Flapping micro plane *watches* where it goes

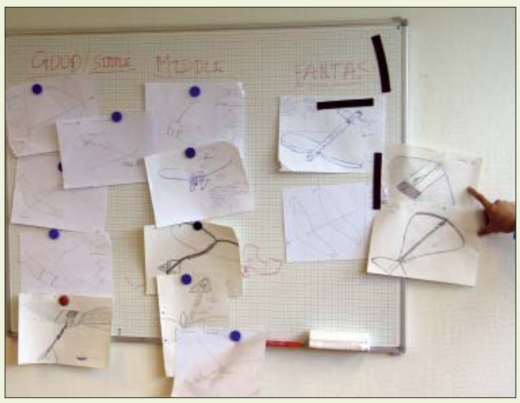
Worldwide there is a keen interest in ultra small aircraft, otherwise known as MAV (Micro Aerial Vehicles). These aircraft can be used in a variety of fields, such as surveillance, reconnaissance, intelligence gathering and as "the fly on the wall". In just over four months students at Delft University of Technology managed to develop DelFly, a dragonfly look-alike MAV, weighting as little as 17 grammes. Here DelFly is in flight during a presentation at the First US-European MAV Competition held in Garmish-Partkirchen in September 2005.

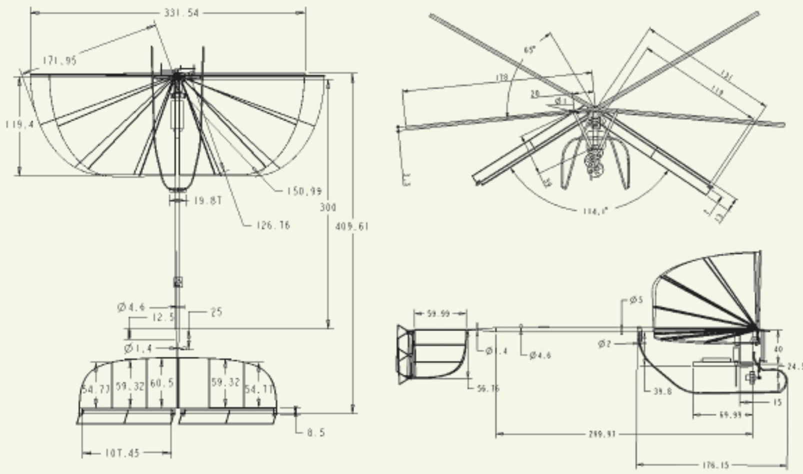
by Bennie Mols

In a time span of only ten weeks, a team of eleven highly dedicated students have managed to design a unique flapping miniature aircraft, named DelFly. The aircraft can hover almost motionless in one spot and fly at considerable speed as well while being more stable and less vulnerable than a helicopter. DelFly, only weighing 15 to 21 grammes, carries a miniature video camera on the nose, that observes its surroundings enabling the Delft aircraft to seek out objects based on the camera images. Last September DelFly attracted a great deal of attention in Germany during an international competition for miniature aircraft, organised by the University of Cambridge. The Delft team won US $35,000 with their unique aircraft.

Inspired by nature, yet not trying to make exact copies. That was the basic thought behind the approach. A dragonfly has two sets of wings positioned behind each other with many degrees of freedom, whereas the DelFly has two sets of superposed wings, pivoting around one point.

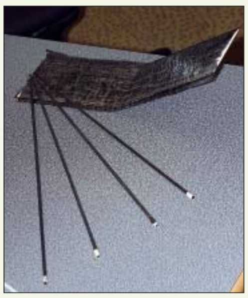
From idea to concepts. Every year Bachelor undergraduates at the faculty of Aerospace Engineering are expected to finalize their third year at the university with a design & synthesis exercise (DSE). During ten weeks groups of ten students work on a single design presented on paper. These concepts are the result of the first five weeks.



