but people in self-flying sky taxis.

This report will focus on the fastest-growing part of the drone business, namely the commercial market in between small, cheap consumer drones on the one hand and large, expensive military ones on the other. It will consider the evolving technology and the emerging opportunities, and examine the new challenges that drones pose for regulators. Having come from nowhere in just a few years, civilian drones are now taking flight. ■

Pointing skywards

Civilian drones, worldwide



Sources: Gartner; CBInsights

*Estimate †Forecast

Technology

Give and take

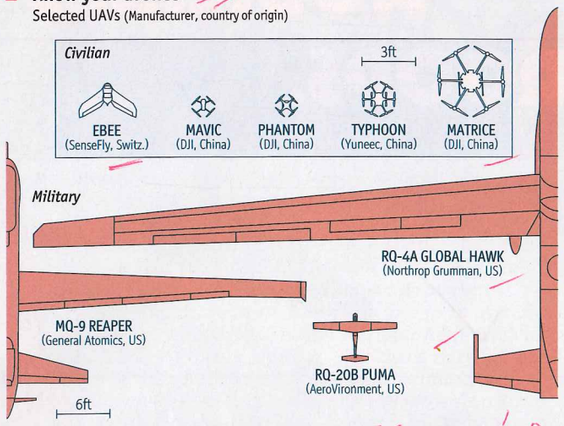
Originally a military technology, drones are now benefiting from rapid advances in consumer electronics

THE first drones were military. The use of pilotless flying machines as weapons dates back to the siege of Venice in 1849, when Austrian forces launched balloons laden with explosives against the city. But the origin of military drones is usually dated to the development of uncrewed, remote-controlled aircraft for use as targets by anti-aircraft gunners after the first world war. The first truly successful example was the de Havilland DH82B Queen Bee, which entered service in Britain in 1935 and seems to have been the inspiration for calling such aircraft "drones" (after stingless male bees); Germany's V-1 flying bomb was another early drone.

In recent years drones have become a vital component of air power. America's armed forces have a fleet of more than 11,000 drones, compared with just a handful in 2001. Peter Singer of the New America Foundation, a think-tank, says around 80 countries now have military drones, including about 20 with armed ones, either already in use or in development. But the vast majority are unarmed surveillance aircraft of various shapes and sizes.

At one end of the spectrum are small, hand-launched fixed-wing surveillance drones such as the Raven, Wasp and Puma, all made by AeroVironment, which fly either autonomously or under short-range remote control. The Raven, used by many countries' armed forces, is the world's most widely used military UAV, with around 20,000 units deployed; it can fly for up to 90 minutes. ▸▸

Know your drones
Selected UAVs (Manufacturer, country of origin)



Sources: DJI; SenseFly; Yuneec; *The Economist*

Larger drones like the Predator and Reaper can typically stay aloft for 12-20 hours and carry weapons. Biggest of all are long-endurance, high-altitude reconnaissance drones such as the Northrop Grumman Global Hawk, which can loiter over an area for 32 hours, longer than any human pilot.

Perhaps surprisingly, the recent rise of consumer drones owes little to military systems. Instead, it springs from two completely different technologies: hobbyists' radio-controlled (RC) aircraft on the one hand and smartphones on the other. Many people working in the drone industry started out flying small RC aircraft powered by tiny petrol engines, which were "annoying, messy and super-finicky", says Adam Bry of Skydio. The combination of brushless electric motors and lithium-polymer batteries, used in laptops and smartphones, allowed RC aircraft to be electrically powered, making them lighter, quieter and more reliable.

Cheap microcontroller chips, which allow a small computer to be squeezed into a box the size of a cigarette packet, led to the development of open-source autopilot software for fixed-wing hobbyist aircraft. Microcontrollers also provided the on-board brains for a new design of drone, with four or more helicopter-style rotors. By 2005 several research groups had figured out how a drone with four vertical-axis rotors could control its position and movement by adjusting the speeds of different rotors—much easier than controlling a traditional helicopter. "That enabled a completely new way for drones to fly around, hover and so on," says Dario Floreano, a roboticist at the Swiss Federal Institute of Technology in Lausanne.

But for all this to work, a quadcopter needed to know its orientation and direction of movement. Serendipitously, the price of accelerometers based on micro-electromechanical systems, used as tilt sensors in smartphones, had come down rapidly. Drones also borrowed small, cheap camera sensors and fast Wi-Fi chips from smartphones. Moreover, handsets loaded with suitable apps could be used as drone-control units, taking advantage of the phone's screen, radio and processing power. "Drones have really been riding the smartphone revolution," says Dr Floreano.

The stability of multirotor flight meant that small electrically powered aircraft could suddenly be used in all kinds of new ways, beyond what was possible with small fixed-wing aircraft. Researchers were soon getting small multirotor drones to form amazing feats of agility. In a popular online video from 2013, Raffaello D'Andrea, a roboticist at the Swiss Federal Institute of Technology in Zurich, demonstrates quadcopters balancing broomhandles, carrying a glass of water without spilling a drop and returning ping-pong balls by hitting them in mid-air. Eight of Dr D'Andrea's drones, resembling flying lampshades, even perform in "Paramour", a Broadway show by Cirque du Soleil.

