ENGINEERING

Flight of the RoboBee

Tiny flying vehicles require intricate design trade-offs and have previously relied on an external power supply. The sustained flight of an untethered, insect-sized robot represents a major advance. See Letter p.491

KENNY BREUER

Going back to the time of Leonardo da Vinci, animal flight has inspired human enquiry, and we have sought to emulate nature by building machines that attempt to fly using flapping wings. On page 491, Jafferis *et al.*[1] report a key step towards the emulation of insect flight with what they claim to be the lightest insect-scale aerial vehicle so far to have achieved sustained, untethered flight.

Apart from the aesthetic joy of mimicking nature, flapping-wing robots have several potential advantages over the fixed-wing drones and quadcopters (four-rotor helicopters) that have become so popular in commercial and recreational applications. Flapping wings make animals and machines highly agile and manoeuvrable — for example, bats can fly with ease through basements, caves and dense forests. Moreover, flapping wings typically move with lower tip speeds than do propellers, and are therefore quieter and inflict less damage if they come into contact with people or property.

In addition, biologists can use flapping-wing robots to address fundamental questions about the evolution of flight and the mechanical basis of natural selection. For all these reasons, bio-inspired flapping-wing flight has been an area of intense interest, particularly over the past couple of decades. As a result, there have been impressive advances in our understanding of the aerodynamics and control of bio-inspired robotic flyers[2,3], as well as several examples of engineered autonomous flapping robots[4–6].

Achieving robotic flight at the insect scale presents three specific challenges. First, the materials used to build the robot must be strong, yet lightweight. Second, human-engineered actuators (devices that convert energy into movement) and batteries are still far from realizing the power and energy densities, respectively, of biological tissue. And third, the sensing and control algorithms that animals routinely use to maintain steady flight and to manoeuvre are mind-bogglingly complex. These algorithms have proved difficult to mimic even with the use of a supercomputer, despite the fact that a typical insect brain has only about a million neurons — which is orders of magnitude less than the number of components in the processing system of a supercomputer.

Figure 1 | The RoboBee. Jafferis *et al.*[1] present a centimetre-sized aerial vehicle that flies using flapping wings. Solar cells, which power the vehicle, are positioned above the wing system; essential electronics are located below this system. The vehicle shown is held by tweezers.

ADAM DETOUR FOR *NATURE*

Jafferis and colleagues' work builds on several years of impressive research and development. The authors combine a multitude of diverse technologies in a tour de force of system design and engineering to achieve the sustained flight of an insect-sized robot dubbed the RoboBee X-Wing (Fig. 1). Sustained, powered flight is an energetically demanding mode of transport, and existing battery technology lags far behind nature in its ability to provide a lightweight power source. Previous insect-sized robotic flyers[7–10] have relied on an electrical 'tether' to supply the flight system with the necessary energy.

The current authors sidestep this problem quite ingeniously, by using solar panels perched on top of the RoboBee. Illumination of the panels by a high-intensity light source provides the approximately 120 milliwatts needed to drive the 259-milligram flight system. This light-powered approach is similar to at least one other demonstration of the lift-off of an ultralight robot[6]. Jafferis and colleagues' claim that their robots achieve sustained flight, rather than just jumping or lift-off, is perhaps arguable, and pivots on what is defined as "sustained" — we'll let historians decide that issue.

Building a lightweight yet strong wing–body structure has always been the first hurdle in the engineering of aircraft. Small flight systems can benefit from the cube–square law whereby, as a vehicle decreases in size, its body mass decreases faster than its wing surface area (which is proportional to the generated lift force). However, other issues are more challenging for small vehicles than for large ones, such as the problem of manufacturing and assembling a robust and precise artificial wing-muscle system.

At the core of the RoboBee is a flapping-wing system made of a composite material and constructed using a process known as laser machining. This process has been a hallmark of the study's authors, who belong to a research group at the Harvard Microrobotics Laboratory in Cambridge, Massachusetts. The group has developed a design and manufacturing tool that has evolved and matured to become an invaluable (and enviable) resource for the fabrication of small-scale robotics. The current design of the flapping-wing system uses an innovative four-wing configuration that wiggles back and forth. This motion is driven by integrated piezoelectrics (materials that convert electricity into mechanical forces), and generates sufficient lift with acceptable power demands.

One perennial drawback of piezoelectrics is that, although they can apply large forces to a material, they induce tiny displacements and require high voltages. Key advances in the current work are the optimization of a mechanical transmission to generate the appropriate force–displacement characteristics and the development of a lightweight electronic circuit that converts the low voltages generated by the solar panels into the 200-volt pulses needed to power the piezoelectrics.

All these components are combined to produce the resulting test system — a tall, gangly device, which has its solar panels perched high above the wing system and its electronics hanging below. It is certainly not the most aesthetically pleasing flyer, but when the lights come on, it lifts off and achieves sustained, autonomous, untethered flight. Although the device by itself is an impressive achievement, equally rewarding is the detailed description of the modelling and design that the team has put into the system. The flight of the RoboBee represents much more than just the sum of the parts. It also reflects the successful compromise that has been achieved between the competing interests of weight, power, control, strength, resilience and even cost.