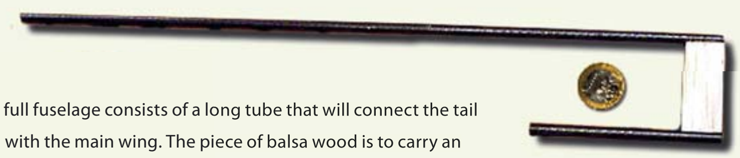


From concept to design. The second half of the DSE was spent on working out the details of the most promising concept. This final report included full specifications. On top of that the students had to write a construction manual. This was an exceptional exercise, since this time there was money available to build the design and participate in the First US-European MAV Competition.

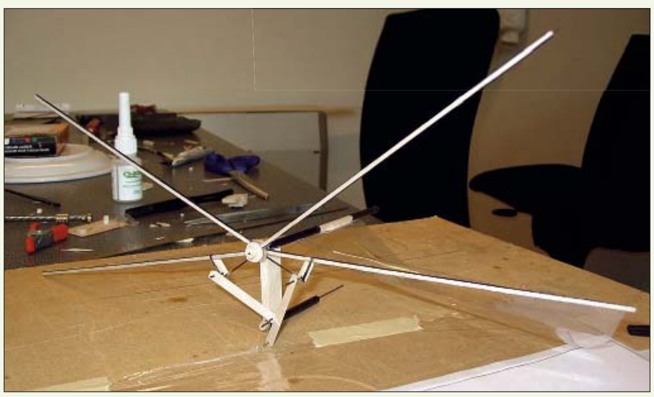
The students had two months during the summer holidays to build the actual aircraft. First they produced the wings and the tubing for the fuselage. The main wing spars are built of 1.5 millimetre thick balsa wood reinforced with ultra thin carbon fibre on top and on the bottom. By applying vacuum suction with plenty of breather material the surplus epoxy is absorbed, thus keeping the spars as light as possible.



The V-shaped balsa-carbon plate is ready to be cut into small slices, which will form main wing spars. The thin tubes (the future fuselage) are made of carbon fibres that have been modelled around a steel rod with a flexible silicone hose.



The full fuselage consists of a long tube that will connect the tail end with the main wing. The piece of balsa wood is to carry an electric motor and transmission wheels. The remaining electronics and batteries will be fixed to the small tube.



The main wings consist of Mylar foil glued to the main spars. They are then mounted to the fuselage on the main wing hinge. The four wings (left and right, upper and lower wings) are attached to only two main spars (the left upper wing is attached to the same spar as the right lower wing).

Most of today's miniature aircraft – known as Micro Aerial Vehicles (MAV) – have only a single pair of fixed wings, just like any commercial airliner. These wings serve to provide the necessary lift, but they do not offer any means of propulsion. The wingspan of a typical MAV is between 20 and 60 centimetres, so that a fixed wing is not necessarily the most interesting method of flight, especially when flying at very low speeds.

"As the aircraft becomes smaller, giving it flapping wings like those of a bird or insect becomes an increasingly attractive proposition," says Christophe de Wagter, a post-graduate student of visual observation for Unmanned Aerial Vehicles at the faculty of Aerospace Engineering at Delft University of Technology. "Flapping is more efficient than flying with a fixed wing at a size of about three to four centimetres, and as the size decreases to one centimetre, flapping remains the only viable option for flight, leaving aside the helicopter concept."

He picks up a small aircraft that looks like an enormous insect. Ultra light at only fifteen grams, the aircraft features a very thin fuselage with two pairs of transparent wings at the front end. After releasing the aircraft, De Wagter uses a pair of joysticks on the radio control unit to fly it around the room with great ease. It looks like a giant moth flapping over the tables and chairs. Control by an external pilot is one option, but not necessarily ideal for this type of aircraft. The aircraft has its own miniature camera, so it can see where it's going and detect objects.