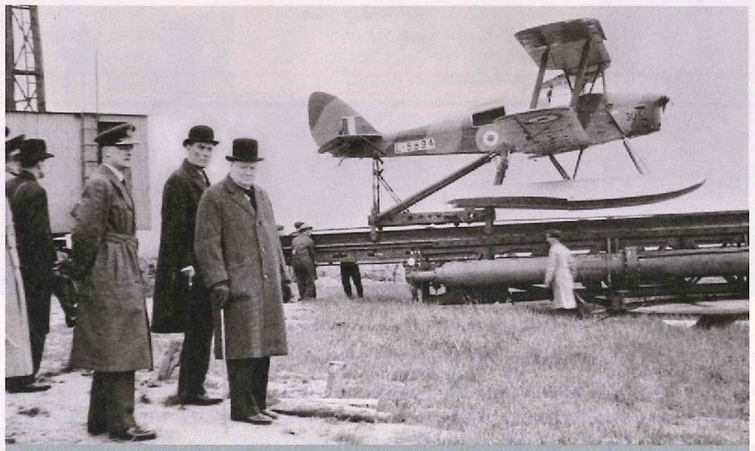
And for my next tricks…

Military drones are built to survive in demanding conditions, have special requirements (such as stealth capabilities or long endurance) and tend to be expensive. So although makers of military drones are keen to adapt some of their products for civilian use, commercial drones are more likely to be based on scaled-up consumer drones than on scaled-down military ones. Gartner estimates that military suppliers will capture just 10% of the commercial-drone market by 2020. The drones being put to commercial use now "are pretty much all consumer", says Mr Bry.

For their part, military types are paying increasing attention to consumer-drone technology, particularly for indoor use in urban combat. "We're interested in having something that can operate in a building, in a confined space," says a NATO spokesman. And as their adversaries adopt low-cost drones (Islamic State has used off-the-shelf consumer drones in Iraq for surveillance and to drop explosives), Western armed forces are trying to work out how to stop them reliably and inexpensively. A member of Britain's special forces says that a shotgun is currently the simplest method.

Military and consumer drones alike are being transformed by rapid progress in two cutting-edge areas of drone research: autonomy and swarming. If you automate away the need for a skilled operator, drones suddenly become much more useful. Military ones that do not require the oversight of a human operator can be radio silent and stealthier. Consumer ones can follow runners, skiers or cyclists and film them from above. Commercial ones can fly a specific, pre-planned path over a field, building site or quarry, avoiding obstacles as they gather data. Improved flight-control algorithms, more on-board processing power and progress in machine vision will allow drones to handle more decisions themselves, rather than relying on fallible or inexpert humans. Most existing drones simply move the pilot from the vehicle to the ground. The next generation of drones will not need pilots at all–just orders.

Greater autonomy also opens the way to swarms of drones



Churchill with the Queen Bee, the mother of all drones

that act as a single unit. In a test carried out in October 2016 over California, 104 tiny fixed-wing Perdix drones, with a wingspan of 30cm, were launched from three American fighters and performed a series of manoeuvres. This is the shape of things to come, says Mr Singer. A swarm of small military drones might be released into a theatre of operations, spread out to look for targets and then collectively assign tasks to different drones within the swarm. When one target has been destroyed, the swarm can move on to another. Away from the battlefield, too, some tasks, such as search-and-rescue missions or mapping, might best be done by drone swarms. They are already used in entertainment: 300 Shooting Star drones, made by Intel, perform a regular light show at Disney World in Florida.

Getting swarms to collaborate, avoid collisions and cope with the odd failure is no mean feat. But as the technology advances, says Mr Singer, the prospect of autonomous military swarms is running into both ethical objections—there is no human "in the loop" to make life-or-death decisions—and cultural resistance from military types who want to retain a role for human pilots and traditional aircraft. (Tanks faced similar objections in the first world war, when they were initially seen merely as an adjunct to infantry.) Such constraints do not apply in the business world, however, where companies see ever more potential in drones as they become smarter, more numerous and more capable. ■

Commercial applications

Seeing is believing

Today's drones are mostly flying cameras. They are already being put to a wide range of business uses

PHOENIX DRONE SERVICES, operating from a business park on the outskirts of Phoenix, Arizona, is typical of the small firms that have sprung up in recent years to pursue the commercial opportunities around drones. Its founders, Mark Yori and Brian Deatherage, started off by building radio-controlled planes. To stream live video, they modified a baby monitor and attached its camera to a fixed-wing drone. These were the days of "crash, smash, rebuild and try again", Mr Deatherage recalls. Then in 2011 they used a drone-mounted smartphone to take some pictures, for which they were paid $200. "That's a business," Mr Yori concluded, and their company was born, one of the first permitted to operate drones commercially under a "section 333 exemption" granted by the Federal Aviation Administration.

In the company's offices, fixed-wing and multirotor drones of various shapes and sizes hang on the walls like hunting trophies. A technician surrounded by tools and components tends to a half-built drone in a workshop area; a black DJI hexacopter sits on a table, poised like some giant insect. For years Mr Deatherage and Mr Yori built their own drones, and still use custom-built aircraft for some types of work. "In the beginning you had to be able to build and repair your own aircraft," says Mr Deatherage, who has a computing degree and taught himself how to use the various tools to process the data from his drones.

Mr Yori likens the fast-moving drone business to surfing: "You always have to be ready to catch the next wave," he says. There have already been several waves of enthusiasm for drones, as various industries have woken up to their potential and small firms have rushed to meet their needs. The introduction of the "part 107" rules in America last year has removed the previously formidable barrier to entry for commercial-drone operators. The industry is now looking for the most promising applications and trying to gauge how the market will evolve.

