A Flapping of Wings

Robot aircraft that fly like birds could open new vistas in maneuverability, if designers can forge a productive partnership with an old enemy: unsteady airflow

IN A PACKED CONFERENCE HALL, ALL HEADS are turned to the back of the room. The crowd murmurs as a man holds up what appears to be an enormous model of a seagull with its wings outspread. The murmurs turn to silence as the wings begin to flap while it is still in his hands. Then he tosses the bird forward … and with a whir, SmartBird takes off.

The silence gives way to applause as the bird flies once, twice, three times around the auditorium. As it glides gently to a stop, the audience gets up and gives the SmartBird a standing ovation.

More than a million and a half people have watched the video of the SmartBird flying at a TED conference in Edinburgh last July (www.youtube.com/watch?v=Fg_JcKSHUtQ). And humans aren't the only ones who find it fascinating. At the same conference, when the robotic bird flew outside, it attracted a mob of curious seagulls.

The last couple of years have been an exciting time for flapping-wing flight. Another bird-inspired aircraft, AeroVironment's Nano Hummingbird, made *Time* magazine's list of 50 top inventions of 2011 (see sidebar, p. 1433). The U.S. Defense Advanced Research Projects Agency and the Office of Naval Research are investing millions of dollars into so-called micro air vehicles and nano air vehicles, as well as basic research into how birds and insects fly.

Online
sciencemag.org
Podcast interview (http://scim.ag/Indo_6075) with author Dana Mackenzie.

A century after the Wright brothers, fixed-wing aircraft have become a routine part of our lives. But flapping-wing aircraft, or ornithopters, still elicit wonder. "Just about everybody gets a thrill out of seeing one for the first time," says Nathan Chronister of Rochester, New York, who makes ornithopter kits for hobbyists and science classes. At the same time, there is serious science behind them. While the theory of airflow over a flapping wing remains surprisingly rudimentary, humans are now making significant progress in understanding how to fly, control, and land flapping-wing aircraft. "It's not the physics that's the problem any more," says aeronautical engineer Wolfgang Send, the mastermind behind the SmartBird.

Soaring. Festo's SmartBird (*above*) and MIT's Phoenix (*left*) take robotic flapping-wing flight to new levels of grace and precision.

Dead end?

From Daedalus to Leonardo da Vinci to Otto Lilienthal, early researches in flying emphasized flapping wings. And in fact, the first rubber band–powered ornithopters, made by Alphonse Pénaud of France in 1874, predate motorized airplanes.

But after the spectacular success of the Wright brothers, flapping-wing aircraft began to look like a technological dead end. Even now, engineers struggle to understand unsteady airflow. "Not even for the simplest flight situation—level cruising flight—is there a global, recognized theory, accepted by most of the experts," says Horst Räbiger of Nuremberg, Germany, a longtime designer of ornithopters. Yet, he adds, such a theory "is necessary to compute the best lift distribution along the wingspan at every moment, the ideal airfoils at every part of the wing, the best flapping angle, best flapping frequency, and much more. Today, every expert makes his own theory—including myself."

Ornithopters also languished for many years because they are simply inferior in aerodynamic efficiency to airplanes with rotating parts. "The limit of efficiency for a flapping vehicle for thrust is when it works

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like a bad propeller," says Russ Tedrake of the Massachusetts Institute of Technology (MIT) in Cambridge. "For hovering, the limit of efficiency is when it approximates a helicopter."

However, ornithopters should have advantages, too, if they can be built. They should be more maneuverable than fixed-wing airplanes. They should be able both to hover and to fly forward. Birds, for example, direct their thrust upward at takeoff, flapping their wings at a large angle of attack to push themselves away from the ground. In cruising flight, the wings level out to a lower angle of attack, minimizing drag, generating mostly lift and only a little bit of thrust. When landing, the bird shifts once again to a high angle of attack with a lot of drag, in effect stalling out and using the wings as a parachute.

Conventional airplanes are not so versatile. Pilots scrupulously avoid high angles of attack and stalling. To take off or land, an airplane must reproduce the conditions of cruising flight—high speed, low drag, low angle of attack—while on the ground. That is why airplanes require runways. Such aerodynamic conservatism was understandable in the early days of flight, when unsteady airflow killed many pilots. (Lilienthal, for instance, died in 1896 when his glider stalled and crashed.) But does it still make sense today, with modern sensors and computers and mathematical techniques at our disposal—and no pilot on board?