A flapping aircraft that can really hover almost motionless in one spot or fly at a relatively fast pace, and in addition can fly autonomously by evaluating its own camera images, in an advanced virtual reality environment is a unique phenomenon. This miniature aircraft, named DelFly, was designed in a period of only ten weeks by a team of eleven students and three supervisors. On 24 June 2005 it won the best design award at the Symposium for Bachelor graduation studies at the Delft faculty of Aerospace Engineering. Once it had actually been built, it caused a great deal of excitement in late September 2005 at the 1st US-European Micro-Aerial Vehicle (MAV) Competition that was held in conjunction with the 1st US-European Micro-Aerial Vehicle Workshop at Elmau Castle near Garmisch-Partenkirchen, in the south of Germany. The team won a Certificate of Appreciation and a prize of US $35,000.

Detecting terrorists It all started in January 2005. The competition was organised by the University of Cambridge in cooperation with other universities, aeronautical research institutes and the US Army. Dr. S.G. Sampath of the European Research Centre of the US Army visited a number of European universities to stir up enthusiasm for this first American–European MAV competition. The competition rules stated that the miniature aircraft had to be capable of flying half a kilometre, remaining airborne near an objective for half an hour, and of detecting a person carrying a red case (a 'terrorist'). Professors Michel van Tooren and Bob Mulder of the faculty of Aerospace Engineering of Delft University, and professor Johan van Leeuwen of Wageningen University rose to the challenge.

Since De Wagter was already working with professor Mulder on the initial designs for a vision-based UAV (unmanned aerial vehicle), the obvious course was to rope in the post-graduate student to work on the new project.

"We had eight months to select suitable technologies, find development partners, complete a design, and finally, actually build the thing. This kind of effort takes a whole team, and so we came up with the idea of having the design stage done as a third-year synthesis exercise for student teams, which is an annual exercise. Our aim was to take part in the MAV competition as a technology demonstration, to establish a new concept, rather than to win the contest."

De Wagter was charged with supervising the vision section.

At Wageningen University, post-graduate student David Lentink was working on the preliminary stages of a similar assignment to design the smallest possible flapping MAV, supervised by professor Van Tooren and professor Van Leeuwen. Van Tooren was the one to bring the two post-graduate students De Wagter and Lentink together. They decided to ask the students to develop a flapping miniature aircraft with a camera system.

"We wanted a small aircraft that would be capable of flying very slowly, hovering almost in one spot, as well as of flying at speed. At the same time, it had to be stable," De Wagter says. "The only viable option was to use flapping wings, since a flapping aircraft generates more lift than a fixed-wing aircraft at the same air speed. It also means that it can fly more slowly than a fixed-wing aircraft. Given a certain camera system, an aircraft capable of slow flight has a better opportunity for observing its surroundings. Our aim was to make the aircraft capable of flying very slowly and autonomously through a frame, guided by its own camera images."

Birds & insects Lentink, the flapping wing expert of the group, graduated at the Delft Aerospace Engineering faculty and is now working at Wageningen University and the Californian Institute of Technology as a post-graduate researching optimum fluid mechanics strategies in animal flight and swimming. He has lots of experience both with building small aircraft, flapping and otherwise, and with studying the flight of birds and insects.

A design team of eleven students were given ten weeks to come up with a design for a flapping-wing aircraft capable of autonomous flight.

Lentink: "The main problem was the lack of literature on the subject of constructing a small aircraft with flapping wings. In fact, very few successful flapping-wing aircraft have ever been built, so the design of miniature aircraft with flapping wings is only just starting to get off the ground. Moreover, we wanted to build a very light aircraft weighing no more than fifteen to twenty grams, and to top it all, it was going to carry a miniature camera. Building such lightweight structures is a science in itself. When we told the students that we wanted a 15-gramme aircraft, they thought at first that we meant 150 grammes."

Then there is the special technique of the flapping-wing flight.

"Normal knowledge of aerodynamics is of little use in a flapping-wing design," Lentink continues. "In the 1930s there was an aerodynamic expert who did some calculations on insect flight. His conclusion was that insects could not possibly fly. The analysis stopped there. It was biologists who explained the dynamics of bird and insect flight. Some 75% of the useful literature on flapping-wing flight is by biologists."