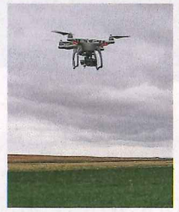
The first commercial use of drones (and still their main use for consumers) was to act as flying cameras. Over the past 150 years cameras have changed shape from bulky wood-and-brass contraptions to handheld devices and then smartphones. In many ways drones are the logical next step in their evolution. It is telling that GoPro, a company known for its indestructible action cameras, recently launched its first drone; and that DJI, the dominant maker of consumer drones, has acquired a majority stake in Hasselblad, an iconic Swedish camera firm. Using drones for photography is much cheaper than using manned helicopters. Aerial shots have proliferated on television in recent years, and are also popular with property agents and for dramatic wedding videos.

Eye in the sky

Paul Xu of DJI lists photography as one of five areas of opportunity for commercial drones, along with agriculture, construction, inspection, and public safety and other civil-government uses. Once you have a flying camera, there are lots of things you can do with it. Agriculture, and measuring the health of crops in particular, was identified early on as a promising market for commercial drones. Crop health can be assessed by taking pictures using special multispectral cameras which "see" more than the human eye. By measuring the relative intensity of colour in particular frequency bands, they can identify undernourished or diseased crops. This can be done by satellite, or by sending people into fields with clipboards, but drones can do it more cheaply. A GPS-equipped tractor can then precisely spray water, fertiliser or pesticides only where needed, increasing yields and reducing chemical run-off.

In a report published in 2013 the Association for Unmanned Vehicle Systems International (AUVSI), an industry body, identified precision agriculture as by far the most promising market for commercial drones. But enthusiasm for drones in agriculture has cooled lately. In part, that is because at the time of the AUVSI report most civilian drones were of the fixed-wing variety, ideally suited to flying over large areas; the rapid progress made since then by multirotor drones, which have a shorter range but can hover, opened up other markets that are now seen as more promising.

Encouraging farmers to adopt drones also proved harder than expected, notes Chris Anderson of 3D Robotics. The agricultural use of drones sounds good in theory—feed the world, save the planet—but is difficult in practice. The market is very fragmented and conservative, with many subsidies and distortions, and some of the social goods that flow from using drones, such as reducing run-off of chemicals, do not benefit farmers directly. The agricultural market "is littered with struggling technology companies that have tried to break in", says Jonathan Downey of Airware.



Various industries have woken up to the potential of drones

Mr Anderson believes that the most immediate opportunity lies in construction and related industries. Most big construction projects go way over budget and end in a lawsuit, he says. Mistakes made early on in a project may not be noticed until much later, and cost time and money to rectify. . Buildings are designed in a flawless digital environment but must be constructed in the much messier real world. "It's all an information problem," says Mr Anderson. So the industry has been pursuing the idea of "reality capture", using technology to measure buildings precisely during construction and track the use of raw materials on site to ensure that everything ▸▸

is going according to plan. Drones are ideally suited to the task. Thousands of aerial photographs are crunched into a 3D site model, accurate to within a few centimetres, called a "point cloud", which can be compared with the digital model of the building. And safety worries that hamper the use of drones in other fields are kept to a minimum because construction sites are closed areas, workers wear hard hats, and drones fly within line of sight.

Andrew Kahler of John Deere, a maker of agricultural and construction machinery, explains how drones can also streamline the process of grading—preparing the ground for constructing a building, road or railway. This involves measuring the original topography, which by conventional methods might take several weeks for a large site; using bulldozers and other equipment to move large quantities of earth; then "fine grading" the site to within an inch or two of the desired final shape. The great benefit of drones, says Mr Kahler, is that they can carry out a topographic survey in half an hour, and the 3D model is ready the next day. That makes it possible to resurvey the site frequently and make any necessary changes. Mr Kahler's company recently struck a partnership with Kespry, a startup, to provide drones and related software and services.

Up in the air, down on the farm

Keep away from the cliff edge

Drones are also useful farther up the construction supply chain, in mining and aggregates, says George Mathew, Kespry's boss. Working out how much material is sitting in a stockpile in a mine or quarry usually involves taking a few dozen measurements with manual surveying equipment and then calculating the volume. A drone can measure the volume of dozens of stockpiles in a single flight, taking thousands of measurements that are turned into an accurate point cloud within an hour. As well as being far quicker and more accurate, it is also much safer. Falling off stockpiles is one of the industry's biggest occupational hazards. Using drones to survey quarries and building sites also means human surveyors do not need to venture close to dangerous sheer drops.

Such is the interest in drones, says Mr Kahler, that he is asked about them at every site he visits. Customers are "ready and willing to jump into this technology", he says. Sarah Hodges of Autodesk, which makes software used to design and model buildings, notes that drones are making it possible to digitise the construction industry, which has been relatively slow to adopt new technology. With a complex building like a hospital, being able to check that plumbing, heating and electrical systems are being installed correctly "is really transforming—it's eliminating a lot of errors". In China, she says, drones are being flown over building sites at night (which current American rules forbid) to measure progress made during the previous day and ensure that everything is going precisely to plan. Autodesk and others are also starting to use virtual reality and augmented reality to overlay digital models with real-world views.

Drones are attracting interest in a related field, too: the inspection of buildings and other infrastructure, such as pipelines, wind turbines, electrical pylons, solar farms and offshore platforms. At the moment, inspecting a roof for storm damage or checking the state of an electrical pylon involves sending someone up a ladder, which can be dangerous. "We are working with a lot of power companies," says Mr Xu of DJI. His company has developed the Matrice 200, a drone specially equipped for use in harsh environments by adding features like backup batteries and GPS systems, magnetic shielding and weatherproofing.

