NEWS & VIEWS

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BIOMIMETICS

Flying like a fly

When biologists unravelled the principles of insect flight, they inspired a generation of engineers to build on their aerodynamic feats. Thanks to a revolution in micro-manufacturing techniques, the first robotic fly now flies.

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A robotic fly discreetly monitoring our homes and command centres was a pop-cultural manifestation of cold-war paranoia. It was also pure fiction, because scientists of the time were unable to explain the mechanics of insect flight. Relying on aerodynamic theory that was appropriate for fixed-wing aircraft, their calculations could infer only that insect wings generate too little lift to remain aloft. But our understanding of insect aerodynamics, and ability to build robots that mimic and exploit it, has increased immensely over the past two decades. A culmination of this is the report by Wood and colleagues[1] (Ma *et al.*) in *Science* of the first controlled flight of an at-scale robotic fly.

An important step on the way to elucidating the secrets of insect flight came in 1996 from researchers using a gigantic, dynamically scaled model hawkmoth[2]. This robot flapped its wings at a stately frequency of only once every 3 seconds, which was calculated to reproduce the airflow and lift force of a hovering moth. By releasing smoke from within the wings, the authors were able to visualize a tornado-like vortex that ran outwards along the leading edge of each wing. The remarkable stability of this leading-edge vortex enables the wings of insects to operate at angles of attack at which the wings of an aircraft stall, and consequently to generate more lift.

Although the smoke experiments revealed the vortex, they did not quantify the extra lift. To measure this force, another group[3] created the Robofly, a robotic fruitfly enlarged by a factor of 100, which they studied submerged in a tank of mineral oil. Fluid force is proportional to the ratio of viscosity-squared to density, and for otherwise-similar flow patterns this force is 50,000 times greater in oil than in air. This amplification allowed the authors to record and disentangle the myriad aerodynamic mechanisms that fruitflies exploit to perform their intricate hovering flight manoeuvres.

Insight from the Robofly enabled electrical engineers to design at-scale robotic flies[4] that researchers had previously only imagined[5], kicking off robot-fly evolution. At the time, fly-weight robots were an engineer's fabrication nightmare, because electronic components were heavy. No wonder, then, that the first flapping robot that hovered like a fly — the 360-millimetre-wingspan Mentor — weighed more than 400 grams[6]. This weight limited Mentor to short vertical and hovering flights, which were stabilized by an autopilot. The next incarnation, the 280-mm DelFly (Fig. 1a), which relied on passive stability instead of bulky electronics, weighed only 16 g and could fly for 16 minutes[7]. DelFly performed vertical take-offs and landings, hovered, and flew forward like a dragonfly.

Subsequently, a young hobbyist scaled this design down to a mere 60-mm wingspan and 930-mg mass, and flew it indoors. A 2009 video posted on YouTube (go.nature.com/qhrbnl) demonstrates the remarkable battery-powered flight, lasting more than 1 minute, of this robot, which was developed at a time when competing multimillion-dollar research projects that aimed to achieve similar results could not get off the ground. But things changed with the Nano Hummingbird[8], the first tailless flapping robot that could take off and land vertically (Fig. 1b). Measuring 160 mm, the robot can fly for 11 minutes on battery power, is stabilized by an autopilot and steers by controlling the angle of attack over the course of each wingbeat — just like real hummingbirds, which have been dubbed nature's honorary insects. The robot's extreme manoeuvrability is comparable to that of hummingbirds and flies. On the flip side, it still weighs 5 times more than common species of hummingbird and 1,000 times more than a house fly.

These robots confirmed the experimental prediction that flapping flyers could be scaled down to insect size and still function; fundamentally, this is because the aerodynamic mechanisms that underlie their flight are not limited by scale[7]. However, further miniaturization was prevented by the absence of efficient lightweight fabrication technology at the millimetre scale. But researchers in the Wood laboratory have spent more than a decade devising ways to bridge this technological gap. The group last year reported a revolutionary millimetre-scale manufacturing technique, inspired by pop-up books, that can mass-produce 30-mm fly-like robots weighing only 80 mg[9]. To get around the implacable scaling laws that degrade the performance of electric motors and bearings at this scale, the team also developed efficient replacements in the form of miniature piezoelectric actuators and low-friction flexible joints.

These advances led to the remarkable realization of Wood and colleagues' at-scale robot fly (Fig. 1c). However, the device comes with strings attached: a tether connects the robot to a grounded battery and autopilot. The latter monitors and adjusts the flight path of the robot almost beat by beat. Although micrometre-scale on-board autopilot is close to completion, the development of microbatteries remains remarkably challenging. Radically new battery technology is needed to power this wave of free-flying, flapping microrobots out of science fiction and into contemporary society.

When this occurs, insect-sized robots will

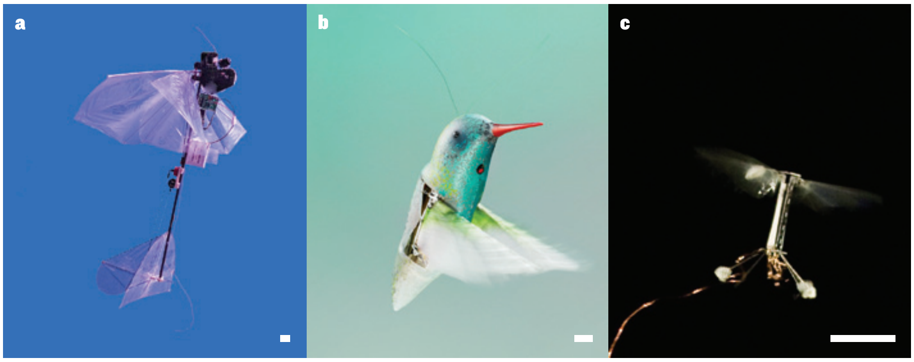

Figure 1 | Winged victories. Three successive iterations of miniaturized robots that each mimic certain aspects of animal hovering flight. **a**, The passively stable DelFly[7] hovers like an insect that is controlled by its tail. **b**, The tailless Nano Hummingbird[8] is stabilized by an on-board autopilot, which controls the wings' angle in a way analogous to that seen in real hummingbirds. **c**, Ma and colleagues' robot fly[1], shown here on its maiden flight, is controlled by a tether that provides modulated power to each flight 'muscle' of the wing. Scale bars, 10 millimetres (estimated).

A, JAAP OLDENKAMP; B, JAMIE CHUNG; C, KEVIN MA & PAKPONG CHIRARATTANANON

probably be used first as inconspicuous (and inexpensive) eyes in the skies to help us to obtain situation awareness, for example during hostage situations or in urban war zones, and later perhaps as artificial agricultural pollinators. Ma *et al.* suggest that their robot fly will also advance our biological understanding of insect flight. The robot could, for example, be manipulated to test specific hypotheses that concern stability and control. Unfortunately, the flapping wings of the robot will not push the boundaries of aerodynamic efficiency — in one-on-one comparisons, helicopter rotors consistently require less power, based on weight, than flapping wings[7,8]. Flapping robots are, however, poised to fly more robustly in cluttered and turbulent environments. Here, whereas animals succeed, the current generation of microdrones fails drastically. Perhaps soldiers of the future will need to carry a swatter on the battlefield. ■

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