Don't just copy nature De Wagter became responsible for the vision section, Lentink handled the flapping-wing part, and Rick Ruijsink was drafted in for the electronics. This aeronautical engineer has a consulting company in the field of industrial aerodynamics. The company also designs measuring systems. On top of that Ruijsink is an expert in electronic control systems for model aircraft with a worldwide clientele. For many years in the nineteen-nineties he held the world record for the smallest commercially-marketed wireless receiver. Since then he has helped other electronics engineers to improve their remote control systems.

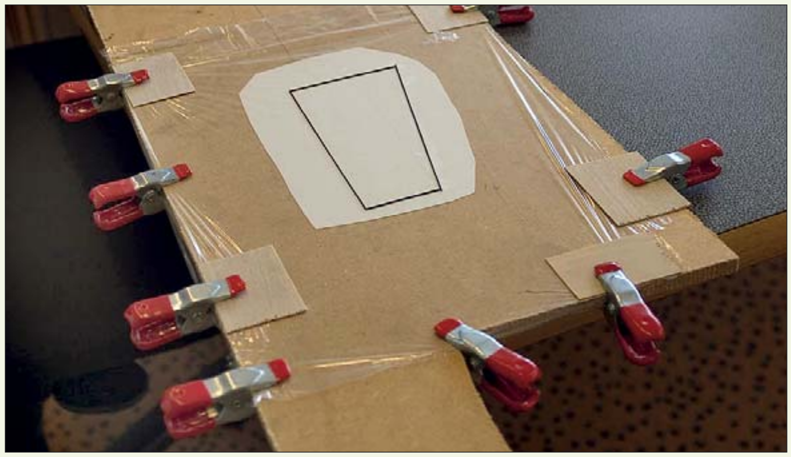
"The thorough integration of these three fields of know-how formed the key to our success," Lentink says.

To outsiders, the flapping wings are the part with instant appeal. Anyone watching DelFly in flight cannot help but notice them. The team of students were given two to three weeks to familiarise themselves with the subject matter. Then they had three weeks to select a basic design with the MAV competition rules in mind. That left four weeks to finalise the design. The first choice the students had to make was between a monoplane configuration with a single pair of flapping wings, like a bird, a tandem configuration with two pairs of wings set one behind the other, like a dragonfly, and a biplane set-up with two superimposed wing pairs, which is non-existent in nature. The students built simple versions of each basic design configuration which they then tested at a sports centre. A series of nifty quantitative tests showed that the biplane set-up with its superimposed pair of wings was superior.

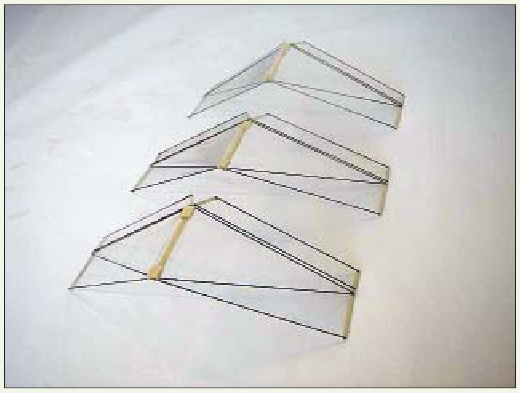
"One of the major advantages of a biplane configuration is that it produces far less vibration in flight than the other types," Lentink says. "This makes for much more stable camera images, which makes it easier to recognise the environment. In addition, the biplane requires only marginally more energy to fly than the monoplane, which is the least power consuming of the three basic design types."

Although the biplane resembles a dragonfly with two pairs of wings, it flies in a different way.