But for utilities and other large companies to make the most of drones, they need to be able to integrate them smoothly with their existing computer systems and workflows. A single drone flight can generate as much as 100 gigabytes of data, says Anil Nanduri of Intel. Airware, which is working with large insurance companies in Europe and America, has developed a system that handles the whole process. The insurance company specifies what data it wants, and in what format, and Airware's software generates a suitable flight plan. This is sent to an operator who uploads it into the drone, which gathers the required data completely autonomously. The results are then sent back, converted into the form needed by the claims assessor and a summary is delivered into the insurance company's systems. What makes the insurance industry particularly attractive, says Mr Downey of Airware, is that it is highly concentrated: "By working with the top ten players you can target a pretty big proportion of the market."

Inspection by drone will get even better with further automation, says Mr Xu. Some dream of "drone in a box" systems, where drones sit charging in weatherproof boxes in remote areas, popping out when needed to gather data entirely autonomously. The use of machine-learning systems to identify anomalies could automate the process even further. Kespry, which is also targeting the inspection and insurance market, has built a machine-learning system that can count hail strikes on a roof. "It's mind-blowing for people in property and casualty insurance," says Mr Mathew.

After a flood or an earthquake, drones are already used in search-and-rescue operations to sweep large areas for people who need help. By enabling relief workers to see the bigger picture, they allow relief efforts to be co-ordinated more effectively. After flash floods in Chennai, India, in December 2015, for example, the police used drones to locate and rescue around 200 people. A trial carried out in 2016 by Donegal Mountain Rescue in Ireland found that a drone could sweep an area for a missing person more than five times faster than a ground-based team of rescuers. In February four skiers in British Columbia, who got lost and ended up in the dark, were spotted and rescued with the help of an infra-red camera mounted on a DJI Matrice drone.

For police use, drones are a cheaper and quieter alternative to helicopters for monitoring crowds and can be used to create detailed 3D models to help investigators of traffic accidents. Journalists and environmental groups are also experimenting with drone-based photography. Fixed-wing drones monitor animal populations and detect and deter poachers in Kenya, Namibia, South Africa, Tanzania, Zambia and Zimbabwe; multirotor drones ▸▸

keep an eye out for sharks off Australian beaches.

As drones expand into all these areas, what shape will the industry take? Some drone startups took a "vertical" approach, focusing on specific industries and creating integrated drone hardware, software and services for particular applications, as Kespry does in mining. Others, like Airware, bet that hardware from different makers would become standardised around a single drone operating system that would run on a wide range of designs from different vendors, just as Google's Android operating system powers most of the world's smartphones. Some companies focused on making specific components, such as sensors, complete drone airframes, or software tools to analyse data from drones.

For the moment the commercial drone industry does not look remotely like the smartphone industry; instead, it is a mirror image of it. DJI so dominates the hardware side that its on-board software has emerged as the industry's main platform. The leading software platform for drones thus belongs to a single company and is tied to its own hardware; it is what the smartphone industry would look like if Apple's market share were 80% rather than 20%. An equivalent of Android for drones does exist—a free, open-source platform called Dronecode, used by 3D Robotics, Yuneec, Intel, Parrot and others—but DJI's platform is more widely used.

Once it became apparent that DJI's hardware and software was emerging as the standard, many drone companies switched their focus to building enterprise-grade software and services for specific industries—an area that DJI seems happy to leave to others, given that some companies might prefer not to hand over their data to a Chinese company. For software providers the vertical model is winning, as startups target clients in particular industries.

Start here

But how, in practice, will companies adopt drones? Initially, they may choose to pay drone-services companies to work for them on a job-by-job basis. Matchmaking services like Measure, DroneBase, Fairfleet and Airstoc have already sprung up to connect companies that want to get a particular task done by drones with small firms and individuals who can do it for them. DJI has a stake in DroneBase, and some makers of drone software, including Airware and DroneDeploy, operate similar services. But this may just be an interim solution. "Companies usually want to start by hiring a service provider," says Mr Downey, "and then they see how easy it is, and realise they can do it themselves."

Drone companies, for their part, have been forming partnerships with incumbent suppliers, notably in the construction industry, which already have access to a large customer base. Hence partnerships have been formed (many of them underpinned by an equity stake) between Kespry and John Deere, 3D Robotics and Autodesk, Airware and Caterpillar, and Skycatch and Komatsu.

Mr Xu of DJI reckons that more needs to be done to promote growth in the industry over the next five to ten years, so his company is fostering insurance, repair and financing services for drones that corporate customers are likely to want. With full automation some years away, it is also encouraging the training of drone operators. "We are transforming this from a hobby to a profession," says Mr Xu. So far DJI's training schemes, launched in June 2016 and outsourced to third parties, are available only in China. Each month 500-600 people are certified for particular kinds of drone operation, such as photography, pesticide spraying or infrastructure inspection. The company is also trying to assist startups that act as "UAV systems integrators", helping companies in particular industries integrate drones into their business.

Thus many overlapping models and initiatives are competing to shape the future of the drone business. Mr Downey thinks that consolidation over the next five years will leave a couple of dominant providers in each industry. But in essence, all the commercial applications being pursued today use drones to gather data. As the machines become more capable, they will start moving things around, which will give rise to a vast range of new uses. ■

Future uses

Can drones deliver the goods?