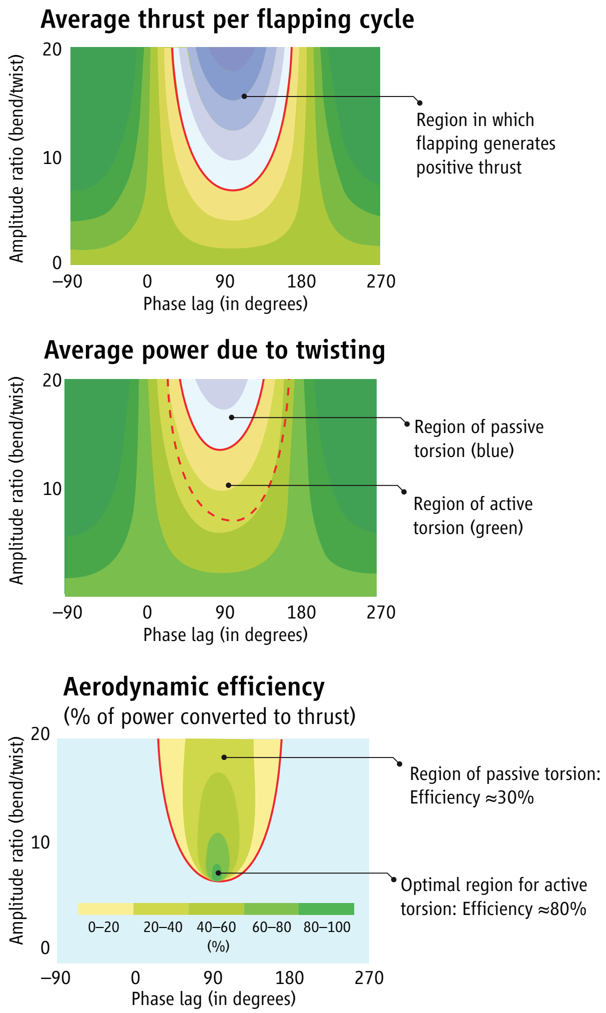
An elegant pitch

For decades, a few dedicated amateurs and professional engineers doing research in their spare time have kept the dream of flapping-wing flight alive. One of the latter is Send, an engineer at the German Aerospace Center (DLR) until his retirement in 2009.

For years, Send has believed that the secret of high-efficiency flapping flight lies in two papers written by Theodore Theodorsen, an American engineer, and Hans Georg Küssner, a German engineer, in 1935 and 1936. Both researchers viewed flapping as something to be avoided; they were trying to understand the causes of wing flutter in fixed-wing aircraft. They found mathematical solutions for the aerodynamic forces on a flat plate that is both plunging (going up and down) and pitching (making an S-shaped motion). In bird flight, these two motions are typically about 90° out of phase, with the wing's highest angle of attack occurring when its vertical displacement is zero, and zero angle of attack when the vertical displacement is highest.

Send viewed the phase lag as a control variable, together with the ratio of plunging amplitude to pitching amplitude (see figure, below). In the two-dimensional control space, flutter occurs spontaneously in the blue region on the middle graph of the figure, where the pitching amplitude is low and the phase lag is about 90°. In this region, the pitching motion extracts energy from the airflow. Most ornithopters employ this "passive torsion," allowing the wind to twist the wing to a positive or negative angle of attack. However, the aerodynamic efficiency (a measure of thrust as a percentage of power input) is quite low, only about 30%, as the bottom graph shows.

Send realized that a wing with active torsion—using engine power to twist the wing more than the airflow can do alone—could achieve an aerodynamic efficiency of more than 80%. This efficiency occurs in the small green "sweet spot" seen in the bottom graph, the region in which the SmartBird operates.



Sweet spot. SmartBird's designers used active torsion to maximize aerodynamic efficiency. In passive torsion (*center*), a wing twists spontaneously and extracts energy from the airflow. In active torsion, the twisting must be powered by a motor. Maximum efficiency occurs in a tiny "sweet spot" (*bottom*). Figures show theoretical solutions for a flat rectangular wing; SmartBird achieved an efficiency of 80% to 90%.

CREDIT: WOLFGANG SEND

Send's views were definitely not shared by most of the ornithopter community. Some ornithopters had used active torsion—and Lilienthal had observed the twisting and the phase lag in bird wings in 1889—but other researchers did not consider it essential. "My colleagues were interested, but there was a skepticism," Send says.

In 2007, Send approached Festo, a company based in Esslingen, Germany, with the idea of turning his ideas on active torsion into a model. Festo was the perfect fit: a company that specializes in biomimetic automation. Its projects include robotic grippers inspired by an elephant's trunk and a helium-filled dirigible inspired by stingrays. "I asked them who is the aerodynamicist, who is the theoretician?" Send says. "They just smiled and looked at me." After retiring from DLR in October 2009, Send plunged into the SmartBird project at Festo.

Although Festo did not have an aerodynamicist, it did have a gifted team. "It was a very rare occasion in which the right people came together, from my point of view," Send says. "Rainer Mugrauer is the Mozart of model builders. Without him, that bird wouldn't ever have been constructed." Agalya Jebens and Kristof Jebens provided the control systems, which are essential to maintain the delicately controlled choreography of plunging and pitching that keeps the SmartBird in the aerodynamic "sweet spot."

SmartBird made its debut at the Hanover Trade Fair in 2011, where it drew more than 20,000 visitors. Festo will not reveal the cost of the project, which Send estimates at a couple of hundred thousand euros. At present, Festo is not planning to sell SmartBirds and denies any interest in military applications. Theme parks might be a possibility, Tedrake says: "Disney would like Tinker Bell to fly in and land on a lantern in Disney World."