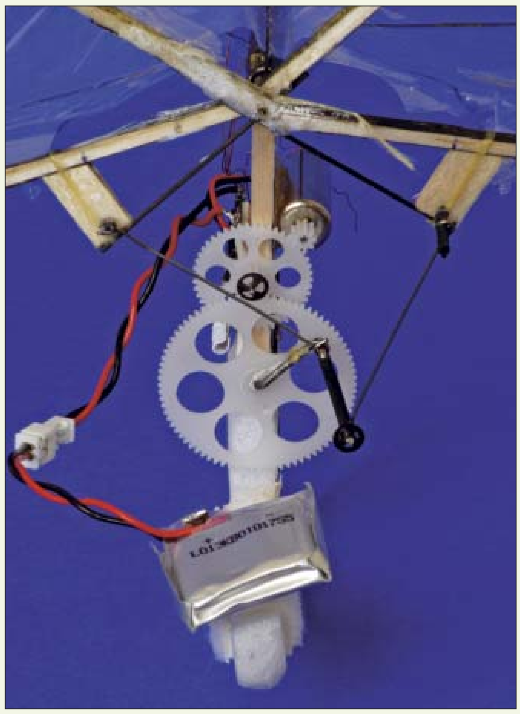
"No natural insect has ever evolved to use its wings in the way DelFly uses its two wing pairs," Lentink explains. "It may be all the rage to say we must have aircraft that can fly just like a bird or an insect, but in fact that is nonsense. I love to watch birds and insects in flight, but it would be very naive to suppose we must copy Mother Nature in every detail. We should let the natural world



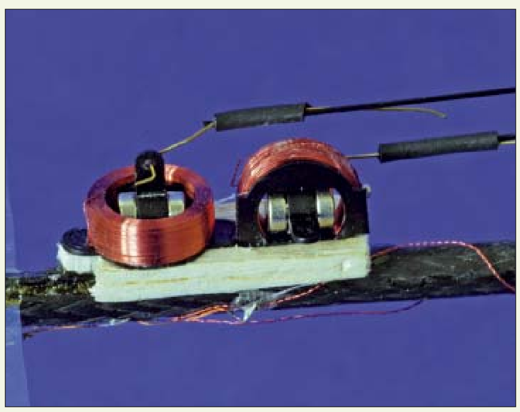
The tail planes are constructed from very thin carbon rods and Mylar foil. The rods are glued together to form a frame. Next the foil is stretched and glued onto the frame.



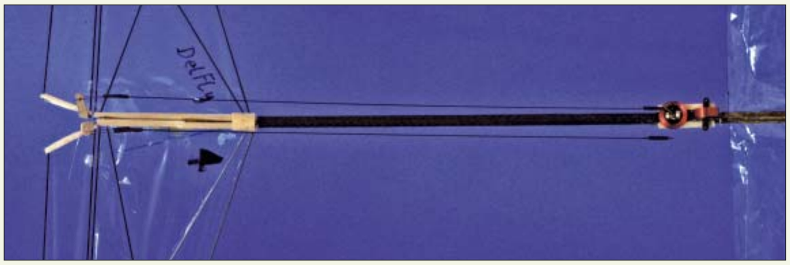
Assembled tail planes in negative V-shape with the rudders.



The traction of DelFly consists of an electric motor driving two wheels. This simple gearbox allows the motor to be used at its optimal speed. Two rods connect the wings with the larger (and slower turning) wheel by means of a crankshaft. All four wings move at the same time. The result is that the upper and lower wings flap towards each other, almost touching each other. The lithium polymer battery pack (3.5 grammes) contains 140 mAh of energy, enough for at least 15 minutes of flight when carrying the camera system.



The ruddervators (a combination of the elevator and rudder) of the V-tail are driven by magnet actuators. These consist of a coil with a hinged magnet inside. A current through the coil will turn the magnet. Using so-called pulse width modulated signals can create a proportional force, resulting in a smooth and precise control.

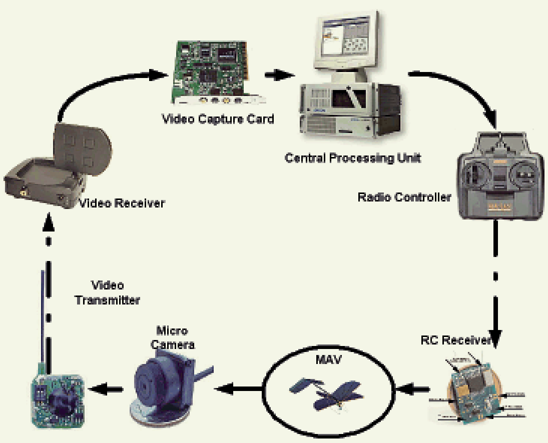


Top view of the tail end of DelFly. Carbon rods run between the rudders and the actuators . The rudders act as elevator and rudder/aileron at the same time. Moving both rudders up and down simultaneously will increase or reduce the pitch angle. But asymmetric motions of the ruddervators result in a simultaneous rolling moment and yawing moment.