The wait for cargo-carrying drones may be longer than expected

THERE is a striking disparity between the commercial applications drone companies are pursuing in fields like construction, inspection or agriculture and the public perception of commercial drones. Media coverage is dominated by one particular application: delivery. Experimental deliveries of parcels, pizzas and other items conjure up visions of skies abuzz with drones ferrying packages to and fro. But although delivery and logistics companies are interested in drones, many drone companies are not interested in deliveries. "It's not on our immediate radar," says Paul Xu of DJI.

Astro Teller, the boss of X, Google's semi-secret research laboratory, is one of the lucky few to have received a delivery by drone. It was dispatched last September as part of a test carried out in Virginia by Project Wing, Google's drone-delivery programme. Its machines come in a variety of shapes: some are "tail-sitters", flying wings capable of flipping upright and hovering; others are fixed-wing drones augmented by vertical-axis rotors like those on a quadcopter. Both designs combine the benefits of a fixed-wing aircraft for efficient long-distance flight with those of a multirotor for hovering and vertical take-off and landing. When delivering a package the drones do not actually land but float above the recipient and use a winch to lower their cargo: in Dr Teller's case, a freshly prepared burrito.

Receiving something by drone is "kind of magical", he says, launching into an impassioned case for drone delivery. Imagine you had a magic elf that could bring you anything you asked for within a minute or two, provided it could fit in a breadbin. You would no longer worry about what to take with you when going out. Nor would you keep common items, like batteries or perishable foodstuffs, on hand at home just in case you needed them. You might not need to own some rarely used objects at all if you could summon them when needed. Rapid drone delivery could thus accelerate the trend from ownership to access in the "sharing economy", says Dr Teller. He claims delivery drones could be faster, quieter and more environmentally friendly than large delivery trucks. Project Wing now carries out experimental flights daily.

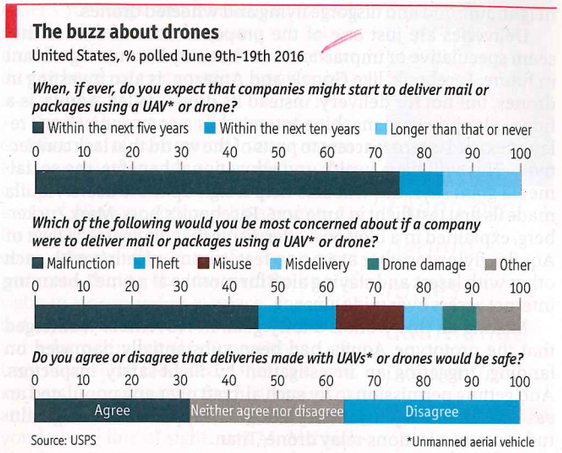
Lunch has arrived

The technology giant most closely associated with delivery drones is Amazon. When its boss, Jeff Bezos, revealed his plans for drones in December 2013 on "60 Minutes", an American television programme, they were widely assumed to be a publicity stunt. But Amazon is quite serious: it carried out its first trial delivery to a customer near Cambridge, England, last December—"13 minutes from click to delivery," says Gur Kimchi, the head of Amazon's drone effort. In March 2017 it conducted its first delivery demonstration in America, at a conference in Palm Springs. Like Google, Amazon is evaluating a range of different designs, all of which involve the drone lowering its package onto a target in the recipient's garden or backyard. Logistics firms such as DHL and UPS, as well as some startups, are also looking at drone delivery.

But if widespread drone delivery is to become a reality, many technical and regulatory hurdles must be overcome. These include ensuring that drones do not fall and cause injury, and can land safely if something goes wrong; and preventing collisions with power lines, trees and other aircraft. Moreover, small drones have limited cargo-carrying capacity; not everyone has a garden or backyard; and deliveries require beyond-line-of-sight, autonomous operation, which requires special permission. So at least for now, many drone firms are steering clear. "It's very challenging, and we do not want to promise something we can't deliver," says Mr Xu. "Delivery just bundles together all the hard problems," says Mr Bry, who worked on Project Wing before leaving to found Skydio. He thinks it could take a decade to solve these problems.

One application where drone delivery may make more sense, and is already in use, is ferrying medical supplies to remote areas that are hard to reach by road. Zipline, an American start-up staffed by veterans of Google, SpaceX, Boeing and NASA, began delivering medical supplies in rural Rwanda using fixed-wing drones in October 2016. It has an agreement with the government to deliver blood products to 21 transfusion clinics from two bases, the first of which is already serving five clinics. Zipline's drones can fly 150km on a single charge and work in rain and winds of up to 30km an hour. They are launched using a catapult, fly below 150 metres (500 feet) and drop cargo packages weighing 1.5kg by parachute.

Rolling out the service means mapping the best routes for the aircraft, which fly autonomously, co-ordinating with military and civilian authorities, training clinic staff to receive cargo and reassuring the local communities along the route. Whether all this is economically viable, or just a publicity stunt by Rwanda's tech-loving government, is unclear. But the company is talking to governments in other countries about operating similar services, focusing on medical deliveries outside urban areas. It hopes to change public perceptions of the word "drone". Zipline's Justin Hamilton says one of the firm's engineers once told him that he used to work on drones that drop bombs, "and now he builds drones that drop blood."



Other startups say that drone delivery in urban areas is already possible—but using drones moving on the ground rather than in the air. Starship Technologies, based in Estonia, and Dispatch, based in California, have both developed wheeled, coolbox-sized drones that trundle along pavements to make local deliveries. Starship's drones are being tested in several cities around the world, and Dispatch is about to begin tests in the San Francisco Bay Area. Both firms use a "partial autonomy" model, meaning that their drones can be remotely piloted for some or all of a route. As the drone approaches its destination, the recipient receives a smartphone alert, and when it arrives he uses his phone to pop open a lockable compartment to retrieve the cargo.