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SmartBird's technological tour de force has impressed other ornithopterists. "I was totally gobsmacked by the SmartBird," says James DeLaurier of the University of Toronto in Canada, who built the first engine-powered remote-controlled ornithopter to be recognized by the Fédération Aéronautique Internationale, in 1991. Räbiger is more cautious. "Before the SmartBird, I didn't believe that a servo-controlled wing twisting is a good solution," he wrote in an e-mail. "[Now] I must say: maybe."

Finding a perch

There is one thing SmartBird still doesn't do: land like a bird. It needs conventional landing gear or a human to catch it in midair. If Tinker Bell wants to land on a lantern, she will have to learn how to perch. That is the focus of one of the newest entrants into birdlike flight, Tedrake's Robot Locomotion Group at MIT.

In 2010, Tedrake and his former Ph.D. student, Rick Cory, built a fixed-wing glider, launched from a crossbow, that successfully perched on a wire 19 times out of 20. They have also built an ornithopter, called the Phoenix, that can perch successfully but is not yet as well understood theoretically.

Surprisingly, the most novel technology behind the perching glider was mathematics. When approaching a perch, the glider has a desired trajectory that will bring it into a safe landing. However, the complicated aerodynamics of stall mean that it cannot necessarily hit that trajectory, and the actual trajectory cannot be fully anticipated. A beautiful mathematical device called Lyapunov functions makes it possible to identify a "funnel" within which all trajectories are attracted toward the desired one.

Engineers have long known of Lyapunov functions, but they were hard to compute. The difficulty lies in proving that a polynomial function of several variables is always positive, except at one point (the center of the "funnel"). That changed in 2000, when Pablo Parrilo of the California Institute of Technology (now at MIT) showed that such functions can be found in a quick and dirty way by limiting the search to functions that are sums of squares: numbers that are never negative.

With the sums of squares method, "we are now in the game of applying Lyapunov functions to very complicated tasks," Tedrake says. "A planned trajectory can be much more aggressive, like a bird darting through the forest."

Unlike Festo, Tedrake's group has funding from the military; he is the principal investigator for a $7.5 million multi-university research initiative from the Office of Naval Research. The military interest is understandable. Maneuverable robotic birds would be useful for flying through cluttered urban settings; robots that resemble actual birds would be easier to disguise; and perching robots could conduct surveillance for long periods of time without consuming energy. Such applications, however, are far off; the research is still in a conceptual phase.

"Our goal is to do maneuvering flight," Tedrake says. "I'm not convinced that flapping wings are strictly necessary for that, but it's plausible. It's just a primal belief on my part that there will be a benefit from flapping. There are some remarkable success stories in nature where they're doing things that airplanes cannot do." **–DANA MACKENZIE**

Dana Mackenzie is a writer in Santa Cruz, California.

CREDIT: AEROVIRONMENT INC.—NANO AIR VEHICLE

It's a Bird, It's a Plane, It's a … Spy?

If a hummingbird follows you into a building, one of two things is going on: Either your perfume is too strong, or the world's smallest spy plane is on your tail.

In 2011, AeroVironment, a company founded by Paul MacCready, the inventor of the first human-powered aircraft to cross the English Channel, unveiled a new crewless aircraft called the Nano Hummingbird. With a wingspan of 17 centimeters and a weight of 19 grams, the robot is hefty for a hummingbird. But it can hover in place and fly in any direction (including backward) as fast as 18 kilometers per hour. It can fly through doorways and can be steered by a remote pilot using only video from an onboard camera. All of these abilities met or exceeded the targets for a second-generation "nano air vehicle" funded by the U.S. Defense Advanced Research Projects Agency.

Very small ornithopters like the Nano Hummingbird face different challenges from their larger kin. As a flyer (animal or robot) gets smaller, flying becomes more and more like swimming. Less energy goes to lift and more to thrust. Instead of sculpted airfoils, the wings can and should be simple, rapidly beating membranes. For robots, miniaturization of components and power sources may impose the biggest constraint. A real hummingbird can fly across the Gulf of Mexico without stopping; the Nano Hummingbird can go for only 11 minutes.

The main role envisioned for nano air vehicles is military surveillance and reconnaissance. But they could also be used for civilian applications such as search and rescue or environmental monitoring (for example, inside crippled nuclear reactors).

Miniature devices have taken off in the past decade. In 2002, the dragonfly-like Mentor, developed at the University of Toronto and SRI International, demonstrated hovering flight. In 2006, the (also dragonfly-like) DelFly, developed at Delft University of Technology in the Netherlands, added a camera and forward flight; later versions have shrunk to 3 grams and a 10-centimeter wingspan.

Nano flyers aren't yet fit for duty, however. "The Hummingbird is way cool. I can't say enough good things about it," says Ephrahim Garcia, an engineer at Cornell University. "But it has a limited endurance." Eleven minutes is not much time to scan a building for insurgents or earthquake survivors. Even so, Garcia adds, "Everything doesn't have to be practical. We can learn a lot about flow-structure interaction from these devices." **–D.M.**