There is still much work to be done, and we are not quite at the point at which a robot swarm will take to the skies — as is nightmarishly depicted in dystopian science fiction such as Michael Crichton's novel *Prey*. Jafferis and colleagues' robot requires intense light to generate sufficient power for take-off (at least three times the intensity of the Sun). Moreover, the robot flies for just under a second before veering off out of view, presumably heading for a crash landing. Nevertheless, advances in battery technologies could soon eliminate the need for solar panels, and with the ever-improving capabilities of small-scale electronics and communication technology, the controlled flight of tiny robots seems within our grasp. ■

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ANTIBIOTICS

Death from within

Some bacteria naturally transfer pieces of their DNA within and between species. Such a piece of DNA has been engineered to act as a molecular 'Trojan horse' that unleashes a toxin to selectively kill antibiotic-resistant *Vibrio cholerae* bacteria.

SANNA KOSKINIEMI & PETRA VIRTANEN

Antibiotic resistance among infectious bacteria is an increasing problem worldwide, resulting in large part from the overuse of antibiotics. Writing in *Nature Biotechnology*, López-Igual *et al.*[1] demonstrate a nifty way to selectively poison antibiotic-resistant *Vibrio cholerae* bacteria — the species that causes cholera — from the inside. The authors' aim is to offer a highly targeted alternative to standard broad-brush antibiotics.

Our present scattergun overuse of antibiotics has caused several problems, one being the emergence of antibiotic-resistant bacteria. Another is that typical broad-spectrum antibiotics affect not only the target disease-causing (pathogenic) bacteria but also our normal beneficial bacteria, which protect us against infection and might influence many other aspects in humans, including weight, mood and allergies (see go.nature.com/31x0csa). The specificity of the approach proposed by López-Igual and colleagues could avoid both of these issues.

The authors' method builds on the ability of bacteria to transfer certain pieces of genetic material ('mobilizable' DNA) on cell-to-cell contact, in a process known as conjugation. López-Igual *et al.* take advantage of this phenomenon to transfer a set of genes that encode a toxin (a protein called CcdB) and its antidote (a protein known as CcdA) from donor bacteria into their neighbours. The system is designed so that the toxin will be made only in *V. cholerae* and the antidote will be made only in the *V. cholerae* bacteria that are antibiotic-sensitive, so that just antibiotic-resistant *V. cholerae* will be killed (Fig. 1).

López-Igual *et al.* used several clever tricks to ensure that toxicity occurred only in the target cells. First, they engineered the toxin-encoding genes to be under the control of a *Vibrio*-specific protein, the transcription factor ToxR (which is essential for *V. cholerae* to cause

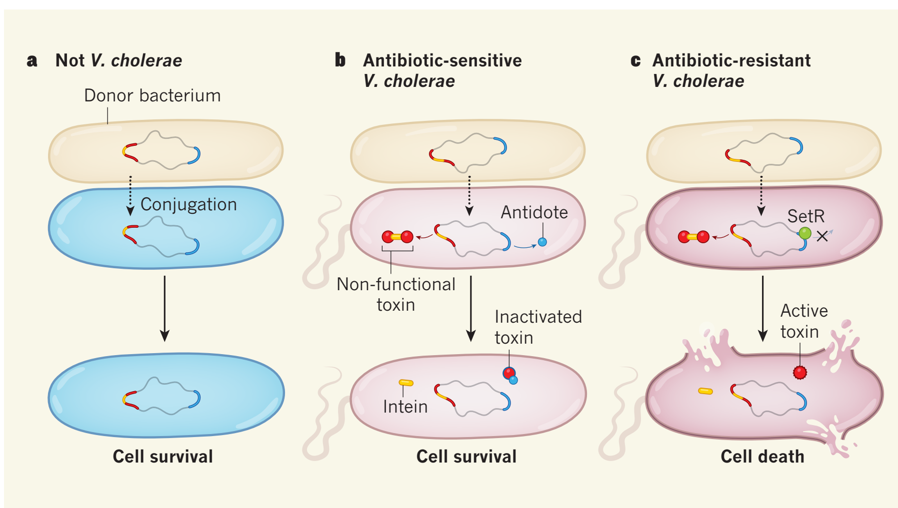

Figure 1 | Time-delayed destruction of *Vibrio cholerae*. López-Igual *et al.*[1] have designed a system with which to selectively kill antibiotic-resistant *V. cholerae*, the bacterial species that causes cholera. They engineered a circular piece of genetic material that encodes both a toxin (red) that is interrupted by a component known as an intein (yellow) and an antidote to the toxin (blue). These genes are inserted into a donor bacterium, and can then be transferred into other bacteria in a population through a transfer process called conjugation (dotted arrows). **a**, If the bacterium that receives the genetic material is not *V. cholerae*, then the toxin and antidote are not expressed because the bacterium lacks the appropriate transcription-factor protein that drives their expression. Such cells survive. **b**, If the recipient is antibiotic-sensitive *V. cholerae*, the bacterium makes the antidote and a toxin that is non-functional because it contains an intein. Over time, the intein removes itself from the toxin. However, the resulting functional toxin is inactivated by the antidote, and the bacterium lives. **c**, If the recipient is an antibiotic-resistant *V. cholerae*, expression of the antidote is blocked by a repressor protein called SetR, which is encoded by a gene that contributes to antibiotic resistance. When the intein removes itself from the toxin, this generates active toxin and the bacterium dies.