What if people steal the drone? Anyone who tries, says Stav Braun of Dispatch, has "just stolen a homing beacon". A bigger concern, she says, is ensuring that the robot is courteous and people feel safe around it. But so far the response has been positive.

Instant gratification

Clement Jambou of Unsupervised.ai, a French delivery-drone startup, thinks the steps and kerbs of urban environments will be too difficult for wheeled robots to navigate, so his firm's delivery drone has legs instead and resembles a dog. He may disagree with Dr Teller on the best way to set about it, but Mr Jambou has a very similar vision for fast, cheap drone delivery. For example, he imagines people renting rather than buying clothes, tools and other household items, dispatched by drone from a neighbourhood depot when needed.

Dr Teller, for his part, is confident that the technical and safety obstacles to flying delivery drones can be overcome. But it will be a gradual process involving "lots of data and demonstration" to satisfy regulators. "The magical elf won't change the world unless it can go beyond visual line-of-sight, fly over people and have a small number of operators responsible for a large number of vehicles," he says, none of which is allowed under current regulations. Google is working on making its drones resilient to the failure of a single rotor, battery or motor, the loss of GPS coverage and other potential problems. "We are building up evidence that we can do this safely," he says. That will take a while, but Google expects its "moonshots" to take up to a decade to pay off. Work on Project Wing began in 2012.

The disagreement over the viability of delivery drones, then, is mostly a matter of timing. For companies that wish to put drones to work now, delivery is not a good bet. But for logistics companies it makes sense to start exploring the possibilities. The end result may well be a hybrid system of delivery trucks that arrive in a

neighbourhood and disgorge flying and wheeled drones.

Deliveries are just one of the proposed uses of drones that seem speculative or impractical now but may become significant in future. Facebook, like Google and Amazon, is also investing in drones, but not for delivery: instead its drone, called Aquila, is a huge solar-powered machine intended as a communications relay, to extend internet access to parts of the world that lack connectivity. This will have health and educational benefits, the social-media giant says, but will also help it sign up more users. Aquila made its first test flight in June 2016. Facebook's boss, Mark Zuckerberg, explained in a blog post afterwards that his goal is "a fleet of Aquilas flying together at 60,000 feet, communicating with each other with lasers and staying aloft for months at a time", beaming internet access over wide areas.

Making all this work is a lofty goal. In November it emerged that the prototype Aquila had been substantially damaged on landing, triggering an investigation by flight-safety inspectors. And getting permission to fly such aircraft over any populated areas will not be easy. In January Google scrapped its own high-altitude communications-relay drone, Titan.

Dr Teller says that Google now sees more promise for extending internet access in high-altitude balloons; they are easier to keep airborne and much more lightly regulated than drones. Military drones such as the Global Hawk can already act as telecoms relays, so that part of the technology is proven; the challenge is to harness solar power to keep drones aloft for weeks or months, not just a day or two. Large, lightweight UAVs can theoretically use solar power to remain in the air for weeks at a time; a prototype Zephyr drone, built by Airbus, Europe's aviation giant, stayed aloft for 14 days during a test flight in 2010.

High-altitude drones have also been proposed as a way to generate electricity, because strong winds blow more reliably well above the ground. Known as wind drones or energy kites, such drones are tethered so that cables can deliver the electricity back to the ground. Makani, a startup acquired by Google in 2013, reckons a single energy kite can generate 50% more electricity than a single wind turbine while using only 10% of the materials. Each Makani drone, which resembles a wing with eight propellers, weighs 11 tonnes, compared with about 100 tonnes for a comparable 600kW turbine. This approach is being pursued by other firms too, including Ampyx Power and Kite Power Systems, both backed by E.ON, a German utility. Tethered drones on a smaller scale are also being considered for indoor use in warehouses, where they might help with stocktaking. Flying indoors neatly sidesteps many regulatory problems, and supplying power via tethers does away with the need for recharging. But GPS cannot be used for positioning.

At the lowest end of the spectrum are insect-like drones, just a few centimetres across, that could be used for surveillance inside buildings, search and rescue, or even pollinating plants. Building very small drones is hard because the technology used in larger drones cannot simply be scaled down; different approaches are needed. In a paper published in February in the journal *Chem*, Japanese researchers explained how insect-sized drones covered in hairs coated with a special gel picked up pollen from one plant and deposited it on another. They concluded that robotic pollinators might offer a remedy for the decline in honeybee populations.

Perhaps the most far-out proposal to date is to use drones to carry human passengers in self-flying taxis. This is harder than using drones for package delivery, because it raises safety concerns for people in the air, not just on the ground. EHang, a Chinese drone firm, hopes to test its one-person drone, which resembles a giant quadcopter with a passenger compartment, in Dubai in July. Other companies, including Airbus, Uber and Kitty Hawk, have proposed similar "flying car" drones. Dario Floreano, a robotics professor at the Swiss Federal Institute of Technology (see Brain scan, previous page), has been thinking about passenger drones as part of the European Union's "myCopter" project. Packages, he says, can withstand sudden accelerations during flight that humans cannot, which makes path-planning and obstacle avoidance more difficult. And the limited energy density of batteries may restrict the range of passenger drones to intra-city hops.