The DIDEL indoor radio control receiver weighs just 0.38 grammes. It regulates the power to the propulsion motor and the two magnet servo controls. It is mounted on the side of the fuselage.

The DelFly carries an NTSC video camera of 1.2 grammes, together with a slightly modified wireless video transmitter of 1.8 grammes, capable of transmitting full colour images at a speed 30 Hz. The camera system enables flight beyond line of sight and even automated flight when in artificial vision mode with the assistance of a ground computer.

The DelFly is launched by hand and flown manually on take-off.



With the aid of artificial vision and awareness software on a ground computer, the DelFly can perform some autonomous tasks. First the video camera images are sent to the video receiver on the ground where they are digitalized by a video capture card. The live digital video stream can be monitored by the operator, recorded for later analysis or analysed by vision and pattern recognition software at the same time. Once the software has deduced useful information from the sequence of images it can then compute control signals, for instance to fly towards a target of interest. The control signals are sent to the DelFly by means of the radio control system.

inspire us, but we must certainly not aspire to copying the exact movements of a bird or insect. We have neither the materials nor the electronics to build a kind of artificial housefly on anything like the correct scale. Then there is the fact that nature has its own set of requirements, which are very different from ours. Insects did not evolve to track terrorists, and our MAVs don't have to attract partners and reproduce."

Indoor aircraft "The flapping wings provide the lift and propulsion. For stability and control, DelFly uses an inverted V tailplane. The tailplane carries the direction and altitude rudders. The V-shape is more efficient than the conventional T-shape you see on normal commercial airliners," De Wagter explains.

"The inverted V would not be very practical on an airliner, because it would smash into the ground on landing, but for our light miniature aircraft that is not a problem."

After the completion of the design, the building, testing, and final adjustment had to take place during July and August, which are normally student holidays. The fuselage of DelFly is made up of carbon fibre tubes, and the wing spars use balsa wood, reinforced with carbon fibre. The miniature aircraft has a wingspan of 35 centimetres and a length of 40 centimetres. The wing surfaces are made of transparent Mylar film. In the end, four aircraft were built, with weights varying from fifteen to twenty grams.

De Wagter: "Although DelFly manages the stresses of flight with ease, the same cannot be said of stresses induced by human contact, so we like to have a couple of planes in reserve."

Considering its weight, DelFly is in fact rather large, which means that its wing loading is relatively low. The disadvantage is that it cannot cope very well with gusts of wind, so in fact it is an indoor aircraft.

De Wagter: "DelFly was optimised for a relatively large payload, including a camera, receiver, transmitter, and batteries. The fact that it is an indoor aircraft is a choice by design and has nothing to do with its lack of weight. Moreover, we have flown it outside, and as long as there is not too much wind, it can cope very well."

Electronics bottleneck A very small electric motor weighing only two grams sits in the nose of the aircraft and drives a pair of rods through two miniature gears. The rods act on the two pairs of wings simultaneously so they move up and down in counter phase. On average the wings flap with a frequency of six hertz. In order to be make the aircraft hover, they need to flap slightly faster, at between eight and ten hertz. In this way, DelFly can vary its speed between zero and twenty kilometres per hour.

The tailplane rudders are actuated by means of a pair of juxtaposed magnetic servos, each of which consists of a small coil containing a minute magnet. When an electric current is sent through a coil, it creates a magnetic field that causes the magnet to rotate. The coils are oriented at right angles to each other so as not to affect each other's magnetic fields. The moving magnets act on carbon fibre push-pull rods attached to the rudders, so their positions can be varied continuously and independently of each other.