It is a big leap from today's drones to these sorts of uses. Trying to imagine how drones will evolve, and the uses to which they will be put, is a bit like trying to forecast the evolution of computing in the 1960s or mobile phones in the 1980s. Their potential as business tools was clear at the time, but the technology developed in unexpected ways. The same will surely be true of drones. ■

Brain scan | Dario Floreano

A pioneer of evolutionary robotics borrows drone designs from nature

THE drones that most people are familiar with today are "very boring", declares Dario Floreano, head of the Laboratory of Intelligent Systems at the Swiss Federal Institute of Technology in Lausanne. He thinks that drones will come in a much wider range of shapes and sizes in future, and that nature will provide the inspiration needed to make them more agile, safer and more capable. "There is space for an enormous range of morphologies and sensing capabilities," he says, giving a slightly worrying example: vampire bats. As well as flying, they can also walk, jump and even run along the ground. Dr Floreano and his colleagues have built bat-like drones with folding wings, and locust-like ones that can jump and fly.

A pioneer in the field of evolutionary robotics, which borrows ideas from nature, Dr Floreano became interested in drones as a result of his work on insect-inspired vision systems. Curved compound "eyes", which (like insect eyes) can "see" in many directions, turn out to be useful in helping a drone sense its surroundings, navigate and avoid obstacles, for example. Dr Floreano's work on fixed-wing drones, with stabilisation and autopilot systems inspired by the way bees navigate, was spun off into a startup called SenseFly, now part of Parrot, a

French drone company. SenseFly's main product is a black-and-yellow fixed-wing mapping drone called eBee.

Birds are another inspiration. Dr Floreano's team recently published research on the benefits of adding artificial feathers to fixed-wing drones. By spreading its feathers, the drone can increase the surface area of its wing, letting it trade speed for manoeuvrability. But not everything needs to be borrowed from nature. Flyability, another spin-out from Dr Floreano's lab, makes a "collision-tolerant" drone that resembles a flying spherical cage, for mapping and inspection in confined spaces.

These sorts of unconventional approaches enable drones to do things that existing designs cannot. Dr Floreano imagines search-and-rescue drones capable of perching on walls or landing on power lines, like birds, to survey their surroundings. This "multi-modal" approach could also increase the safety of delivery drones by allowing them to glide, land or perch if something goes wrong. Multirotor drones can carry a maximum of 30% of their total mass as payload, he notes, so to carry useful amounts of cargo they will have to be quite large and heavy.

At very small scales, fixed-wing and multirotor designs become less efficient, and insect-like drones with flapping wings may make more sense. Tiny drones could be used for virtual tourism, letting remote users "fly" around with the aid of virtual-reality goggles. In short, today's drone designs barely scratch the surface. "There is a huge range of shapes and sizes that we have to explore," says Dr Floreano. "Future drones may look very different."

Regulation

Rules and tools

Regulation and technology will have to evolve together to ensure safety

MOVING bits around the internet is one thing; moving atoms around in the real world is something else entirely. In the two decades of the internet era, many world-changing technologies—web-publishing, file-sharing, online auctions, internet telephony, virtual currencies, ride-hailing—have raised new legal and regulatory questions. In each case, regulators had to work out the rules after the event: figuring out how libel law applies to the web, banning the sale of Nazi memorabilia, deciding whether Bitcoin is a currency, determining whether Uber drivers are employees or contractors, and so on. But drones are a different matter, because of the danger that flying robots pose to life and limb, and the existence of strict rules that govern the use of physical airspace. Their future will depend as much on decisions made by regulators as it does on technological advances. How will it play out?

Global policymakers are currently engaged in a "very interactive process of competition and co-operation", says Greg McNeal, a law professor at Pepperdine University who advises the Federal Aviation Administration (FAA) on drone regulation and is co-founder of Airmap, a drone-software startup. Before the introduction of America's "part 107" rules last August, Google's Project Wing tested drones in Australia and Amazon in Canada, where the regulatory regimes were more accommodating. France's relatively permissive regulation put it at the forefront of the agricultural use of drones. And in Britain a drone cluster has sprung up around an airport in Aberporth, in Wales, where drone-friendly regulations and facilities have been put in place. Now regulators in different countries are working closely together, attending each other's meetings and learning from each other, while also competing to attract drone startups. "It's very good for the industry, because every nation wants to be a leader," says Mr McNeal.

Flying over people raises additional problems

The FAA's part 107 rules, providing for certification of commercial drone operators, are generally seen as a model by other countries. These rules, a decade in the making, allow operators with a remote-pilot certificate (obtained by passing a test costing $150) to fly a drone for commercial purposes during the day, within line of sight, in uncontrolled airspace, and without flying over people who are not involved in operating the drone. Other countries have since followed America's lead, and some are already going further: France and Switzerland allow some operation beyond visual line of sight, says Mr McNeal, and from 2018 Japan will permit it for delivery drones. In America the next set of proposed rules from the FAA, expected later this year, will deal with flight over people and remote identification of drones. Next year there will be proposals for the control of multiple drones by a single operator, "extended visual line of sight" operation over longer distances, and night operation. In 2019, says Mr McNeal, the FAA will propose its first rules governing flights without a visual line of sight, a crucial requirement for delivery drones.

Drone companies can already go beyond part 107 by obtaining special waivers from the FAA, provided they can show that the proposed operation can be conducted safely and meet some additional requirements. This offers a way to test new regulations before they are formalised. Such waivers impose additional safety requirements on drone operators: getting a waiver for night-time operation, for example, requires mounting a light on the drone that is visible three miles away, and providing night-flight training for operators. If all goes well, this could form the basis of a new rule, says Brendan Schulman, head of policy at DJI.