"The one major bottleneck during construction was the electronics," De Wagter recalls. "This involved handling and soldering extremely thin wires. It is a precision job because a short-circuit is easily created. Electromagnetic interference and sub optimal signals from the lightweight electronics also created problems. We really could not have coped without the help of Rick Ruijsink. In some cases he was the only one capable of solving a problem."

A printed circuit board measuring 1.5 by 1.5 centimetres in the nose of DelFly carries a receiver, a motor controller, and two servo controllers. The receiver processes the signals transmitted by the ground station and controls the motor and the rudders. Carrying a 3.5 gramme lithium battery, DelFly can remain aloft for over fifteen minutes while continuously transmitting images to its base station.

Cyclops DelFly's eye is in its nose. A 1.2 gramme pinhole lens camera records images wherever the aircraft flies. DelFly's brain on the other hand is on the ground, inside a computer at the ground station. A transmitter in DelFly's nose transmits the camera images to the ground station. There they are digitised, fed into a PC running a 3 GHz CPU and processed with artificial vision and recognition software. This is also the way that DelFly can be navigated automatically in the near future. The idea is that the PC takes over control of the aircraft using the information from the images. At the moment the image based automatic controller for DelFly operates entirely in a ‘realistic’ virtual environment. For that purpose the team created a 3D computer model of the sports gym at Delft University. The algorithm steers DelFly autonomously though windows or towards targets such as terrorists while avoiding walls in the virtual environment. The target recognition and control software makes successful decisions based on the information of the synthetic camera images recorded on the virtual flapper. In reality DelFly detects targets on its own, while automated steering remains a challenge.

“The computer first improves the image quality by removing any vibration artefacts and noise resulting from the wireless transmission”, De Wagter says. “Next, using pattern recognition techniques and by detecting colours, shapes, and motion, DelFly can determine the position of an object. The software will use this information to direct itself to a certain target, or away from it, in our next test phase.”

During the official MAV competition in Germany last September, DelFly managed to fly very slowly through a 1.2 metre square frame set up inside a sports centre.

“It was manoeuvred through the frame without any problem whatsoever,” De Wagter recalls, “and DelFly was also the only entry capable of autonomously detecting the make-believe terrorist, a man carrying a red case”, says De Wagter. DelFly still has to be flown manually mostly because of the level of camera image interference. The pilot on the ground can see on a display what DelFly sees, and so can control the aircraft, even when it is out of sight.

“The software for autonomous flight can do quite a lot already,” De Wagter says, “but we will need better camera images if DelFly is to do everything on its own.” Although a helicopter can hover (which after all is what it was designed for), DelFly offers a few major advantages over a helicopter.

De Wagter: “DelFly is more stable, and easier to control. Students who had never before flown a miniature aircraft by remote control were able to fly DelFly with ease after only a few days. A helicopter takes months, if not years, to get under control. Also, DelFly uses a simpler mechanism and is more robust than a helicopter. If the tip of a helicopter blade comes into contact with a wall or window, all you can do is pick up the pieces. DelFly will survive incidents like that. It can be flown much closer to walls and objects without fear of damaging it.”

Applications

The specific properties of DelFly make it suitable for a number of useful applications. The military is interested in its possible use for reconnaissance flights. It could also be used to inspect buildings, bridges, remote installations, or unsafe and inaccessible areas. Police forces could use the concept for observing large crowds. And then there is the toy industry.

De Wagter: “We have had many people ask us where they could buy a DelFly.” The only sensor carried by the current model is the camera. DelFly is a vision-only-control aircraft, which has its limitations.

De Wagter: “When making a rapid turn in flight, the images become blurred, which affects the precision of the automatic control system. A combination of a camera and a small gyroscope would yield better results. Gyroscopes are good at rapid motion responses, just like a fly uses two rapidly vibrating halter-like structures to register rapid movements. And just like the eyes of a fly, the camera captures very detailed images, as long as the fly (and DelFly) don’t turn too fast.”

Lentink: “By working closely together, and by thoroughly integrating three very different fields of knowledge, a group of third-year students managed in ten weeks to produce something that not even the most experienced engineers could manage. The innovative strength of DelFly lies not so much in the sense that it yielded new scientific insights as in its system design, the integration of the flapping technique, its automatic vision system, and the electronics. Not only is it one of the very few successful flapping-wing miniature aircraft, it also is one of the few aircraft that can use its own camera to help control its flight and recognise objects.”

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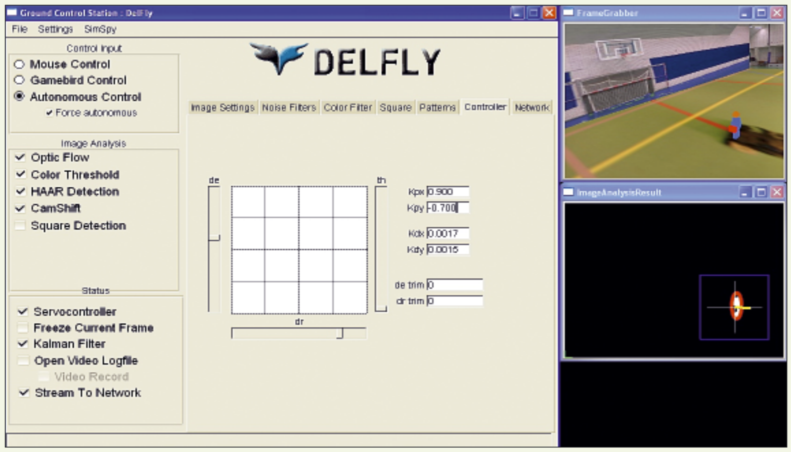
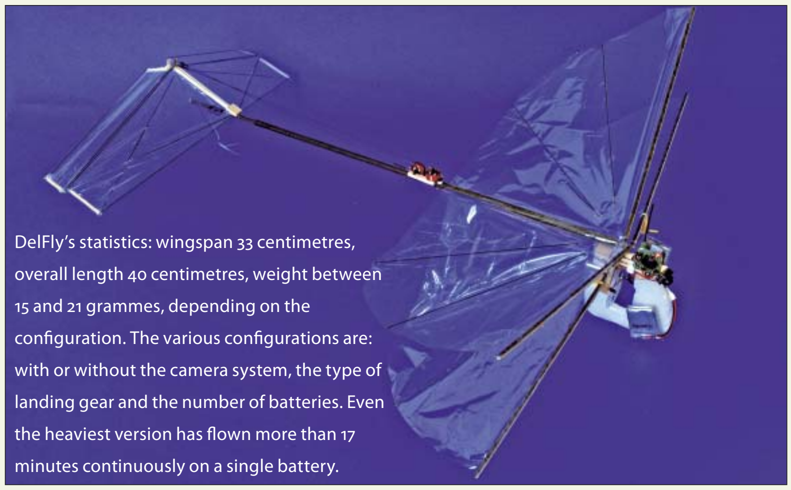


Images are first enhanced for wireless transmission noise and vibration artifacts, followed by a variety of colour, shape, pattern and motion filters to subtract useful information. Once targets of interest are found and the optimal estimation filters have computed their position, a controller directs the MAV either towards or away from this object. The software package shown in this figure can be run in simulation mode or in hardware mode, fed either by recorded video images or by real-time streaming video to allow a variety of tests and debugging. In this simulation the DelFly is following a person with a red suitcase running through a sports hall. Top right: the virtual camera image from the DelFly. Top left: the artificial vision settings and controls, while the result of the image analysis that has detected the person with the red suitcase is shown on the bottom right. This information has proved sufficient to steer the DelFly towards the target.



DelFly’s statistics: wingspan 33 centimetres, overall length 40 centimetres, weight between 15 and 21 grammes, depending on the configuration. The various configurations are: with or without the camera system, the type of landing gear and the number of batteries. Even the heaviest version has flown more than 17 minutes continuously on a single battery.

The DelFly passing through a corridor. The two pairs of interconnected wings are flapping at about 6 hertz.

The DelFly flying outdoors.