Flying over people raises additional problems. The FAA's proposed rule, due out later this year, is expected to ask drone operators to show how they would mitigate the risk of injury to bystanders. The best way to do this, explains Mr Schulman, is to specify an acceptable level of risk, and then require dronemakers to show that their vehicles meet that standard. This might involve adding cushioning or parachutes to drones, or ensuring that they can still operate if some parts fail, or making them so small and light that they would cause little injury if they fell on someone.

An idea from Australia also deserves to be more widely adopted, he suggests: the creation of a special category for very small drones, allowing commercial operation without any certification. In Australia's case this applies to drones weighing less than 2kg. Similar rules apply in Mexico and Canada, and are being considered in India and several European countries. In America all drones weighing less than 25kg are still treated the same. But broadly speaking, regulators are learning from a variety of approaches being tried in different countries.

Traffic lights in the clouds

To operate drones beyond visual line of sight and in large numbers, particularly in densely populated areas, will take not just extra rules but the establishment of new traffic-management systems, akin to air-traffic-control systems, to prevent drones crashing into each other or veering off course. Around 80% of consumer drones, including those made by DJI, Yuneec and Intel, already support "geo-fencing", using technology provided by Mr McNeal's company, Airmap. Its database of where drones are and are not allowed to fly is built into the software used to control them, working with satellite positioning to prevent an operator

In perfect formation

from flying a drone too close to an airport, for example. Airmap's database can be updated in real time to keep drones away from unexpected events such as fires and other incidents.

But once drones are flying beyond their operators' line of sight, a more elaborate system will be needed to track large numbers of them and ensure they avoid each other and stay away from manned aircraft, says Parimal Kopardekar of NASA's Ames Research Centre. He is leading the development of a system called Unmanned Aerial Systems Traffic Management (UTM), an automated traffic-management system for drones. Existing air-traffic-control systems are operated manually, with human controllers co-ordinating with human pilots during flight, but that will not work for unmanned drones flying in much larger numbers. The UTM system will be automatic, with drones filing requests to use particular flight paths with a local data exchange, which then co-ordinates all the movements. "The regulator only sets the rules and defines the exchanges, so it's a very different way of doing things from air-traffic control," says Dr Kopardekar.

Last year NASA carried out a trial of its UTM architecture across the United States which revealed several challenges, notes Dr Kopardekar. In particular, it turned out that fixed-wing and multi-rotor drones respond very differently when they encounter rising columns of air, called thermals. Fixed-wing drones "bounce around quite a bit, by a few hundred feet", says Dr Kopardekar, which means drones cannot be stacked too closely together. Route planning will, in short, require a detailed understanding of micro-climates and of the behaviours of different types of drones. Building the necessary systems will take a few years.

Where are you going?

The FAA plans to introduce the first rules around UTM from 2019. Drones will need to be equipped with "sense and avoid" systems and long-range radio to communicate with each other and with the data exchange. That also poses a challenge, says Jane Rygaard of Nokia, a maker of network equipment, because existing mobile networks are designed to work with users on the ground, not in the air. Networks will have to be augmented with antennae that point towards the sky. This technology already exists to provide in-flight connectivity to aircraft, but will have to be extended more widely to take in drones as well.

And even once all these rules and tools are in place, not everyone will respect them. Some people may want to use drones for nefarious purposes. A range of anti-drone technologies is already being tested. Police forces in some parts of the world have trained birds of prey to attack small drones. Nets can also be used to trap them, either fired from bazooka-like launchers or dropped by other drones. America's Department of Defence holds an annual event called Black Dart at which various anti-drone technologies are evaluated. "The biggest surprise to military folks was how difficult it was to combat small drones," says Grant Jordan, the founder of SkySafe, an anti-drone startup, who worked on Black Dart a few years ago when he was in the air force. When the target is "tiny, very light and relatively slow", the assumptions of traditional air defence are all wrong, he says.

Big laser systems worked pretty well, he recalls, but are expensive and complex. Israel has used Patriot missiles to shoot down fixed-wing drones operated by Hamas, Mr Jordan says. By contrast, his firm disables drones by intercepting their control signals and video feeds. Examining the radio traffic to and from a drone makes it possible to determine what type it is, track it and if necessary take it over to disable it or force it to land. Anti-drone systems made by SkySafe, and rivals such as Dedrone and DroneShield, are being evaluated for military and government use and to police airspace around airports, stadiums and prisons (to prevent smuggling of phones, drugs and other items to inmates). But it is unclear who has the legal authority to stop drones that pose a threat to public safety, says Mr Jordan. Existing air-safety rules aim to protect passengers in aircraft; for drones, "the logic of these laws falls apart."

It is clear that the complexities of operating drones in large numbers have barely begun to be understood. As the first widely deployed mobile robots, drones already offer many exciting possibilities today, and no doubt other, as yet undreamed-of uses will follow in the future. Frank Wang, the founder of DJI, pictures people being followed around by tiny personal drones, like fairy sidekicks. Astro Teller of Google foresees delivery drones that can come up with any item on demand. And passenger drones might some day act as magic carpets, whisking people across cities from rooftop to rooftop.

Drones make the extraordinary power of digital technologies physically incarnate. But because they operate in the physical rather than the virtual world, exploiting the many opportunities they offer will depend just as much on sensible regulation as on technological progress. ■